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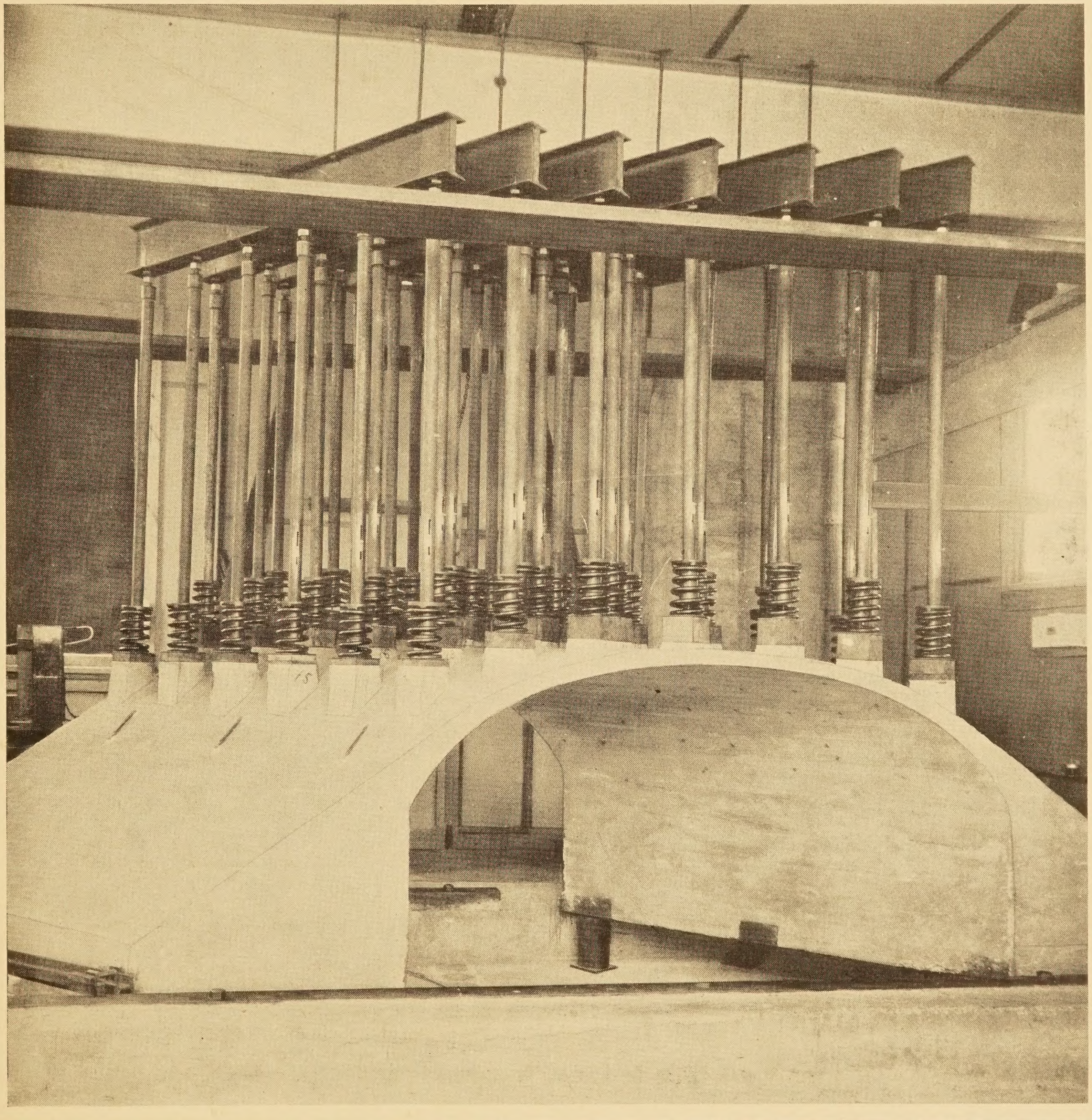

Model Concrete Skew Arch Showing Method of Applying Test Loads

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PROGRESS REPORT OF SKEW ARCH TESTS

BY THE DIVISION OF TESTS, U. S. BUREAU OF PUBLIC ROADS

Reported by **G. W. DAVIS**, Associate Engineer of Tests

LACKING evidence to indicate the necessity for special design, early bridge designers assumed the stress distribution in skew arches to be similar to that in a symmetrical right arch. Rankine says:

> Skew arches are of figures derived from those of symmetrical arches by distortion in a horizontal plane. The elevation of the face of a skew arch, and every vertical section parallel to its face, being similar to the corresponding elevation and vertical section of a symmetrical arch, the forces which act in a vertical layer or rib of a skew arch with its abutments, are the same with those which act in an equally thick vertical layer of a symmetrical arch with its abutments, of the same dimensions and figure, and similarly and equally loaded.[1]

"The angle of skew, or obliquity," as defined by Rankine and still commonly accepted, "is the angle which the axis of the archway * * * makes with a perpendicular to the face of the arch. * * * The span of the archway, 'on the square,' as it is called (that is, the perpendicular distance between the abutments) is less than the span on the skew, or parallel to the face of the arch, in the ratio of the cosine of the obliquity to unity. It is the span on the skew which is equal to that of the corresponding symmetrical arch." [1]

Hool expressed a similar opinion, as follows: "Skew arches may be treated exactly as right arches, the span being taken parallel to the center line of roadway and not at right angles to the springing lines of the arch." [2]

This assumed theory of design was apparently discredited when, on May 14, 1903, a Monier arch of considerable size and extreme skew collapsed under a trial test at Bendigo, Australia, with loss of life. The failure was sudden and unexpected and unlike those which had been recorded in the cases of similar arches in Europe and elsewhere, in which signs of failure were visible long before the final collapse. The contractor, believing the failure to be due to faulty design, retained W. C. Kernot to determine the reasons for the collapse, and his report contains some valuable information. "Assuming the abutments to be immovable," said Mr. Kernot, "which must be very nearly correct, as they are small in height, massive in section, and founded on solid rock, and that the arch was perfectly and uniformly elastic, so that the stress in any given direction would be proportional to the change of dimensions, the following calculation was made. The arch was supposed to have been pressed down to a given small extent by its own weight, and the superincumbent load, and the consequent reduction in length of lines traced on its extrados in the positions AB and AC (fig. 1), were computed, the result being that the percentage of shortening in the direction AC was found to be almost exactly double that in the direction AB or in any line parallel to AB. Consequently, it followed that the heaviest stress in the arch was diagonally across from A to C, that the stress in the direction AB was only half as great, while that in the direction BD was found by an extension of the same calculation to be excessively small." [3]

An investigation of the failure confirmed these computations. It was found that the abutment at the obtuse angle of the arch "had been absolutely pulverized though of good, strong concrete, thus bearing witness to the great local intensification of stress." To overcome this unequal distribution of stress it was recommended that the mass of concrete in the abutment of the obtuse angle of the arch be increased, and that the arch ring be thickened. The thickening reommended was from one-fourth to one-half the thickness computed for a right arch corresponding to a variation in the skew from 20° to 50°.

The increased thickness was to diminish in all directions until it vanished at a distance equal to one-fourth of the skew span. Similar provisions were made for the abutments. The acute angles of the abutments were also replaced by right angles.

This failure added to the doubt which was already felt by some engineers as to the soundness of the theory of design which treated skew arches exactly as right arches except that the span was taken parallel to the faces of the arch and not at right angles to the springing line. As a result, a few tests have been made in recent years to determine the distribution of stresses in skew arches. C. R. Young[4] showed by means of india-rubber models that the generally accepted practice was in error. Tests made by C. H. Spofford, of the Massachusetts Institute of Technology, as well as a series of tests, using model concrete arches, carried on under the direction of John R. Chamberlin, deputy highway commissioner of Ohio, and Clyde T. Norris, of Ohio State University, by P. H. Ellman, and W. Hartline, all tended to show that the resultant pressures of skew arches fell near the obtuse angle of the arch.

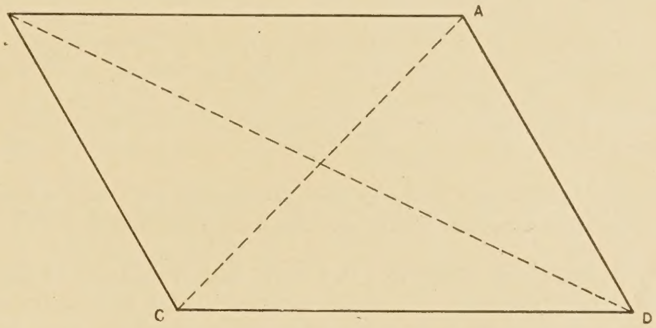

FIG. 1.—Plan of typical skew arch

BUREAU TESTS MADE NECESSARY BY SKEW ARCHES PROPOSED FOR FEDERAL-AID HIGHWAY SYSTEM

The lack of experimental data and the occasional necessity of using skew arches in peculiar locations on the Federal-aid highway system caused the Bureau of Public Roads to begin a series of tests in July, 1922. The information sought was the distribution and intensity of the abutment reactions and the amount of deformation of the arch ring along the springing line under uniform loads. It was hoped that the results would provide a more rational basis for design.

The results have been encouraging, but the experiments may not yet be regarded as complete. The

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[1] A Manual of Civil Engineering, by W. J. M. Rankine, p. 429, sec. 295.

[2] Reinforced Concrete Construction, G. A. Hool, vol. III, p. 43, sec. 22.

[3] The Stresses in Skew Arches, by W. C. Kernot, Engineering News, vol. 49, no. 24, June 11, 1903, p. 529.

[4] University of Toronto, Toronto, Ontario, Canada.

tests have been made on model concrete arches, one-quarter size, with skews of 15°, 30°, 45°, and 60°. In all, the span parallel to the faces has been uniformly 7 feet; consequently the span at right angles to the springing line has been variable. Before it will be possible to formulate a mathematical basis for design, therefore, it will be necessary to make complete tests, (1) with the transverse width of the arch and the span at right angles to the springing lines constant and the skew variable, (2) with the transverse width of the arch and the skew constant and the span at right angles to the springing lines variable, and (3) with the span at right angles to the springing lines and the skew constant and the transverse width of the arch variable. All of these tests, moreover, should be made for various heights of rise.

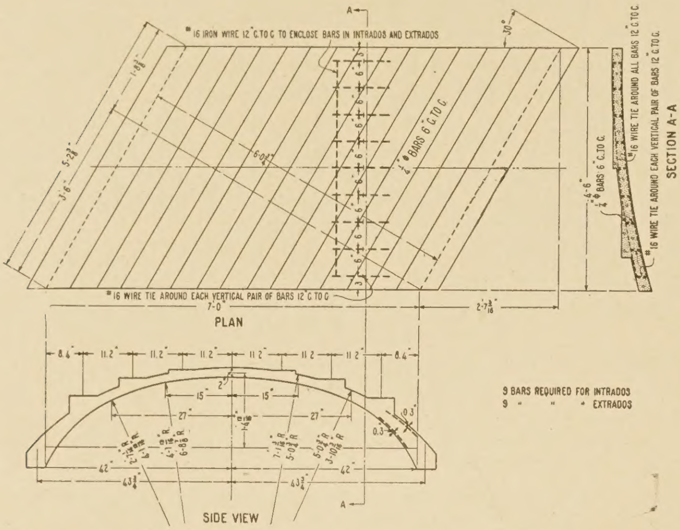

Fig. 2.—Detailed sketch of 30° skew arch. The structural details and dimensions for the 15°, 45°, and 60° arches were the same with the exception of the span at right angles to the abutments and the oblique length of the abutments

TENTATIVE CONCLUSIONS DRAWN FROM BUREAU TESTS

As a result of the tests thus far made by the bureau the following tentatvie and general conclusions may be drawn.

1. The vertical reactions varied uniformly from a maximum at the obtuse angle of the arch to a minimum at the acute angle.
2. The increase of the vertical reaction at the obtuse angle of the arch varies directly as the angle of skew.
3. The resultant pressures of both the horizontal and vertical components move toward the obtuse angle of the arch with an increase in the skew.
4. The direction of the side thrust is toward the face of the arch at the acute angle and the intensity increases with the degree of skew.

DESCRIPTION OF THE TESTS

The mechanical difficulties of the tests resolved themselves into the development of a method of applying uniform loads to the model arches and some means of accurately measuring the resultant vertical and horizontal reactions without movement of the arch under load. A preliminary test was made during the summer of 1923 on a 30° skew arch with abutments, using Kreuger cells to measure the abutment reactions and Berry strain gauges to measure the stresses in the arch ring. The results were unsatisfactory due to the difficulty of obtaining complete sets of readings on a number of Kreuger cells which was caused principally by poor impressions on some of the carbon films, and because of the variation in the Berry strain gauge readings due to the personal equation. These results were finally discarded and the successful tests were made as follows:

The model arches tested, which were one-fourth full size, had skews of 15°, 30°, 45°, and 60°. All were 7 feet in span as measured parallel to the faces, 1.4 feet in rise, 4½ feet face to face, and 2 inches thick at the crown. They were made of mortar mixed of 1 part Portland cement and 3 parts Potomac River sand with a slump of 3 to 4 inches. The reinforcement consisted of eighteen ¼-inch deformed bars placed in vertical pairs parallel to the faces of the arch, 6 inches center to center, with ties, both horizontal and vertical around each pair, made of No. 16 iron wire spaced 12 inches center to center. (Fig. 2.)

All arches were cut off at the springing line and a base or abutment with a squared section 4 inches on a side and reinforced with two ½-inch deformed bars was cast as an integral part of the arch rings. Steel bearing plates were cast in place in the base at those points at which reactions were to be measured.

UNIFORM LOAD APPLIED BY SPRINGS

Uniform loads were applied on 42 symmetrically placed loading points on the arch ring by compressing helical springs 5 inches in diameter and 7 inches high, of a uniform compressive strength (within 2 per cent) of 915 pounds per inch. Forty-two vertical struts of 1½-inch pipe bolted at their upper ends to a cribbing of I-beams took the vertical thrust. This cribbing was supported by a heavy beam directly over the experimental arch, and the carrying beam was, in turn, supported at each end by a 2-inch bolt which engaged a steel yoke bolted to the webs of two upright channel irons anchored to the floor and separated from each other by a space sufficient to clear the overhead beam. By this arrangement the entire cribbing could be raised or lowered by means of nuts running on the supporting 2-inch bolts.

Approximately the entire desired load was applied simultaneously by lowering the steel cribbing, thus doing away with possible cross stresses which might have been introduced had the load been applied by screwing down the springs one by one. Final fine adjustments were made by individual screw jacks at the top of each vertical strut. These jacks consisted of 1-inch cap screws working through a nut forced into a coupling on the upper end of each pipe. The compression of each spring was measured by a fixed scale and a moving vernier actuated by a plunger inside of the strut. As the plungers rested at the center of the springs the compression measured was the mean compression of the spring. Scales and verniers read to hundredths of an inch or the nearest 10 pounds of load.

In the measurement of abutment reactions, procedure was as follows: The entire arch was surrounded by a rigid frame of concrete and steel angles bolted to the concrete floor. One side of the arch was fixed, being supported at three points on blocking and a ¾-inch steel ball. Horizontal thrusts at the fixed end were taken up by blocking and spherical bearing blocks placed between the rigid frame and the arch. At the other end measuring devices were placed to take both vertical and horizontal reactions in positions symmetrical with the fixed supports and blocking at the anchored end. (Fig. 3.)

Measuring devices for determining the amount of reactions consisted of soil pressure cells actuated by 16 to 1 lever arms. These lever arms consisted of a length of 25-pound rail resting on knife edges, the one at the load end resting on the floor and the other on the center of a soil pressure cell. These knife edges were 32 inches on centers. The load was applied through a ¾-inch ball and clock-spring knife edges at a point 2 inches from the fixed knife edge thus giving a reduction of 16 to 1. The area of diaphragm in the soil pressure cell being 10 square inches, it was possible to balance a 1,000-pound load by approximately a 6-pound air pressure.

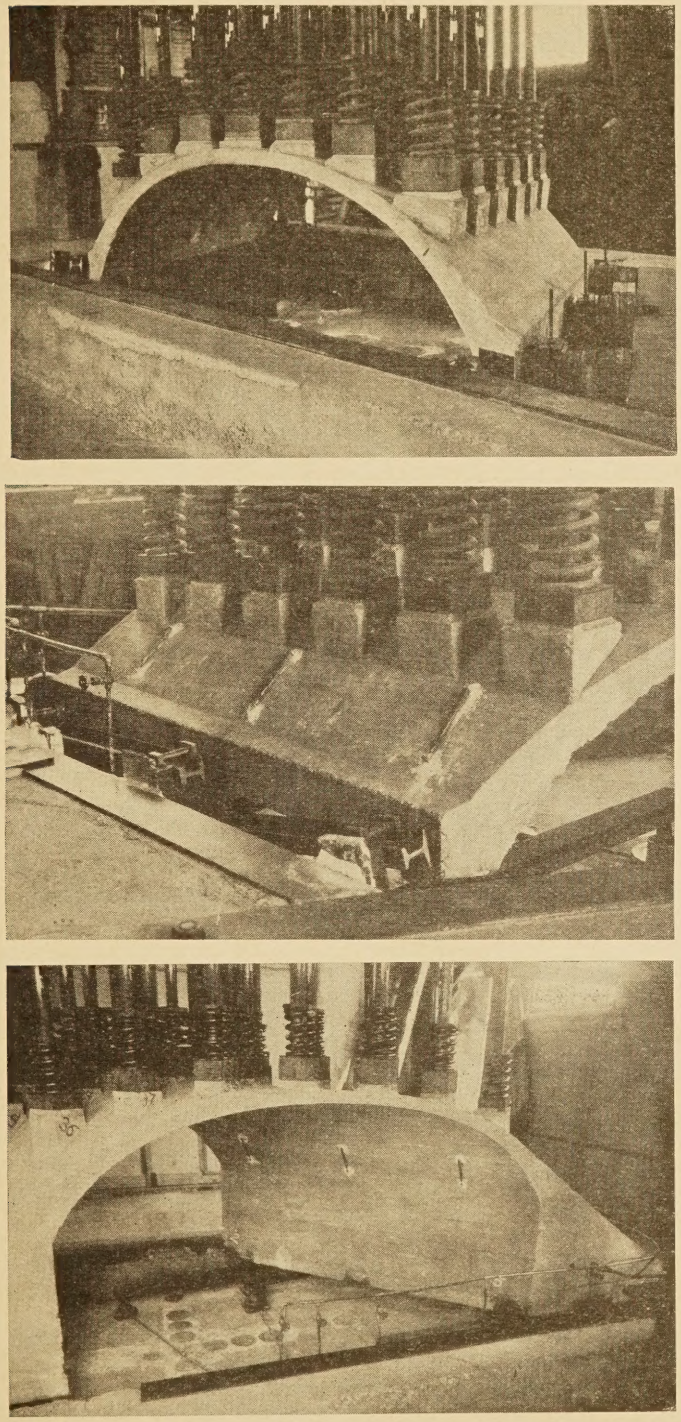

FIG. 3.—*Upper.*—Showing rigid frame surrounding an arch and blocking and spherical bearing blocks to take longitudinal thrust at fixed end of arch
Middle.—Showing graphic strain gages on extrados and levers for measuring horizontal thrusts and vertical reactions
Lower.—Showing graphic strain gages on intrados and levers and soil pressure gages for measuring vertical reactions

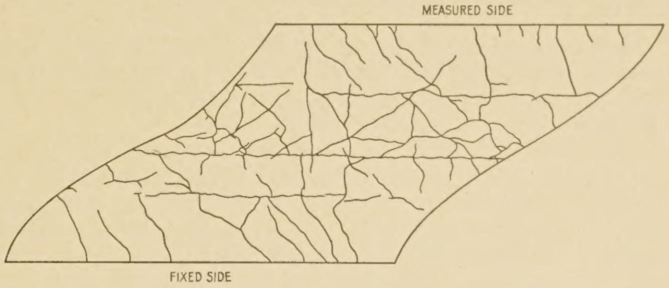

FIG. 4.—The intrados of the 60° skew arch showing the cracks which developed under final load of 60,000 pounds

Each soil pressure cell with its lever arm and knife edges was calibrated by placing it under the head of a testing machine under known loads. In place of the conventional pressure gauges used with the pressure cells for measuring soil pressures, a sealed monometer tube or mercury column was used and the readings in millimeters of the height of mercury column for each known load were recorded. Expansion of the air and mercury was controlled and the column brought back to a known zero by means of a jacket of ice water and the circulation was maintained by means of a rubber bulb. Several sets of readings were taken for each cell, the variation being negligible. The movement of the lever over the cell was found to be only 0.0004 inch, and the ratio of the lever arms being 16 to 1, the movement at the load point was obviously so small that the arch could be considered to remain stationary, which is one of the conditions sought in the tests.

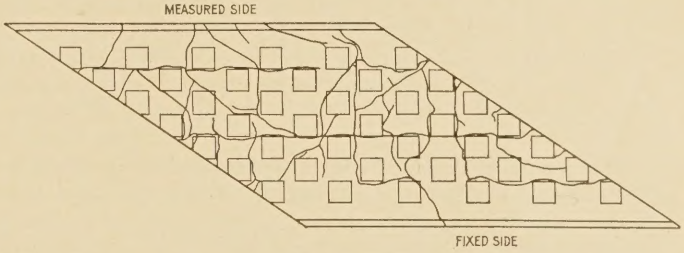

FIG. 5.—The extrados of the 60° skew arch showing the cracks which developed under final load of 60,000 pounds

The deformations of the arch ring were measured by means of graphic strain gauges mounted at three points on the intrados and three points on the extrados on the measured side of the arch. These gauges were placed 6½ inches above the springing line, one at the center and one on each side midway between the two outer loading points on each side and near the obtuse and acute angles respectively.

TEST OF SIXTY-DEGREE SKEW ARCH

The 60° skew arch was poured April 21, 1923, and loaded to destruction December 11 the same year, 235 days after pouring. The total applied load was increased by increments of 4,200 pounds, equal to 100 pounds on each spring, and the arch failed under a total load of 25.2 tons, equal to a spring load of 1,200 pounds. At each application of load up to the spring load of 500 pounds, the vertical reactions and horizontal thrusts at the springing line were measured at the obtuse and acute angles and at the center. Beyond the 500-pound spring load they were not measured because they exceded the capacity of the knife edges and measuring devices. The nature of the failure is shown in Figures 4, and 5.

Six test cylinders made at the time the arch was poured showed at the end of 125 days a mean breaking strength of 4,235 pounds per square inch and an average modulus of elasticity of 3,370,000.

The mean vertical reactions measured at the three points are shown in Table 1, and in graphical form in Figure 6, from which it will be seen that, in each case, they vary uniformly from a maximum at the obtuse angle to a minimum at the acute angle.

TABLE 1.—*Mean vertical reactions at three points of the 60° skew arch*

Theoretical applied load on one-half of arch	Mean measured vertical reactions due to applied load								Variation of measured reaction from theoretical applied load
	Obtuse angle		Center		Acute angle		Total		
Pounds	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Per cent*
2, 100	1, 365	70	550	28	40	2	1, 955	100	6. 9
4, 200	2, 880	69	1, 225	29	65	2	4, 170	100	. 7
6, 300	4, 360	68	1, 945	30	110	2	6, 415	100	1. 8
8, 400	5, 940	67	2, 820	32	130	1	8, 890	100	5. 8
10, 500	7, 780	69	3, 470	31	80	--------	11, 330	100	7. 9
Mean----	--------	69	--------	30	--------	1	--------	100	----------

The mean horizontal thrusts are shown in Table 2 and also in Figure 6, from which it will be seen that the average thrust at the obtuse angle is approximately 63 per cent of the live load applied, while at center it is only approximately 4 per cent. The thrust at the acute angle decreases from 2.3 per cent of the live load under a theoretical load of 2,100 pounds to a negative thrust equal to 0.3 per cent of the live load under a theoretical load of 10,500 pounds.

TABLE 2.—*Mean horizontal thrusts at three points of the 60° skew arch*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured horizontal thrusts due to applied load							
		Obtuse angle		Center		Acute angle		Total	
		Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*
2, 100	1, 955	1, 260	64. 4	80	4. 1	45	2. 3	1, 385	70. 8
4, 200	4, 170	2, 610	63. 0	175	4. 0	60	1. 4	2, 845	68. 4
6, 300	6, 415	3, 775	59. 0	255	4. 0	25	. 4	4, 055	63. 4
8, 400	8, 890	5, 300	59. 6	455	5. 1	−5	--------	5, 750	64. 7
10, 500	11, 330	7, 665	67. 7	560	4. 9	−30	−. 3	8, 195	72. 3
Mean----	--------	--------	62. 7	--------	4. 4	--------	. 8	--------	67. 9

The variation of the total measured reaction from the theoretical applied load as shown in Table 1 is probably due to inaccuracy in the application of the load rather than to errors in the measured values.

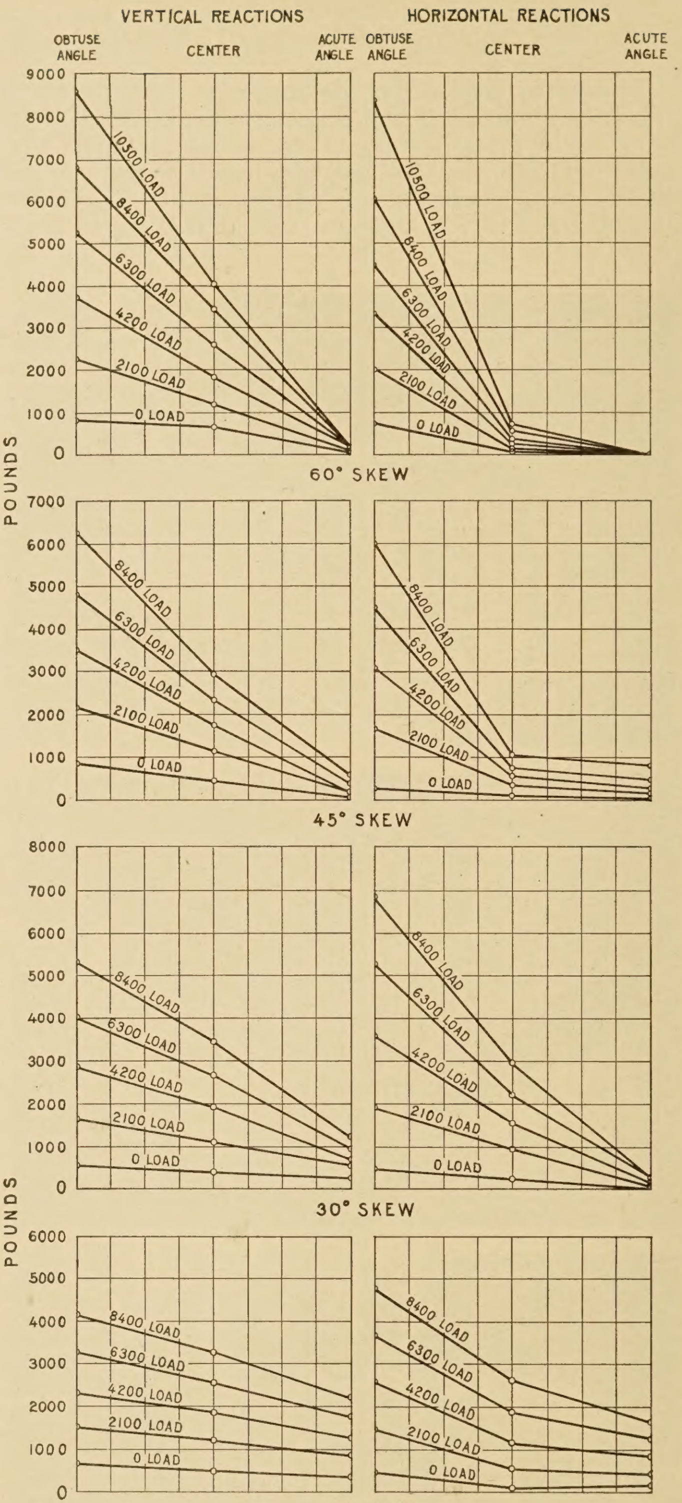

FIG. 6.—The amount of the vertical and horizontal reactions at the obtuse angle, center, and acute angle of the 15°, 30°, 45°, and 60° skew arches with no applied load and applied loads at increments of 2,100 pounds

This is apparent from the close agreement in the measured values themselves as indicated in Table 3.

The strain-gauge readings on this arch were erratic. It has since been found that this was due to the turning of the gauges in the bearing points when the smoked-glass slides of the strain gauges were moved up to a new position. Although the recorded deformations were not consistent for equal increments of load, the

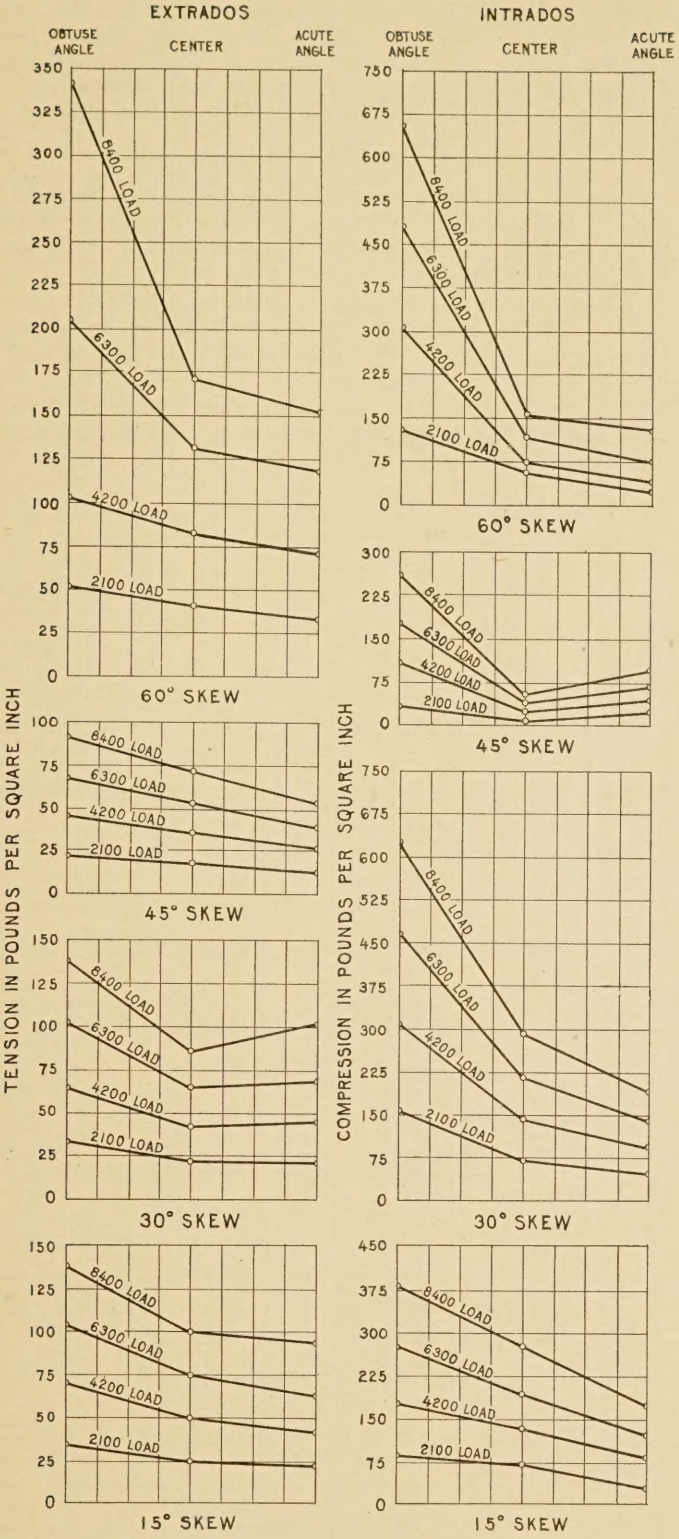

FIG. 7.—Stresses computed from strain-gage readings on the extrados and intrados of the 15°, 30°, 45°, and 60° skew arches for several increments of load

relative stresses checked the reactions as recorded, from four to five times the deformation shown at the acute angle being recorded at the obtuse angle. The stress indicated in the intrados at the obtuse angle under a total load of 16,800 pounds was approximately 650 pounds per square inch as against 130 pounds per square inch at the acute angle. (See fig. 7.)

TABLE 3.—*Variation in measurements of vertical reactions and horizontal thrusts on the 60° skew arch*

Theoretical applied load on one-half of arch	Vertical reactions		Horizontal thrusts	
	Number of readings	Maximum variation from mean sum	Number of readings	Maximum variation from mean sum
Pounds		*Per cent*		*Per cent*
2, 100	13	2. 3	13	8
4, 200	13	2. 0	13	9
6, 300	8	. 5	8	3
8, 400	6	. 5	6	7
10, 500	4	2. 0	4	2

TEST OF THIRTY-DEGREE SKEW ARCH

The 30° skew arch was poured December 15, 1923. The loading and set-up for the test, the points at which the reactions were read and the relative positions of the strain gauges were the same as in the test of the 60° arch. In this case, however, the rotation of the strain gauges was prevented by placing wooden wedges between the body of the gauge and the arch.

It was shown by the tests of the 60° skew that the thrust is diverted toward the obtuse angle resulting in tortion or a tendency of the arch to swing on the abutments. This tendency of the arch to swing or rotate—causing the acute angle to pull away from the measuring device—was so great under all but small loads that ribbon knife-edges were thrown out of the vertical position and sheared. To prevent the breaking of the knife-edges, it was found necessary to counteract this swinging tendency by fixed wedges placed against the face of the arch at the acute angle on the anchored end with a pressure cell and a 2 to 1 lever between the face and rigid framework at the acute angle at the measured end.

Six sets of readings for the vertical reactions, horizontal thrusts, and side swings were taken with unit spring loads varying from 100 to 400 pounds. The mean vertical reactions, as measured at three points, are shown in Table 4, from which it is apparent that for the 30° skew 54 per cent of the load applied is transmitted to the obtuse angle of the arch, 34 per cent to the center, and 12 per cent to the acute angle. By reference to Figure 6 it will be seen that in this case, as in the 60° arch, the vertical reactions vary uniformly from a maximum at the obtuse angle to a minimum at the acute angle.

TABLE 4.—*Mean vertical reactions at three points of the 30° skew arch*

Theoretical applied load on one-half of arch	Mean measured vertical reactions due to applied load								Variation of measured reaction from theoretical applied load
	Obtuse angle		Center		Acute angle		Total		
Pounds	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Per cent*
2, 100	1, 100	54	685	33	260	13	2, 045	100	2. 6
4, 200	2, 305	55	1, 418	34	445	11	4, 168	100	. 7
6, 300	3, 455	54	2, 245	35	690	11	6, 390	100	1. 4
8, 400	4, 745	54	3, 075	35	935	11	8, 755	100	4. 2
Mean	--------	54	--------	34	--------	12	--------	100	----------

The mean horizontal thrusts for six sets of readings are given in Table 5, and the mean side thrusts in Table 6. The variation in the reaction measurements are shown in Table 7. It is evident from the latter table that, in this test as in the test of the 60° skew arch, the principal inaccuracy is in the application of the load rather than the measurement of the reactions. The large percentage of variation in the side thrust under the first three loads is due to the small pressures. It should be noted that the fourth reading is more stable.

Table 5.—*Mean horizontal thrusts at three points of the 30° skew arch*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured horizontal thrusts due to applied load							
		Obtuse angle		Center		Acute angle		Total	
		Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*
2, 100	2, 045	1, 425	70	705	34	35	1. 7	2, 165	105. 7
4, 200	4, 168	3, 105	74	1, 300	31	75	1. 8	4, 480	106. 8
6, 300	6, 390	4, 775	75	1, 950	30	125	2. 0	6, 850	107. 0
8, 400	8, 755	6, 335	72	2, 710	31	205	2. 3	9, 250	105. 3
Mean			72. 8		31. 5		1. 9		106. 2

Table 6.—*Mean side thrusts toward face of 30° skew arch at the acute angle*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured side thrust due to applied load	
		Side thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*
2, 100	2, 045	85	4
4, 200	4, 168	295	7
6, 300	6, 390	510	8
8, 400	8, 755	785	9
Mean			7

Table 7.—*Variation in measurements of reactions on the 30° skew arch*

Theoretical applied load on one-half of arch	Maximum variation of any sum from mean sum of reactions		
	Vertical reaction	Horizontal thrust	Side thrust
Pounds	*Per cent*	*Per cent*	*Per cent*
2, 100	4	5	50
4, 200	3	2	60
6, 300	3	5	20
8, 400	3	1	1

The strain-gauge readings on this arch were consistent for equal loads, undoubtedly due to the wedging of the gauges which prevented the rotation of the gauge points. Tension was found to exist at all three points measured on the extrados with a maximum at the obtuse angle of 138 pounds per square inch under a total load of 16,800 pounds. All three points on the intrados were found to be in compression, with a maximum at the obtuse angle and a minimum at the acute angle. The maximum compression developed under a total load of 16,800 pounds was 630 pounds per square inch. Figure 7 shows the mean values for various loads. Six test cylinders showed a breaking strength of 5,240 pounds per square inch and a mean modulus of elasticity of 3,813,000 at the end of 123 days.

TEST OF FORTY-FIVE-DEGREE SKEW ARCH

The 45° skew was poured April 24, 1924. Loading set-up and relative points at which reactions were measured and gauges placed were the same as in the 30° and 60° skews previously described.

Thirteen sets of readings for vertical reactions, horizontal thrusts, and side thrusts were taken with unit loads varying from 100 to 400 pounds per spring. These are shown respectively in Tables 8, 9, and 10, which are similar to the corresponding tables for other tests. The accuracy and consistency of the measurements is indicated by Table 11.

Table 8.—*Mean vertical reactions at three points of the 45° skew arch*

Theoretical applied load on one-half of arch	Mean measured vertical reactions due to applied load								Variation of measured reaction from theoretical applied load
	Obtuse angle		Center		Acute angle		Total		
Pound	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Per cent*
2, 100	1, 305	65. 0	680	34. 0	25	1. 0	2, 010	100	4. 3
4, 200	2, 660	65. 6	1, 290	31. 8	105	2. 6	4, 055	100	3. 4
6, 300	3, 960	64. 4	1, 920	31. 2	275	4. 4	6, 155	100	2. 3
8, 400	5, 365	64. 0	2, 510	30. 0	505	6. 0	8, 380	100	. 2
Mean		65. 0		32. 0		3. 0		100	

Table 9.—*Mean horizontal thrusts at three points of the 45° skew arch*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured horizontal thrusts due to applied load							
		Obtuse angle		Center		Acute angle		Total	
		Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*
2, 100	2, 010	1, 375	68. 4	260	12. 9	65	3. 2	1, 700	84. 5
4, 200	4, 055	2, 830	69. 8	515	12. 7	215	5. 3	3, 560	87. 8
6, 300	6, 155	4, 240	68. 9	730	11. 8	455	7. 4	5, 425	88. 1
8, 400	8, 380	5, 730	68. 4	995	11. 9	695	8. 3	7, 060	88. 6
Mean			68. 9		12. 3		6. 1		87. 2

Table 10.—*Mean side thrusts toward face of 45° skew arch at the acute angle*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured side thrust due to applied load	
		Side thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*
2, 100	2, 010	175	9
4, 200	4, 055	410	10
6, 300	6, 155	680	11
8, 400	8, 380	905	11
Mean			10. 2

Table 11.—*Variation in measurements of reactions on the 45° skew arch*

Theoretical applied load on one-half of arch	Maximum variation of any sum from mean sum of reactions		
	Vertical reaction	Horizontal thrust	Side thrust
Pounds	*Per cent*	*Per cent*	*Per cent*
2,100	3.4	7.2	15
4,200	3.7	8.5	14
6,300	3.4	7.3	10
8,400	1.2	8.3	9

Test cylinders made at the time the arch was poured showed a mean breaking strength of 4,885 pounds per square inch at 90 days and a mean modulus of elasticity of 3,309,000.

By the strain-gauge readings tension was found to exist at all points measured on the extrados with a maximum at the obtuse angle of 92 pounds per square inch under a load of 16,800 pounds on the entire arch. Compression existed at all three points on the intrados with a maximum of 260 pounds per square inch at the obtuse angle under a total load of 16,800 pounds. The strain-gauge readings were consistent and showed a distribution similar to the vertical and horizontal reactions.

TEST OF FIFTEEN-DEGREE SKEW ARCH

The 15° arch was poured on September 22, 1924. The set-up of loading and measuring devices as well as the location of the strain gauges was the same as in the previous cases.

Eleven sets of readings were taken for vertical reactions, horizontal thrusts, and side thrusts with unit loads per spring from 100 to 400 pounds in 100-pound increments. These are shown respectively in Tables 12, 13, and 14, and the accuracy and consistency of the measurements is indicated by Table 15.

Test cylinders at the end of 80 days showed a mean breaking strength of 5,060 pounds per square inch and a mean modulus of elasticity of 3,151,400.

Table 12.—*Mean vertical reactions at three points of the 15° skew arch*

Theoretical applied load on one-half of arch	Mean measured vertical reactions due to applied load								Variation of measured reaction from theoretical applied load
	Obtuse angle		Center		Acute angle		Total		
Pound	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Per cent*
2,100	845	44.2	660	34.4	410	21.4	1,915	100	8.8
4,200	1,765	44.3	1,355	33.9	870	21.8	3,990	100	5.0
6,300	2,650	43.9	2,070	34.3	1,310	21.8	6,030	100	4.3
8,400	3,510	43.2	2,850	35.1	1,770	21.7	8,130	100	3.2
Mean----	--------	43.9	--------	34.4	--------	21.7	--------	100	----------

Table 13.—*Mean horizontal thrusts at three points of the 15° skew arch*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured horizontal thrusts due to applied load							
		Obtuse angle		Center		Acute angle		Total	
		Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction	Thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*	*Pounds*	*Per cent*
2,100	1,915	980	49.5	490	24.8	330	16.7	1,800	91.0
4,200	3,990	2,070	51.9	1,100	27.6	625	15.6	3,795	95.1
6,300	6,030	3,200	53.1	1,780	29.5	1,005	16.7	5,985	99.3
8,400	8,130	4,330	53.3	2,540	31.3	1,495	18.4	8,365	103.0
Mean----	--------	--------	51.9	-------	28.3	--------	16.9	--------	97.1

Strain-gauge readings gave practically a straight line distribution under all loads and showed tension on the extrados and compression on the intrados. Maxima were found at the obtuse angle in both cases and showed a maximum tension of 138 pounds per square inch and a maximum compression of 378 pounds per square inch under a total load of 16,800 pounds on the entire arch. It is not believed that a direct comparison of stresses as measured in the arches of various skews would be of value, due to varying temperatures

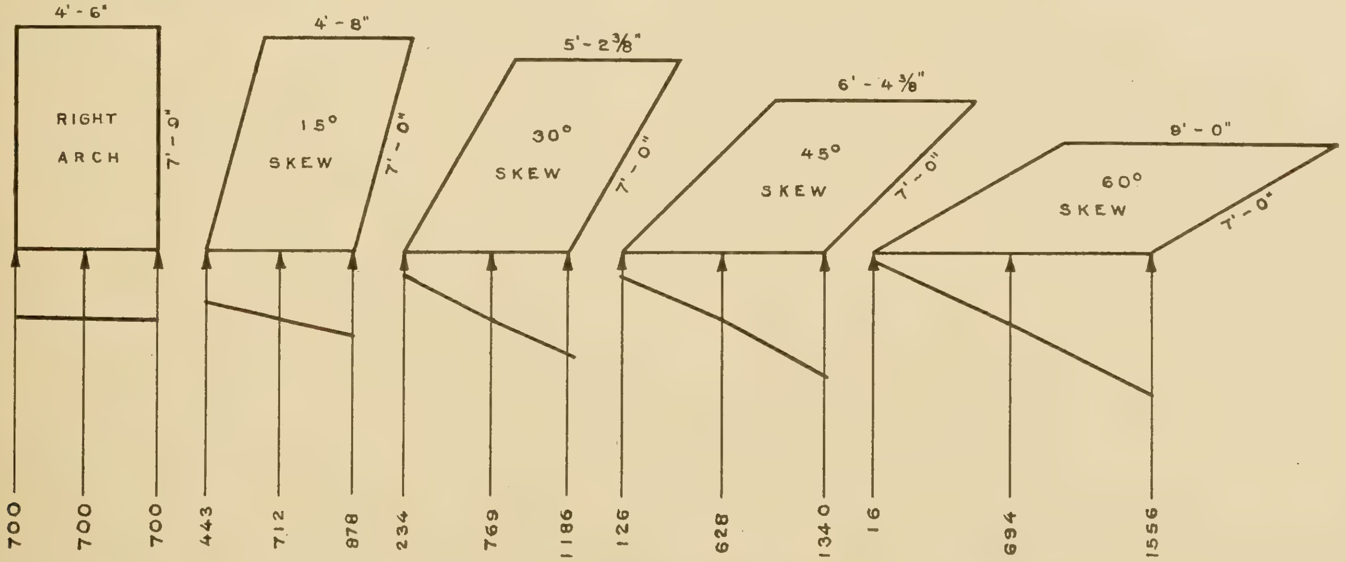

Fig. 8.—Mean vertical reactions of the 15°, 30°, 45°, and 60° skew arches and a right arch. The figures represent the mean of reactions corresponding to an increment of load of 2,100 pounds on one-half of the arch

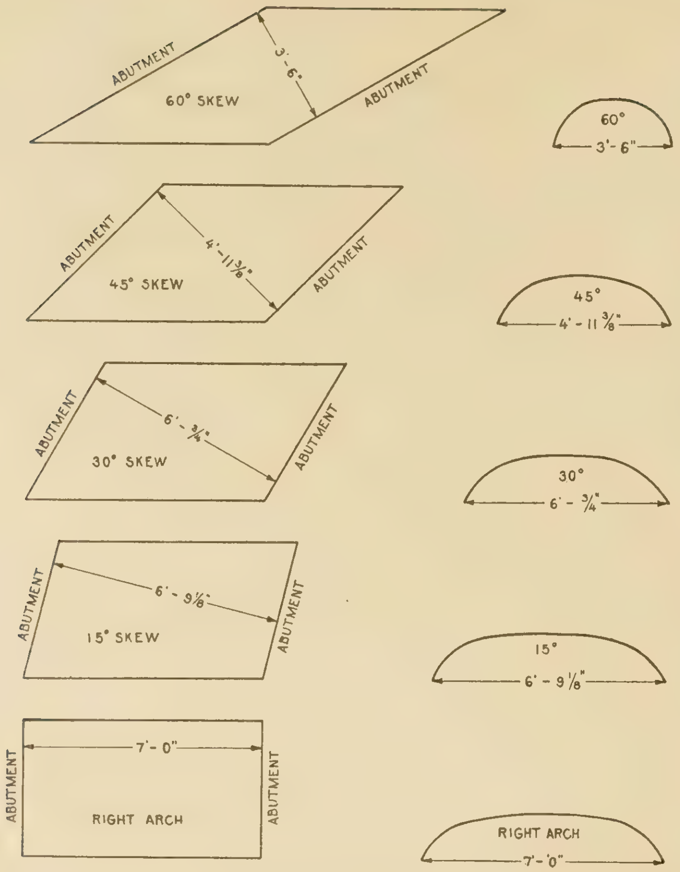

Fig. 9.—Plan of skew arches and dimensions of arch rings at right angles to the abutments. The shortening of the arch ring increases with the degree of skew

existing during the periods in which tests were made. The distribution of the recorded stresses is, however, a check on the recorded reactions for the various arches. Figure 7 shows the strain-gauge readings for the various arches.

Table 14.—*Mean side thrusts toward face of 15° skew arch at the acute angle*

Theoretical applied load on one-half of arch	Measured vertical reaction	Mean measured side thrust due to applied load	
		Side thrust	Relation to measured reaction
Pounds	*Pounds*	*Pounds*	*Per cent*
2,100	1,915	130	7
4,200	3,990	295	7
6,300	6,030	475	8.
8,400	8,130	690	8
Mean			7.5

Table 15.—*Variation in measurements of reactions on the 15° skew arch*

Theoretical applied load on one-half of arch	Maximum variation of any sum from mean sum of reactions		
	Vertical reaction	Horizontal thrust	Side thrust
Pounds	*Per cent*	*Per cent*	*Per cent*
2,100	4.3	7.6	35.0
4,200	1.0	7.0	22.0
6,300	2.3	6.9	29.0
8,400	3.0	5.0	12.5

COMPARISON OF THE TEST RESULTS ON ALL ARCHES

Vertical reactions.—A comparison of the vertical reactions for the right arch and the 15°, 30°, 45°, and 60° skew arches is shown in Figure 8. Values used for the right arch are theoretical values; those for the skew arches are measured values. Vertical ordinates as plotted are mean increments due to successive loads of 100 pounds per spring or an increment in load of 2,100 pounds on one-half of the arch. Comparisons are made at the obtuse angle, the center, and at the acute angle.

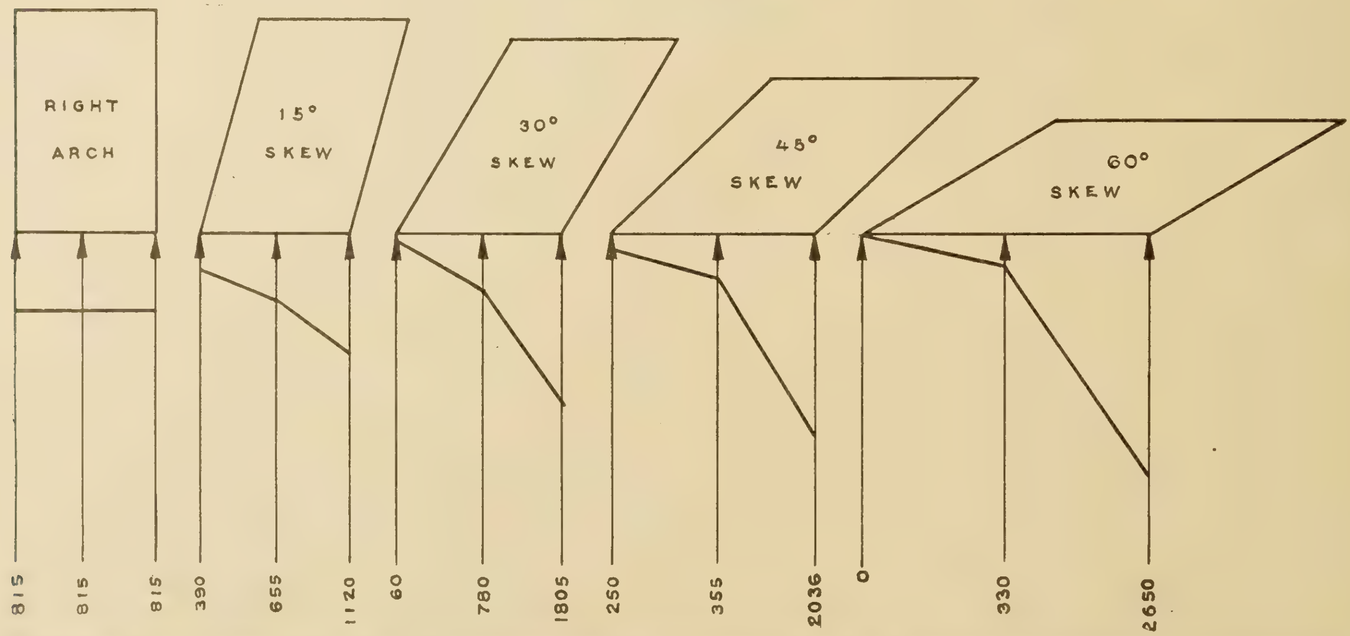

Fig. 10.—Mean horizontal reactions of the 15°, 30°, 5°, and 60° skew arches. The figures represent the mean of reactions corresponding to an increment of load of 2,100 pounds on one-half of the arch

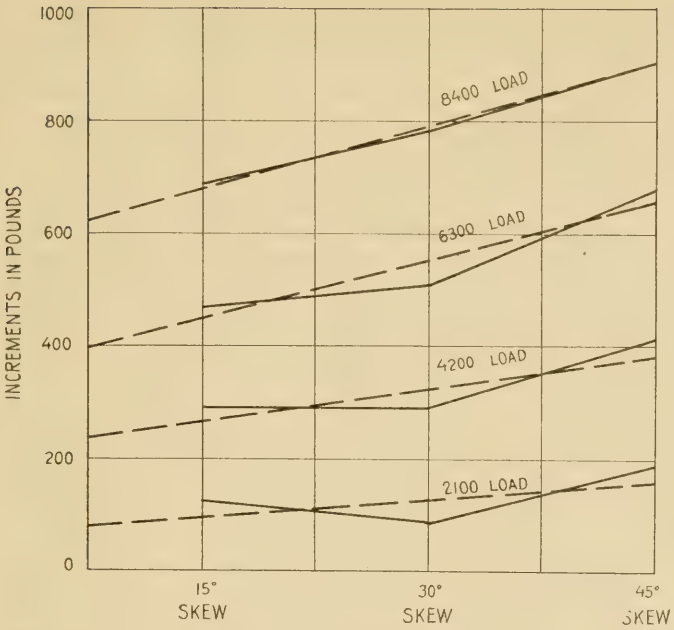

FIG. 11.—Mean side thrusts toward the face of the arch at the acute angle of the 15°, 30°, 45°, and 60° skew arches. The figures represent the mean of reactions corresponding to an increment of load of 2,100 pounds on one-half of the arch

From an inspection of Figure 8, it will be seen that the vertical reactions increase at the obtuse angle from one-third of the load applied for the right arch to two-thirds of the load applied for the 60° skew and that this increase varies uniformly as the angle of skew. At the center point the vertical reactions remain constant at one-third the load applied for the right arch and all the skew arches. At the acute angle vertical reactions decrease from one-third of the load applied for a right arch to practically zero (1 per cent) for a 60° skew, this decrease varying uniformly with the angle of skew. It should be noted that the sum of the vertical reactions for any given arch equals the load applied within allowable limits (less than 6 per cent).

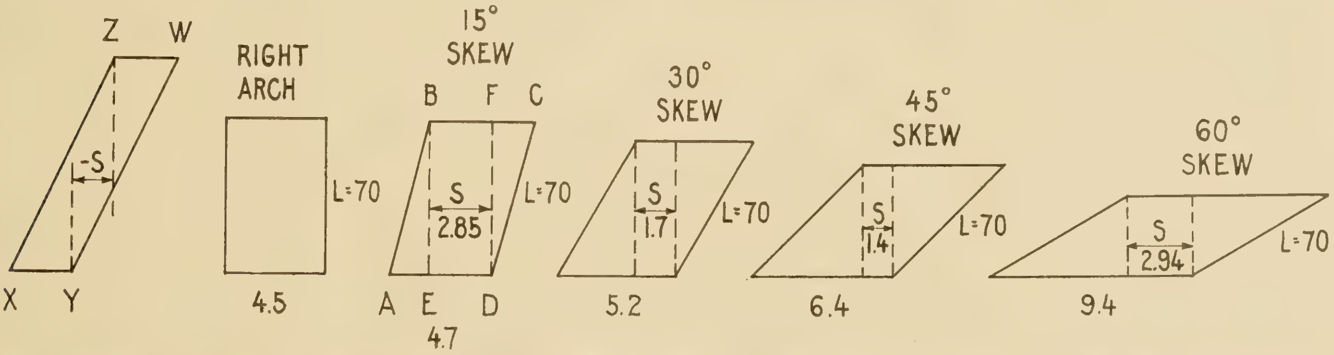

FIG. 12.—Sections showing variation in abutment length and span "on the square" for right and skew arches of various skews with uniform width normal to the faces of the arch. The width of sections of right arch included within the measured arches is indicated by S. Section X Y W Z shows a type of arch in which there is no right section. This type was not included in the tests

Horizontal reactions.—The model arches used in these tests were all built using the same arch ring with a 7 foot span. As the degree of skew was increased, the actual barrel or span of the arch normal to the abutments was reduced to an amount equal to the span of the right arch times the cosine of the angle of skew, or in the case of the 60° skew, a shortening of 50 per cent. (See fig. 9.) Theoretical thrusts for right arches of these shortened spans under the same loading vary from theoretical thrusts for a right arch of 7-foot span directly as the cosine of the angle of skew causing the shortening. In order that a direct comparison of the horizontal thrusts might be made, the measured thrusts were corrected by dividing by a factor equal to the cosine of the angle of skew to bring all the readings to the basis of an arch with a barrel span of 7 feet, equivalent to that of the right arch. The comparative thrusts for the various skews are shown in Figure 10. It will be noted that the same general relationship exists as is shown for the vertical reactions.

Side thrusts.—A comparison of the side thrusts for those arches in which this force was measured is shown in Figure 11. No measurements were taken for the 60° skew. The wide variation in the recorded results for the other skews makes any comparison approximate, although in a general way it is apparent from Figure 11 that the side thrust increases directly with the corresponding increase in the angle of skew. It is also interesting that the differences in the average increments of side thrust due to 2,100-pound increments of load varies from 25 pounds between 15° and 30° to 30 pounds between 30° and 45°. This indicates that the side thrust increases almost directly with the angle of skew. The measurements made for the small loads are unreliable because of the difficulty of making accurate measurements of small loads.

Strain-gauge readings.—There are some obvious deductions which may be made from Figure 7, although the strain-gauge readings are not measures of the comparative stresses existing in the arches because of the wide variations in the readings caused by changes in temperature. The stresses are greatest in the arch ring adjacent to the obtuse angle of the arch and decrease as the acute angle is approached. This furnishes a rough check on the measurements of the horizontal and vertical reactions.

TESTS MUST BE CONTINUED

In comparing the results for the different degrees of skew it must be remembered that the transverse width of the arch (4 feet 6 inches) and the length parallel to the face of the arch (7 feet) have remained constant, but the span at right angles to the springing lines has varied. This prevents an accurate comparison of results. For example, consider Figure 12. For each one of the arches lines have been drawn normal to the springing lines from the obtuse angles. This results in a section of right arch for each test case. The distance *S*

(Continued on page 202)

EFFICIENCY IN CONCRETE ROAD CONSTRUCTION

A REPORT OF OBSERVATIONS MADE ON GOING PROJECTS BY THE DIVISION OF CONTROL, BUREAU OF PUBLIC ROADS

Reported by **J. L. HARRISON**, Highway Engineer

PART I.—EFFICIENT PRODUCTION

FOR many years the construction of concrete pavements has been an important element in the volume of highway work offered contractors. It has also been a large and a growing item in the improvement of city streets and alleys. Probably no figures which purport to give the volume of this work are absolutely accurate, for the very multiplicity of the sources from which such figures must be collected renders absolute accuracy difficult of attainment. However, there is no reason to doubt that recent statistics which show that concrete pavements are now being produced at the rate of about 92,000,000 square yards a year and at a gross annual cost in the neighborhood of $250,000,000, fix the order of importance of this element in the paving contractor's work with sufficient accuracy to justify the statement that it constitutes an extremely large item in the highway construction field.

There can be no doubt that any construction field in which this enormous sum is spent annually ought to be the subject of constant study. This is true without regard to what the field may be, for research and investigations are likely to prove quite as profitable here as they have in such fields as the physical sciences, and in such industries as the manufacture of automobiles. Highways of all sorts are now all but exclusively financed by, and constructed under the direction of governmental agencies with the result that in this field there is a direct relation between efficiency and the tax burden which makes it particularly important that constant effort be made through research and investigation to develop efficiency.

Efficiency is a broad term. Full efficiency in the highway field would begin at least as early as the selection of the routes to be improved. It suggests the development of the principles governing location. It dictates that the designing engineer shall consider the effect of his plans and his requirements on the cost of construction as well as on the probable adequacy of the finished structure. It is as insistent on the proper performance of all necessary operations as it is on the elimination of all that are unnecessary. It urges the contractor toward greater thought in planning and arranging his work and finally it imposes on those in charge of maintenance the requirement that whatever is built shall be so cared for as to yield the greatest service to the community.

Efficiency in the construction of highways is, then, only a part of the greater field of efficiency in highway development and maintenance, and efficiency in the construction of concrete surfaces is but a part of the whole highway construction field. Still, the savings which would result from full efficiency in this field are so large that they justify the annual expenditure of considerable sums of money in research and investigation if thereby approach can be had to complete efficiency. The current difference between ordinary practice and full efficiency will be appreciated when it is known that the studies made by the Bureau of Public Roads indicate that there are very few projects on which the average daily output can not be increased 25 per cent, that on many it can be increased from 50 to 100 per cent, and that as this can be accompanied by some reduction in the amount both of labor and equipment, the labor expended per mile of pavement laid, can, in general, be reduced by perhaps 50 per cent, and charges for depreciation of equipment by an even greater amount.

The series of articles, of which this is the first, is based on extended field studies of going projects by the division of control of the Bureau of Public Roads. In these studies it has been the purpose to determine what efficiency contractors at present secure, what causes prevent the securing of full efficiency, the degree to which these causes interfere with full efficiency, and how they can be remedied. Finally, having determined these facts in what has appeared to be a satisfactory manner, the effect on production of eliminating the ascertained causes of low efficiency has been tried on a number of projects with results that have quite satisfactorily confirmed the accuracy of the studies.

> Studies made by the Bureau of Public Roads indicate that there are few concrete paving projects on which the average daily output can not be increased 25 per cent. On many jobs the output can be increased 50 to 100 per cent, and this can be accompanied by some reduction in both the amount of labor and equipment employed.
>
> Full production on a concrete paving job is 48 batches an hour. By whatever amount a contractor fails to reach this standard he is failing to reach full efficiency in production, assuming that the specifications require a one-minute mix.
>
> The mixer is the bottle neck on every concrete paving job. No matter what material supplies are available, what correlated equipment is on the job, what skilled labor is available, nor what other conditions may prevail, be they ever so favorable, the mixer sets a rigid limit on production which can not be honestly avoided.
>
> To reach full production it is imperative that the discharge be opened and the skip started up at the same instant.
>
> There is an average lag of 5 seconds in charging the mixer after the skip reaches the vertical position, and a lag in discharging which averages 2 seconds. The discharge lag partly offsets the charging lag and the difference should be added to the mixing time.
>
> A slow, indifferent, or incompetent mixer operator may easily lose $35 a day on a job with a daily pay roll of $200.
>
> Loss of time due to mixer trouble averages about 5 per cent and runs as high as 10 per cent. A contractor with a daily pay roll of $200 may lose from $2,000 to $4,500 a season from this cause alone. Careful maintenance of the mixer pays.
>
> Long lines of 2-inch water pipe are a "hang-over" from the days of the 3-bag mixer. The high pressure necessary to force water through them bursts hose, splits pipe, opens joints, and springs the valves on the mixer. Leaky valves are probably the outstanding cause of nonuniformity of consistency. Three-inch pipe will carry an adequate water supply at reasonable pressure and reduce water troubles.
>
> Delays due to lack of prepared subgrade and slow delivery of materials due to inadequate truck supply and other causes are inexcusable on a well-managed job.
>
> Arbitrary interference by inspectors and abuse of discretionary clauses in specifications were the cause of considerable loss to the contractor on more than half the jobs studied by the bureau.

FULL PRODUCTION 48 BATCHES AN HOUR

What is full efficiency? In this series of articles it will be assumed that it is measurably secured when a 100 per cent output is obtained from a properly-equipped job with a crew of proper size. There are, then, a number of distinct fields in which efficiency must be attained before full efficiency is secured. To clarify this statement a little, it may be suggested that when a 100 per cent output is obtained with a 150 per cent working force the work is obviously not performed with full efficiency. Similarly, to obtain a perfect output with a working force of correct size but with a plant which represents an investment 50 per cent in excess of reasonable requirements is not to attain full efficiency. Any discussion of efficiency must deal then, if it is to be complete, not only with production but with labor requirements and with equipment as well. But, because production is at once the point of easiest approach to the general problem in hand, and the point at which current practices most clearly show their failure to reach full efficiency, this phase of the general problem was the first studied and will be the first discussed.

At this point it may be well to raise the question, what is full production on a concrete paving job? The answer will be given categorically: 48 batches an hour—1 batch every 75 seconds. By whatever amount a contractor fails to meet this standard he is failing to reach full efficiency in production, assuming, of course, that the specifications require a 1-minute mix. If a 1¼-minute mix is required, one batch should be obtained every 90 seconds, and if a 1½-minute mix is required, one batch should be obtained every 105 seconds. The 1¼-minute mix, then, reduces output to 40 batches an hour, and the 1½-minute mix to slightly over 34 batches an hour. As, for reasons that will later appear, these reductions in output are not accompanied by equivalent reductions either in daily pay roll or in plant investment, any State, county, or municipality using one of these longer mixing periods, should have very conclusive data at its disposal if it is to justify the additional unit cost of pavement laid, which it must expect to pay.

Because of this fact, and because the current tendency, which is governed by recent tests, seems to be to standardize on a 1-minute mix, the discussions which follow will be based on a mixing period of that length. It should not be forgotten, however, by those interested in obtaining the highest standards consistent with reasonable cost, that current practice in testing concrete to determine the proper time of mix, the proper consistency, etc., is much at fault in that it examines the material discharged from the mixer, or as deposited on the subgrade, rather than the material in place and finished. Between the discharge from any really modern mixer and the final belting, the mixed material is poured into a large bucket, dumped upon the subgrade, shoveled, tramped over, etc., by the puddlers, and smoothed or tamped by a modern finishing machine. The subgrade absorbs some of the water content and some evaporates. All of these operations tend to work the concrete more completely, and particularly to distribute and correct the water film with the result that the material which the belt leaves as a completed slab often is by no means the same material which was discharged from the mixer perhaps a half hour before.

OPERATIONS INVOLVED IN PRODUCTION OF A BATCH

Returning now to the production standard defined above—48 batches an hour—and with the fact in mind that this standard is based on a 1-minute mix, the correctness of this standard may reasonably be examined. The operations which must be performed in turning out a batch of concrete are as follows:

1. The skip must be loaded. This can be done while the previous charge is being mixed. Under the somewhat antequated system which requires that the cement be brought to the job in sacks and there piled along the road, the operation of dumping the cement into the skip will sometimes take longer than mixing the batch. Of course this method of handling cement is as obsolete as are all other purely manual methods, but if it chances to be the method in vogue, men who are strong enough and active enough to do this work within the time available should be put onto this work. Ordinarily, however, handling the cement does not prevent charging the skip within the time available for this purpose, generally from 40 to 50 seconds.


For full production the discharge must be opened when the skip is started up

2. The skip must be raised to a vertical position for the purpose of dumping the batch into the drum. On a modern mixer in reasonably good condition this operation takes from 9 to 10 seconds, during which period the material in the skip is discharging into the mixer only during the last 1½ to 2 seconds.

3. The material in the skip is never fully discharged when the skip reaches the vertical position and sets the timer. The better modern mixers sometimes discharge the skip in as little as 3 seconds after it is in vertical position, if the sand and coarse aggregate are dry; but under ordinary working conditions they tend to require from 4 to 5 seconds, running a little over 5 seconds if the aggregate is wet enough to moisten the cement appreciably. A recently developed 6-bag mixer quite generally shows a lag in the skip discharge which runs over 15 seconds—one fourth minute—and an old-fashioned 8-bag mixer, of which a few are still in use, has been found sometimes to take as much as 40 seconds to transfer all of the charge from the hopper into the drum. As there are a number of standard (5-bag) pavers which will discharge the skip in from a little under 4 to a little over 5 seconds and which, under ordinary working conditions, will regularly discharge within 5 seconds after the skip reaches a vertical position, this period is considered standard for the lag in charging as mixers are now designed.

4. The mix must be retained in the drum the full specification period, here assumed to be 60 seconds.

5. Every mixer should have on it some device for timing. A timer which rings a bell at the completion of the mixing period is the one most commonly encountered. When the bell rings the operator must move the discharge lever and the discharge mechanism must open the discharge before material appears in the discharge chute. These operations generate a lag, partly due to the fact that no human being reacts instantly to any ordinary stimulus and partly to the fact that it takes time for the mechanism to work. Two seconds seems to be about the bottom limit for this lag, which is termed the discharge lag. Three seconds is a more common average; and sometimes it runs as high as four seconds. The lag in discharge tends to offset the lag in charging, but can not reasonably be so treated if it is not a uniform lag. Thus a lag which for successive batches is found to be 2.7 seconds, 3.2 seconds, 2.8 seconds, 3 seconds, 3.1 seconds, 3.3 seconds, etc., over long periods might reasonably be treated as a 3-second lag, though the amount by which this lag exceeds 2 seconds is due entirely to a slow reaction on the part of the operator; but a lag reading 1.9 seconds, 3 seconds, 2 seconds, 4.2 seconds, 2 seconds, 2.2 seconds, 5 seconds, 2.1 seconds, 4 seconds, 3.1 seconds, etc., would appropriately be treated as a 2-second lag because the part chargeable to the operator is not uniform.

6. Finally the mix must be discharged. A wet mix can be quite thoroughly discharged from a good mixer in as little as 8 or 9 seconds, but there is no mixer now on the market which will make a complete discharge in less than 10 seconds, if the consistency is such that it meets present requirements as to slump. This is, in a general way, caused by inadequacy of bucket capacity. Concrete having a slump of about 1 inch flows slowly in the chute and piles up in the bucket with the result that as the bucket fills, the discharging concrete finally backs up into the chute, preventing complete discharge within any reasonable period. To complicate matters further, all mixers dribble a good deal. A recently designed 6-bag mixer will often take well over 20 seconds to complete the discharge. Some of the older mixers take quite as long, a few longer. A full batch mixed to proper consistency can, however, be regularly discharged from most of the standard (5-bag) pavers in 10 seconds if the charge in the drum is "built up" slightly, that is, if a part of the first batch is left in the mixer and the mixer is allowed to run that way. The quantity required is small—just enough to force a full rate of discharge during the whole of the discharge period. As, under full efficiency, a new batch is handled every 75 seconds, there is no practical disadvantage in this as the quantity of material appearing in any batch which could possibly have been in the mixer over 15 minutes would be too small to be of any importance whatever. The discharge time may, therefore, be kept within 10 seconds even when a mix of proper consistency is being produced.

SIMULTANEOUS CHARGING AND DISCHARGING NECESSARY FOR FULL PRODUCTION

The full-production mixing time with all specification requirements met may then be calculated as follows:

Specification mixing time, seconds	60
Lag in charging, seconds	5
Simultaneous raising of skip and discharging, seconds	10
Total, seconds	75

Stated in this manner there is, however, no recognition of the lags described above. It is therefore preferable to state the cycle as follows:

1. Specification mixing time, seconds	60
2. Lag in charging, seconds	5
3. Less lag in discharge, seconds	2
4. Net lag as affecting timer, seconds	3
Normal setting of timer, seconds	63
5. Lag in discharge, seconds	2
6. Simultaneous raising of skip and discharging, seconds	10
Total mixing cycle, seconds	75

It will be observed that in order to reduce the mixing cycle to 75 seconds the skip must be started up at the same instant the discharge is opened. As a matter of fact this is the only device available to the operator for regulating the length of the mixing cycle. Most mixers dribble their discharge enough so that even an experienced operator would have trouble in regulating the time of discharge by observation of the discharge itself. The time required for raising the skip is, however, outstandingly uniform and if an operator is trained to open the discharge and start the skip at the same time, and to close the discharge as the skip reaches a vertical position, he has at once an adequate discharge time, an accurate measurement of the discharge time, and, if the lags in charging and discharging are correctly provided for, the correct mixing cycle.

Two things may be observed here. The first is that where the mixer is so designed that 10 seconds is not an adequate period for discharge this system is not applicable. There are such mixers but they can not be reasonably considered in setting a standard of production. Such mixers may require an extra 5, 10, or even 20 seconds as their minimum mixing cycle. Mixers are not all alike in their efficiency any more than the operators who use them. But to obtain full production a contractor must have an efficient mixer and the above discussion will, it is hoped, assist him in determining which mixers are efficient.

The second matter to be noted is that if the practices here outlined are followed the skip will be in a charging position and material will be flowing into the drum during from 1½ to 2 seconds of the discharge period. This is of no consequence whatever, as the standard drum speed is about 15 revolutions per minute or 1 revolution every 4 seconds. During this overlapping of the charge and the discharge—never in excess of 2 seconds—the drum makes only half a revolution, so the material is not moved up and over in the drum enough to combine with any of the discharging material or to appear in the discharge chute. If the drum speed is so high that unmixed material is discharged, the contractor should reduce the drum speed.

THE MIXER IS THE BOTTLE NECK OF THE JOB

The mixer is the bottle neck on every concrete paving job. No matter what material supplies are available, what correlated equipment is on the job, what skilled laborers or how many are available, indeed no matter what other conditions prevail, be they ever so favorable, the mixer sets a rigid limit on production which can not be honestly avoided. This is so axiomatic that it naturally follows that the problem of securing full production becomes a problem of determining the factors which are reducing the output of

TABLE 1.—*Stop-watch studies of concrete road construction*

[Study No. 15 June 26, 1925. Weather fair. Time, 1 hour, from 1.36 to 2. 36 p. m. Number of batches, 24]

Batch No.	Mixing time			Lost time											
	Charge	Mix	Discharge	Truck shortage	Truck delays from causes other than shortage	Mixer trouble		Water supply trouble	Lack of material caused by—		Lack of prepared subgrade	Setting parting strip	Finishers unable to keep up with mixer	Other persistent delays	Miscellaneous delays
						Mechanical	Operative		Mismanagement	Delayed shipment					
	Min. Sec.	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*
1	0 8.5	1 1.0	0 12				0 10.0								
2	8.5	59.5	12				15.5								
3	8.5	1 0	12	2 34.0											
4	8.5	1 0	12				11.5								
5	8.5	1 0	12				13.0								
6	8.5	1 0	12				11.5								
7	8.5	1 1	12	12 12.0											
8	8.5	1 0	12				17.5								
9	8.5	1 0	12				11.5								
10	8.5	1 0	12	1 11.5											
11	8.5	1 0	12	26.5											
12	8.5	1 0	12				9.0								
13	8.5	1 0	12				6.5								
14	8.5	1 0	12				6.5								
15	8.5	1 0	12	6 35.0											
16	8.5	1 0	12					0 14							
17	8.5	1 0	12				6.0								
18	8.5	1 0	12					17							
19	10.0	1 0	12				7.0								
20	9.5	1 0	12					17							
21	9.0	1 0	12					20							
22	9.5	1 0	12				14.5								
23	9.5	1 0	12	18.0			21.5								
24	9.5	1 0	12	30.0			7.0								
Total	3 30.0	24 1.5	4 48	23 47.0			2 48.5	1 8							
Average	9.0	1	12												
Percentage	6	40	8	39.5			4.5	2							

TABLE 2.—*Stop-watch studies of concrete road construction; accumulation of data for study No. 15*

Date	Number of batches per hour	Efficiency of outfit (column 2 divided by 48)	Mixer time				Lost time											
			Charge	Mix	Discharge	Percentage of total time per batch	Truck shortage	Truck delays from causes other than shortage	Mixer trouble		Water supply trouble	Lack of material caused by—		Lack of prepared subgrade	Setting parting strip	Finishers unable to keep up with mixer	Other persistent delays	Miscellaneous delays
									Mechanical	Operative		Mismanagement	Delayed shipment					
		Per cent	*Min. Sec.*	*Min. Sec.*	*Min. Sec.*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
June 11	16	33.3	0 9.5	0 59.5	0 10	35.0				15.0						50.0		
June 12	36	75.0	9.5	1 1.0	10	80.5				10.5				9.0				
June 12	31	64.6	9.0	1 0	12	69.5		9.0		16.5				5.0				
June 15	36	75.0	9.5	1 1.0	10	81.0		9.5		6.0	2.0			1.5				
June 15	34	70.8	9.5	1 1.5	10	76.0		5.0		13.0	6.0							
June 19	31	64.6	9.0	58.0	12	67.0		3.0		17.5				5.5		7.0		
June 20	38	79.2	10.0	59.0	10	82.0	10.0	1.0		6.0	1.0							
June 20	38	79.2	10.0	59.0	10	82.5	6.0			8.0	2.0			1.5				
June 20	31	64.6	9.5	59.0	10	67.0	14.0	1.0		9.0		9.0						
June 25	10	20.8	10.0	1 1.0	10	23.0	13.0	21.5	41.5	1.0								
June 26	17	35.4	9.5	1 1.0	10	38.0	28.0	1.0	27.5	1.5	4.0							
June 26	24	50.0	9.0	1 0	12	54.0	39.5			4.5	2.0							
June 30	20	41.7	9.5	1 1.0	10	44.0	49.0	3.0		3.0	1.0							
June 30	23	47.9	9.0	1 1.0	12	51.5	30.5	2.0		6.0	10.0							
Average	27.5	57.3	9	1 0	11	60.8	13.6	4.0	4.9	8.4	2.0	.7		1.6		4.0		

Lost time due to improper mixer cycle=60.8−57.3=3.5 per cent.

the mixer, what their order of importance may be and finally, how they may be eliminated.

These factors have been determined in the bureau's studies by making stop-watch readings on selected projects for an hour morning and afternoon each day over such a period as seemed necessary to obtain reasonably accurate data. Table 1 shows a record of this sort. These records, accumulated over a period of from two weeks to a month, tabulated and averaged, give a fairly complete picture of what the rate of production is and of why it is less than it ought to be. Table 2 gives the accumulation of hourly readings for one of the jobs studied, the readings in line 12 being the averages taken from Table 1. Table 3 gives the final summary for a number of jobs, line 15 being the summary of Table 2. These three tables indicate the manner in which the data have been collected, tabulated, summarized, and averaged for use in determining both for individual projects and for this work generally, to what extent production is below standard and what causes are producing this condition. A fairly typical job among those listed in Table 3 (for greater detail see Table 2) shows as the average of fourteen 1-hour readings:

TABLE 3.—*Accumulated summary of 21 time studies of going concrete paving jobs*

Study No.	Batches per hour	Production efficiency	Mixer time			Lost time (per cent)													
			Charge	Mix	Discharge	Improper mixing cycle	Mixer trouble: Mechanical	Mixer trouble: Operative	Truck shortage	Material shortage	Water supply	Subgrade	Setting parting strip	Finishers	Moving mixer	Setting expansion joints	Dumping cement in mixer	Miscellaneous	Total delays
		Per cent	*Sec.*	*Min. sec.*	*Secs.*														
1	26.9	56.0	14	1 7	13	14.0	7.37	0.60	8.76	0.33	2.59	1.82	0.31	3.66	0.69	--------	--------	4.45	44.58
2	27.7	57.7	11	1 4	16	12.3	5.09	.13	7.77	--------	7.83	3.62	.44	--------	--------	--------	--------	4.84	42.02
3	31.6	65.8	11	1 4	9	9.01	6.53	--------	13.60	--------	1.67	--------	--------	.18	--------	--------	--------	2.56	33.55
4	29.6	61.7	11	1 5	8	7.11	.47	1.44	6.48	--------	4.53	3.80	.20	4.58	--------	--------	--------	9.57	38.18
5	12.9	26.9	13	1 3	21	7.7	8.30	.40	43.30	--------	.06	--------	--------	--------	.77	1.28	--------	9.25	71.06
6	19.8	41.3	5	1 3	17	5.4	.05	.83	4.30	4.07	--------	.02	--------	--------	--------	4.36	--------	39.76	58.79
7	16.8	35.0	11	1 15	21	15.5	2.00	13.00	23.00	1.00	.50	4.00	--------	--------	--------	--------	5.00	1.00	65.00
8	24.7	51.5	12	1 9	11	13.2	.50	1.70	27.40	2.00	2.00	--------	--------	--------	.50	--------	--------	1.20	48.50
9	35.6	74.1	13	1 3	12	12.3	.90	.40	--------	.10	.80	--------	--------	--------	11.40	--------	--------	--------	25.90
10	35.4	62.1	10	1 2	11	12.8	16.00	.25	--------	--------	.42	--------	--------	--------	8.51	--------	--------	.09	38.07
[1] 11	23.4	68.8	11	1 25	13	1.9	.70	1.10	20.40	--------	.40	--------	--------	5.10	1.10	--------	.40	.10	31.20
[1] 12	24.0	70.6	14	1 12	19	1.3	.20	1.10	20.70	--------	.50	--------	--------	--------	--------	--------	--------	5.60	29.40
[2] 13	25.4	63.5	9	1 19	2	1.7	1.70	.60	11.40	--------	1.50	11.10	2.10	6.10	--------	--------	--------	.30	36.50
14	35.3	73.5	9	1 6	12	12.5	.30	3.70	1.50	--------	1.60	.60	--------	2.40	--------	--------	--------	3.90	26.50
15	27.5	57.3	9	1 0	11	3.5	4.90	8.40	13.60	.07	2.00	1.60	--------	4.00	--------	--------	--------	4.00	39.20
16	36.5	76.0	9	1 4	5	2.9	1.30	.40	5.60	.50	1.80	1.90	--------	--------	--------	--------	--------	9.60	24.00
[2] 17	14.1	58.1	9	1 21	10	6.6	.40	16.70	10.70	--------	--------	6.30	--------	--------	--------	--------	--------	.70	41.40
[2] 18	23.6	59.0	13	1 25	21	18.2	13.20	--------	--------	--------	--------	6.50	.40	--------	--------	--------	--------	2.60	40.90
[2] 19	25.7	64.2	14	1 23	10	11.4	--------	.90	14.50	--------	--------	2.30	--------	--------	--------	--------	--------	6.60	35.70
20	44.5	92.7	10	1 2	4	0.6	--------	--------	--------	--------	.30	--------	--------	--------	--------	--------	--------	6.40	7.30
21	40.8	85.0	10	56	6	3.1	--------	1.80	--------	--------	3.00	--------	--------	--------	--------	--------	--------	13.30	15.00
22	30.8	64.6	11	59	6	4.8	--------	4.80	--------	--------	3.00	6.70	--------	.4	--------	--------	--------	25.30	45.00

[1] In studies Nos. 11 and 12 the specifications called for a mixing time of 1½ minutes.
[2] In studies Nos. 13, 17, 18, and 19 the specifications called for a mixing time of 1¼ minutes.

Batches per hour		27.5
Efficiency in production	per cent	57.3
Average charging time	seconds	9.4
Average mixing time	do	60.0
Average discharge time	do	10.5
Mixing cycle	do	79.9
Loss of working day, due to—		
(1) Excess length of mixing cycle	per cent	3.5
(2) Slow operation other than mixer cycle	do	8.4
(3) Mechanical trouble with mixer	do	4.9
(4) Inadequate truck supply	do	13.6
(5) Delays due to handling trucks	do	4.0
(6) Trouble with water supply	do	2.0
(7) Subgrade	do	1.6
(8) Finishers	do	4.0
(9) Miscellaneous	do	0.7
Total lost time	do	42.7

The above summary resulting from a two-weeks study of a going project reveals typical construction conditions. Nearly 17 per cent of the working day in this case was being lost at the mixer. Nearly a fourth of this is chargeable to poor handling of the mixer. It will be observed that the timer on this job was not set to take care of the lag in charging. This is not an uncommon condition. Most contractors indeed and many engineers seem to suppose that the material in the skip is all transferred to the drum while the skip is being raised to a vertical position. That this is not the case can be determined readily by getting well up on the mixer and watching the discharge. As most specifications make it clear that the mixing time is the period between the moment at which the last of a batch enters the drum and the first is discharged, the contractor, in this case, was obtaining at least a 3-second advantage over the specification requirements but in spite of this, his operator was losing 3.5 per cent of the working time because of failure to overlap the charge and the discharge which together, as measured from the bell (this includes the lag in discharge), should not exceed 12 seconds.

It may be observed that while, as this job was being operated, the loss of time chargeable to the long mixer cycle amounted only to 3.5 per cent of the working day, its importance would have been somewhat increased had other losses been eliminated. In other words, the length of the mixer cycle was cutting hourly production from a possible 48 batches an hour to slightly over 45 batches an hour or to about 93 per cent of full production. There is here then, and for that matter, in some of the other losses which will be discussed, a difference between the efficiency of an operation itself and the net effect of any lack of efficiency on the day's output. It is possible to develop a study of efficiency on either basis but the latter has been followed in this case.

Poor operation other than failure properly to overlap the charge and the discharge account for a further loss of time amounting to 8.4 per cent. Under this heading are included such practices as dumping batches before the skip is raised, splitting batches, failure to move the mixer while it is mixing, slow reaction to the bell, etc. With an up-to-date mixer it is never necessary to do any of these things. If they are done the operator either has not been properly taught or is deliberately wasting time, or the power plant is so out of order that an expert repair man should be called onto the job at once. The observations made by the bureau's representatives indicate that the general cause of delays of this sort is improper training of operators. Occasionally one is encountered who is naturally slow or indifferent, but it is more common to find that the operator has seen few jobs except the ones on which he has worked and that he does not appreciate that such practices as those here noted throw away a large amount of valuable time.

On this particular job the combined effect of failure to overlap the charge and the discharge and of such items as dumping at the wrong time, splitting batches, slow reaction to the bell, etc., accounts for almost 12 per cent of the working day. With a pay roll running in the neighborhood of $200 a day and a depreciation account of perhaps half that amount, neither of these being unusual on concrete paving jobs, the direct loss from these causes amounts to about $35 a day, a sum quite sufficient to justify the statement that a "cheap" mixer operator is apt to be about the most expensive man on the job.

MIXER TROUBLE EXPENSIVE

In this case mechanical trouble with the mixer accounts for delays aggregating about 5 per cent of the working time. As mixers wear out such delays tend to increase. They are small when the mixers are new, but even on new mixers the studies show that there generally is a little mechanical trouble. This appears to be due to the rigorous conditions under which mixers operate and to the fact that so many operators are trained on the job, rather than to any outstanding deficiency in design. But as the mixer wears out, mechanical troubles increase, and with their increase, the lost time mounts sharply. Five per cent appears to be about the average of losses due to this cause. In some cases they amount to upward of 10 per cent. Under the assumptions noted above, a 5 per cent loss of time amounts to about $15 a day and a loss of 10 per cent to $30 a day. If the mixer works 150 days during the year, losses accruing as a direct result of using equipment that is in poor condition will be seen to range from over $2,000 to $4,500 a year. The first of these is enough to pay for a new mixer in about three years, the second in less than two years. It is not the purpose here to go into the question of replacing old machines with new. Rather, it is the purpose to point out that where old or worn-out machines are in use this very fact will prevent full prodution. Some phases of the problems arising in connection with repairing and replacing machines will be discussed in another part of this series of articles, but it will be sufficient to remark here that as a matter of general observation, there is not enough attention given to the mechanical condition of the mixer, few contractors appearing to realize the real financial aspect of the constantly recurring small losses of time which develop when a worn-out mixer is being operated.

On the job under discussion, the nondelivery of materials accounted for a loss of over 17.6 per cent of the working time. Part of this—13.6 per cent—is chargeable to inadequate truck supply, the balance to improper handling of the trucks. This is a rather typical situation. As a matter of general observation, contractors are prone to provide inadequate facilities for the delivery of material. In the case in hand, the apparent truck shortage was 13.6 per cent, that is, with the truck supply available only 13.6 per cent of the working day, worth on the basis of ordinary pay roll and depreciation charges about $40, was being thrown away because of an inadequate supply of trucks, but the real situation was worse than this. Had the mixer losses been eliminated as well as the losses in time due to other causes, the amount of pavement laid would have been increased only by the 4 per cent chargeable to improper handling of the trucks, that is, to a little over 60 per cent of full production. In short, while lack of proper transportation was only costing this contractor some $40 a day as the job was being operated, the value of this loss would have been about $120 a day had the mixer been capable of normal production. It is hardly necessary to observe that the only appropriate method of eliminating this loss is to supply the necessary trucks. Speeding up the trucks in use is not a proper solution, unless the speed at which they are operated is low, which is an uncommon condition. On the other hand, the correction of low efficiency in the operation of the trucks—an entirely different matter will often measurably improve the apparent truck supply. The transportation question is one of the most important with which the paving contractor must deal—too important to treat at length at this point. It is therefore reserved for further comment in the next of this series of articles.

SMALL WATER PIPES CAUSE SERIOUS LOSS

On this project the water supply caused a loss of 2 per cent of the average working day. Shifting hose is the most common cause of such losses. Poor water pressure is also a common cause. This may be caused by using too small a pump, by slip in the pump, by too small a pipe line, line losses due to poor pipe connections, or to the use of too much water on other parts of the work. Where long pipe lines are used, contractors often try to improve the supply by putting in a booster pump. This results in high pressures which open joints, split pipe, and burst hose. It is not unusual to find that when the valves on the mixer and hose connections are closed, the pressure at the mixer rises to from 250 to over 400 pounds. Such pressures are destructive and wholly unnecessary. Relief valves should be installed to protect the line and the valves in the mixer, but these are often omitted. Larger pipe should be used. The 2-inch pipe now in common use is a "hang over" from the days when the 3-bag paver was standard equipment. Instead of putting in a 3-inch line and having an adequate water supply with reasonable pressure and a reasonable wear and tear on the pumps, contractors are holding to the 2-inch lines much to their disadvantage, for water trouble has been found to be of common occurrence and a supply inadequate for the mixer and the various curing operations the general rule.

Where contractors have long lines of the now commonly prevailing small sizes of pipe, some relief from the high pressures incident to pumping any considerable volume of water through these lines can be had by cutting the line and instead of using booster pumps, running the delivery from the first pump into a sump from which the second pump will draw its supply. A great deal of the trouble with short water supply is directly chargeable to line leakage and this, in turn, is chargeable in no small degree to high pressure in the line. With pressures commonly exceeding 250 pounds ordinary connections are opened, and all sorts of trouble resulting in leakage occurs. Even the valves in the mixer are sprung and the leakage which occurs here sooner or later becomes an obstacle to the regulation of the water content of the concrete produced. This is a serious matter, since the strength of concrete is adversely affected by even a comparatively small increase in its water content. Moreover, variations in the water content have an adverse effect on the ease and rapidity with which the pavement is finished and make the production of a very smooth surface difficult.

Where there is any considerable leakage the amount of water improperly reaching the interior of the drum varies with the pressure in the line and with the period between batches. As on all but the best-managed jobs both of these are highly variable, as soon as there is any considerable amount of leakage, real uniformity of consistency becomes quite unattainable. So really serious is this matter that it seems proper to suggest that, as mixers are now operated, this is the outstanding cause of nonuniformity of consistency and one of the most important causes of poor surface finish.

There is therefore very good reason for urging contractors both in their own interest and in the interest of the States and municipalities for which their work is done, to install pipe lines of proper size, fitted with proper relief valves in order that thereby an adequate water supply delivered at a reasonable pressure may be insured. There is also reason to suggest that manufacturers install better and stronger valves in their mixers.

Delay due to lag in finishing is not of common occurrence. Finishing machines are reliable mechanisms and commonly give the contractor little trouble. The 4 per cent loss from lag in finishing recorded on this project is unusual. Occasionally a complicated or cumbersome process in finishing is required and in such cases there sometimes is a failure to keep the finishing up with the mixer. Sometimes too dry a mix is required by the inspector. However, the current tendency is toward simplifying the finishing operations so, except where the inspection is too exacting, there is seldom any difficulty encountered here. Incidentially it may be remarked that the essence of rapid finishing is uniformity in consistency and a consistency of proper slump. Well-mixed concrete of the proper consistency—about 1-inch slump—put down by a modern sliding finisher may be depended upon to be of such uniform smoothness that one man with a long-handled float can finish any output obtainable from a standard mixer. This, of course, implies that the concrete shall be of uniform consistency as well as that it shall be of proper consistency and that the finishing machine shall be correctly operated. In short, there should be no losses of time due to finishing and if any are developing there is something wrong which should be easily corrected.

Occasionally an inspector in his desire to obtain the driest mix possible will attempt to reduce the slump to ½ inch or less. Whatever the theoretical result of such a practice may be, in increasing the strength of the concrete, the practical result under field conditions is to render the concrete extremely hard to work. With a slump as low as this, the finishing machine can not keep up with the mixer. Moreover, in at least two cases which have come to the attention of the writer, the finishing operation did not satisfactorily compact the bottom third of the pavement. Under field conditions there would, therefore, seem to be valid reason for maintaining a somewhat wetter mix than laboratory tests would indicate to be the most desirable. There is also to be considered the fact that the subgrade absorbs moisture from the concrete and that some evaporates, as a result of which processes, the concrete as finally left by the finishing machine, particularly in hot, dry weather, often is visibly drier than when it left the mixer. If satisfactory production is to be secured, the finishing operation can not be unduly slowed down. There is, here, then, room for a good deal of practical study, for although it is important that the best possible concrete be produced, it is also desirable that this be done on the basis of carefully collected data rather than on the basis of personal opinion, and that theoretical considerations be not allowed to interfere with production unless it can be clearly shown that the results to be obtained can and do justify this interference.

DELAYS DUE TO LACK OF SUBGRADE AND OTHER CAUSES

As with the finishing so also with the subgrade, if the crew is not doing its work rapidly enough to keep the subgrade in proper condition and so far in advance of the mixer as to entirely avoid delays from this cause, either the foreman in charge needs instruction, additional men or equipment, or the job needs a new foreman. There should be no excuse whatever for letting the preparation of the subgrade interfere with production at the mixer.

Miscellaneous delays are of small consequence on this job. However, the list of them as affecting production a little here and a little there, not often but occasionally during a long season, is long. Special work at bridge structures falls in this category. Often specifications require a special treatment of the pavement at such points. This special treatment causes delay, generally only because it does not occur often enough so that the crew becomes familiar with the operations involved. Any new operation takes time because men not familiar with it hesitate to proceed lest a mistake be made. Most men working on a construction job do their tasks automatically. Many, if not most, feel confused if any judgment is required. No new or unusual task, no matter how simple, can be handled automatically and most such tasks for a time require at least a little judgment even on the part of the common laborers. For that reason, whatever is new or unusual is done slowly and output suffers until the operations involved are so well learned through repeated performance that they become automatic.

"Waiting for reinforcing rods" is a minor delay typical of a whole series which may be classed under the general heading of "delays due to the failure to deliver minor materials." Generally such delays are due to the failure of some foreman to keep track of the stock on the job but, if reinforcing material, parting strip, prepared joints, etc., are required, the lack of such materials at the site of the work is quite as effective in stopping production as the failure to deliver cement or sand or gravel. Laying a concrete pavement really is a manufacturing process. Modern manufacturing methods do not depend for their success on large stocks. They depend, rather, on the maintenance of uniform balanced rates of delivery. This is as true of a concrete paving operation as it is of an automobile plant. Materials are not stocked. They are ordered for delivery as needed and such stocks as are maintained are like the balancing tanks in a water supply—they absorb the delivery when it exceeds the rate of use and they augment the delivery when it falls below the rate of use. In the case of minor materials perhaps this is not as obvious as in the case of the materials of major importance, but the fact is that for all materials the rate of delivery at the mixer must harmonize with the rate of use at the mixer and any failure to attain such a treatment of the material supply, whether major or minor, is too disastrous to pass unnoticed.

There also is a whole series of minor causes of delay not so easy to cover in a general statement, such as: Broken batch meter; getting the mixer under low electric wires; failure to dump all the batch into the skip; over-wet batches thrown away; water pipes frozen; and forms knocked down by trucks. In a general way, delays of this sort are due to accidents or to accidental conditions and as their causation can not be foreseen, they can not well be avoided. However, they are not a serious factor on most jobs but are mentioned because they illustrate the innumerable minor matters which interfere with securing full production.

THE DAMAGE DONE BY INEXPERIENCED INSPECTORS

Finally no discussion of the causes affecting production would be complete without reference to the inspector. He is a necessary, though, it must be regretfully recorded, not always a favorable factor in the production problem. Generally he is a well-intentioned man who knows but little about the broader technical aspects of the work he is inspecting, very desirous of protecting the interests of those he represents, but not properly equipped to pass on the numerous technical questions that arise on any concrete paving job. He occupies a difficult position because, after all, the contractor's primary desire is production, whereas the State's primary desire is quality. The two are seldom in real conflict, for the best organized and most productive jobs generally do the best work; but high production requires a quick answer to any problem that arises and this, in turn, requires a broad knowledge of technical values or, in the effort to protect the interests of his employer, the inspector will find that he is needlessly injuring the contractor. Without this broad technical background, the inspector is apt to be further handicapped by the fact that he has little appreciation of the real nature of a going construction operation. Here he sees a few men, there a few more. At other points he knows that others are working. He seldom realizes that what he is observing is a machine, the parts of which are so synchronized that to stop one part in effect causes all of the parts to stop functioning. Yet this is literally true.

The modern concrete paving organization, when well developed, is as perfect a machine as a well-built automobile. The subgrade gang is balanced to produce each day the subgrade that the mixer will use the next. The form-setting gang is balanced against the mixer performance in the same way. At the batcher plant the force is kept in harmony with the mixer's utilization of material. The office keeps materials flowing in as they will be needed. In such a balanced production scheme—and this is the very essence of efficiency in production—the injection of any order that stops production at one point stops the whole machine as effectively as taking off a wheel or pulling out the engine stops an automobile. To stop one gang is to stop the whole job. Worse than that, the time lost directly may be of less importance than the time lost indirectly. The writer watched one afternoon an irresponsible inspector while he tinkered with the water gauge on the mixer for a half hour in a misdirected effort to further reduce the slump of concrete which was already well within the specified requirements. The result was a series of batches so dry that the contractor had to stop the mixer for half an hour in order to finish them. This half hour's delay was important enough in itself, but it was a couple of hours before the contractor was able to get his organization to functioning again with its accustomed smoothness.

Although arbitrary acts on the part of inspectors are serious enough, a larger trouble lies in the constant effort of many inspectors to inject new ideas into work on which they are engaged. Some one desires the subgrade prepared in a new way. The finish, it is thought, might be improved. The concrete might be mixed a little drier. It would be improved if mixed a little longer. There are dozens of such requests. It matters not at all that the work now meets the specifications which are in force. If some one thinks that the product can be improved, the contractor will be urged, even forced, into making the desired change. He is told that the change will cost him nothing—may save him money—and will get better results. The point overlooked is that changing the practices on a going job requires more than an order. Men must be trained to perform the new duties properly, and the job may have to be rebalanced to meet the new methods. Often the contractor does not know how to train the men as he has never seen the new ideas in use. He, therefore, hesitates because he knows that such changes may involve large intangible losses, clear enough to him but hard to explain to an inspector.

Of course, the time to decide on what methods and practices are to control on a construction job is when the specifications are drawn. Then, when the job is started, the interpretation which will be placed on new clauses or on any of the older clauses that may be in doubt should be made clear, and the practices that are to be required should be developed as the organization is brought into production. Thereafter all connected with the job should appreciate that while the contractor may request premission to use new methods the inspector and, for that matter, the State, has no right to modify the requirements made on him, unless infraction of specific provisions or commonly accepted interpretations of the specifications can be shown.

ABUSE OF DISCRETIONARY CLAUSES IN SPECIFICATIONS

The clause, "or to the satisfaction of the engineer," and its various equivalents is often written into specifications for the purpose of giving the engineers broad discretionary powers in the interpretation of clauses governing methods, tolerances, etc.; and if a contractor objects to an order or to a request, some clause of this sort is called to his attention. For this reason it seems advisable to remark in this connection that as a general legal principle clauses of this sort give engineers no authority to modify the plain intent of specifications defining methods, tolerances, etc., and that contractors are under no obligation to be governed by orders which make these clauses more than customarily rigorous or which increase the cost of the work. As an illustration, if the specifications clearly state that "the slump shall not exceed 1 inch," a clause of this nature can not be legally invoked to require a contractor to produce concrete having a slump of not more than half an inch. Similarly, if the specifications provide that "irregularity in the finished surface shall not exceed one-fourth inch when measured under a 10-foot straightedge," a clause of this character can not be lawfully invoked to require a contractor to remove areas that are only one-eighth inch high. If the contractor desires to use other than specified methods, etc., and the specifications are not to be followed, then the discretionary clause gives to the engineer broad authority to require that whatever is done under these new methods shall be done "to the satisfaction of the engineer." But in no event are such clauses blanket authorizations for the engineer to make such requirements as he may please.

If it were possible to bring inspectors generally to a realization of the fact that their sole duty is to see that the contractor works within the specified limits, that they are not present to "improve the quality of the work," or to make experiments at the expense of the contractor, the effect on production would be gratifying to many contractors. In making stop-watch studies on going projects it has seldom been possible to separate the effect of improper inspection from other causes which perhaps also contributed to slow operation. Sometimes the fact that an inspector's order is responsible for a procedure that is causing delay has not developed until a good deal of the record has been taken. A case in point was a job where the records showed slow operation of the mixer. In general, the truck supply was adequate and the work well organized, but the mixer operator would not raise his skip until the discharge had been completed. This of course materially reduced his daily output. After the full record for this job was taken it was learned in a chance conversation with the inspector that he would not permit the contractor to produce over 40 batches an hour. There was no specification warranting such a limit on production. The inspector gave no reason for having imposed it. He merely asserted that he thought that production enough. Conditions of this kind as well as the possibility that there might be some difference of opinion as to what is proper inspection, have prevented any general effort to separate the time lost through poor inspection, but some idea of the importance of this element may be gained by the general statement that poor inspection has caused losses of some consequence on more than half the jobs on which the bureau's representatives have made studies during the current season. It is not, therefore, a factor which can be ignored in a study of the causes influencing underproduction.

In presenting these aspects of the inspection problem, the effect of improper inspection and of improper policies governing inspection have been dealt with at some length. It is, therefore, only fair to remark that it is not the purpose to advocate careless or indifferent inspection. Rather the quality of inspection should be improved. The point is that a legal and a moral prerequisite is correct specification writing. If a State desires its concrete pavements finished to a maximum variation of one-eighth inch in 10 feet this can be done. It is perfectly proper that it require such accuracy of final finish and it is practically possible to obtain it. But it is not legally or morally proper to require such a finish under clauses allowing a one-fourth inch variation. Refinements in methods and the reduction of tolerances increase cost. Inspection should be rigid and good work should be insisted on, but back of this there should be a clear specification setting forth what is desired so that the contractor may have a fair opportunity to estimate accordingly.

SOME IMPORTANT GENERALIZATIONS

The above covers the more important causes of low production. It would be possible with the data in hand to strike averages and to say that this or that is the most important factor in causing low production and to ascribe to it a percentage relation to the whole series of causes, but little could be gained by so doing, for each job is a separate problem and general averages have little relation to the specific conditions there prevailing. Studies such as those the bureau has conducted in this field do, it is true, warrant some generalizations. Mixer operators are, for instance, quite generally undertrained, with the result that few mixers show a proper mixing cycle. Transportation generally is inadequate. Often it is woefully so. As a matter of observation it is apt to be poorly operated. The water supply also is generally inadequate; while the mixer is usually pretty well supplied, the quantity available for curing is commonly insufficient. This list could be extended but to do so has little value for the contractor whose problem is to improve production on his own job of necessity must realize that generalities and averages are a poor approach to the solution of his specific problems. It is well enough that he should know that mixers are seldom properly operated and that the truck supply is commonly inadequate, but before he can set about the correction of his own low production, he must have the facts as to specific conditions on his own job. These he should obtain just as they have been obtained for these studies by making stop-watch records over such periods as may be needed in order to clearly show what delays are occurring. With the fact clearly in mind that his job ought to be producing 48 batches every hour, it is as simple a problem to determine what delays reduce the output to 35 batches as it is to measure the top of a desk with a 2-foot rule. For studies of this sort a stop watch is desirable, though they can be made with fair accuracy from the second hand of an ordinary watch. If contractors in this field would equip their timekeepers with stop watches and would require them to take an hour's reading morning and afternoon, setting down the results as in Table 1, and summarizing them as in Table 2, the information obtained would be invaluable.

Inspectors and superintendents should also be equipped with stop watches. This really needs no argument in its support. No inspector would be allowed to pass judgment on the dimensions of a bridge if the best rule he had was graduated only in feet. Neither would a superintendent be allowed to build a bridge with such a rule as his guide. Yet hundreds of inspectors and hundreds of superintendents constantly direct work to-day where seconds are valuable on the best guesses they can make from the second hand of an ordinary watch. It may be interesting to add that in the fastest job the bureau's representatives have studied—the only job so far encountered on which the output was consistently maintained at above 90 per cent of full production—the superintendent had and frequently used a first-class stop watch.

(Continued from page 193)

decreases from 15° to 45° but at 60° is slightly greater than at 15°. It is supposed that the stresses in the right-arch sections will take the shortest course to the abutments, which is at right angles. The stresses in the triangular sections *A E B* and *D C F* will be transmitted with greater intensity to the obtuse angle of the arch. The result should be the greatest intensity of stress at the obtuse angle.

On the contrary, suppose arches had been tested which included no right section as at *X Y Z W*, Figure 12. It is possible in this case that tension might be shown to exist at the acute angle. This did not occur (except in negligible amounts) in the arches tested. For this reason it is evident that these tests include only a special condition of width of arch in relation to skew, and it is not possible to develop reliable mathematical formulæ from the existing data.

WIND RESISTANCE OF MOTOR VEHICLES

A PROGRESS REPORT OF TESTS CONDUCTED BY THE KANSAS STATE AGRICULTURAL COLLEGE IN COOPERATION WITH THE BEREAU OF PUBLIC ROADS

By **L. E. CONRAD**, Professor of Civil Engineering, Kansas State Agricultural College

AS A result of tests conducted during the past four years by the engineering experiment station of the Kansas State Agricultural College with the financial assistance of the Bureau of Public Roads, the resistance of wind at various velocities to a number of standard makes of motor vehicles has been measured and the relation between the wind resistance and relative velocity for these makes has been tentatively established. Both the total wind resistance and the resistance per square foot of the projected area of the vehicle have been determined for each of the makes tested; and from the results of the tests the horsepower required to overcome the wind resistance to each type of car has been computed.

The equations representing the relation between wind resistance and velocity as derived from the experimental data for each car are all of the parabolic form expressed by the type $P=CV^a$, in which P is the wind pressure, V the wind velocity, C a coeficient determined experimentally for each car, and a is an exponent also determined experimentally for each car.

The form of the equation is the same for the total and unit resistance, the only difference being in the coefficient, which for the unit resistance is obtained by dividing the coefficient for total resistance by the projected area of the car.

The average value of the exponent for the 14 stock cars tested is found to be 2.14. In no case is the value below two and in only one of the equations does it equal two.

Of the cars tested a Buick touring car was found to have the highest wind resistance; a Ford roadster the lowest. The resistance of the former was approximately 50 per cent higher than that of the latter. The other makes and styles of body tested have resistances between these two extremes, but the variation does not appear to be consistently related to either the make or the body style. The resistance of open cars does not appear to be consistently higher than that of the closed models as some experimenters have found.

The average equation for the unit resistance of the cars tested is found to be $P=0.00149\ V^{2.14}$. The same relation for flat surfaces is generally considered to be $P=0.003\ V^2$, and other experimenters with automobiles, assuming an exponent of 2, have arrived at coefficients ranging from 0.00234 to 0.00340. If for purposes of comparison, a definite velocity, say 35 miles an hour, be substituted in the average equation above the relation is found at this speed to be equivalent to $P=0.00250\ V^2$.

RESISTANCE OF FULL-SIZED CARS MEASURED IN WIND TUNNEL

After a year's work with natural winds which proved to be extremely variable and gusty it was found to be necessary to resort to the construction of a wind tunnel in order to produce by artificial means a reasonably constant wind velocity. The wind tunnel constructed (see fig. 1) is of rectangular cross section, 10 feet high by 12 feet wide at the throat and 50 feet long, these dimensions being increased at the test section to give an additional 27.5 square feet, which is about the average projected area of all cars measured to date.

The automobiles are set on a swinging platform, forming part of the floor, and supported by two wooden beams which are suspended from the roof by chains outside the tunnel. Side sway is prevented by four ball-bearing rollers running between two longitudinal steel tracks. When a car is blocked on this platform and the fan starts drawing air through the tunnel, the horizontal force exerted on the car causes the platform to swing backward. This horizontal force is measured by a spring balance which is connected to the front end of the platform under the floor, and which is tightened until the platform has returned to its original or zero position.

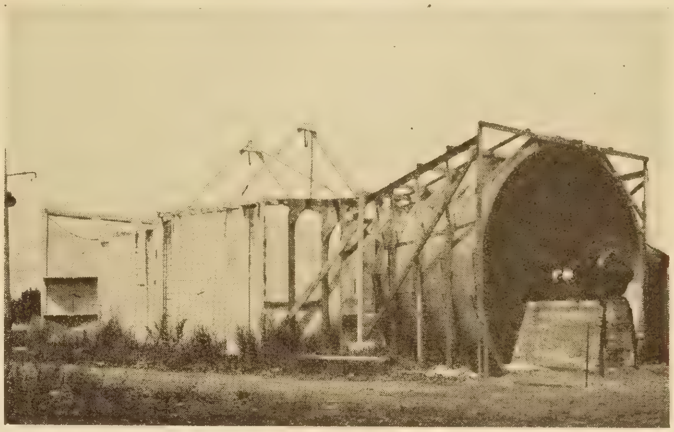

FIG. 1.—The tunnel used in the wind-resistance tests

The horizontal force or pull is made up of two factors, the wind resistance, or drag, of the car at the given air velocity, and the resistance of the platform. With no car in the tunnel, the platform resistance is too small to be measured. It was thought, however, that the presence of the car above the platform probably would increase the resistance of the latter. Accordingly, the car was suspended from the roof of the tunnel so that the wheels almost touched the platform. The resistance of the platform in this case was found to be quite appreciable; and this resistance was subtracted from the total pull in all tests. Figure 2 shows this correction, which is called the platform correction, and which amounts to a little over 3 pounds at 40 miles per hour.

The advisability of installing an air straightener or honeycomb at the entrance of the tunnel was investigated. The installation of a honeycomb usually decreases the maximum obtainable air velocity from 15 to 25 per cent. Furthermore, the honeycomb would have to be removed between tests to allow for changing cars. In view of these facts, it was decided not to use a honeycomb unless the condition of the air stream was found to be extremely bad. The first test was made by hanging streamers at various points in a cross section 7 feet ahead of the car, and noting the direction taken by each streamer. The direction in every case was parallel to the axis of the tunnel.

This test proving satisfactory, a second test was made to determine the air velocity at various points by dividing the cross section of the tunnel into 25 equal rectangular areas and determining the velocity at the center of each area. The results of 12 series of these tests gave an average variation of 6 per cent from the mean velocity, which was not considered sufficient to warrant the installation of a honeycomb. The air speed was measured by a pitot tube and a differential manometer sensitive enough to measure differences in presssure of 1/100 mm. of alcohol.

As remarked above, the cross-sectional area of the tunnel at the test section was increased by 27.5 square feet to compensate for the area of the car. While this added area is almost exactly equal to the average area of all cars tested to date, the area of some of the stock cars departed from the average by 4 or 5 square feet, while the area of one racing car differed by 13½ square feet. In computing the test results, therefore, the velocities for each car were corrected for this difference in area.

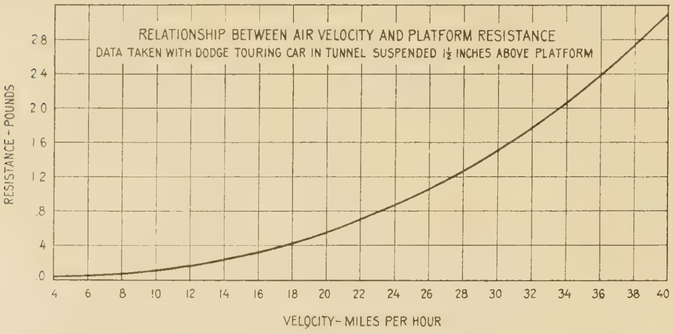

FIG. 2.—Curve used to make correction for wind resistance of platform

EFFECT OF SIZE OF TUNNEL AND OTHER TEST CONDITIONS

In order to ascertain whether the tunnel was enough larger than the automobiles to make the results comparable to actual road conditions, it was decided to determine the velocity of the air currents at certain significant points around the car both on the road and in the tunnel. One series of these tests has been run in which a very close correspondence was found between the action of the air currents around the car in the tunnel and on the road.

The effect of natural winds on the test was found to be quite pronounced; both the air speed and pull indicator becoming quite erratic. Consequently no tests have been run with a natural wind in excess of 2 miles per hour.

To determine the effect of rotation of the wheels a Dodge touring car was raised above the tunnel platform by four stilts. The front and rear hub caps on each side were connected together by leather belts, and idler pulleys were installed to prevent the belts from rubbing on the running boards. The differential of the car was locked so that both rear wheels would run at the same speed, and, after calibrating the speedometer, aligning the front wheels, and tightening the belts, it was possible to run all four wheels at any desired speed. To eliminate the effect of the stilts, belts, and driver a series of tests was run with the wheels stationary. After warming up the motor another series of tests was run with the wheels rotating at speeds corresponding to the various velocities of the air in the tunnel. That there was no appreciable difference between the results of the two series of tests was probably due to the shielding effect of the fenders on the car tested.

The effect of the automobile fan when the engine was running still remained to be evaluated. This was determined by setting the shift lever in neutral and running the automobile engine alone. It was impossible to obtain any movement of the platform indicator even by racing the engine, which is a logical result when it is considered that most of the air after passing through the automobile fan strikes some portion of the engine or car and gives up most of its energy before leaving the car.

COMPLETE TESTS ON 15 CARS

In view of the foregoing results, it appeared that the wind tunnel could be relied upon to furnish reasonably accurate values of the wind resistance, and complete tests were run on 15 different cars. So far as possible the sedan, touring, coupé, and roadster models of several different brands of cars were tested. The tests were made in the following manner. At a time when there was little or no natural wind the automobile to be tested was backed into the wind tunnel, centered on the swinging platform, and securely fastened so that it could not be drawn back into the fan. The zero position of the platform was next determined. The millimeter scale of the manometer was adjusted so that its zero corresponded to the zero position of the meniscus in the tube, and the arrangements for the test were completed by connecting the pitot tube to the manometer.

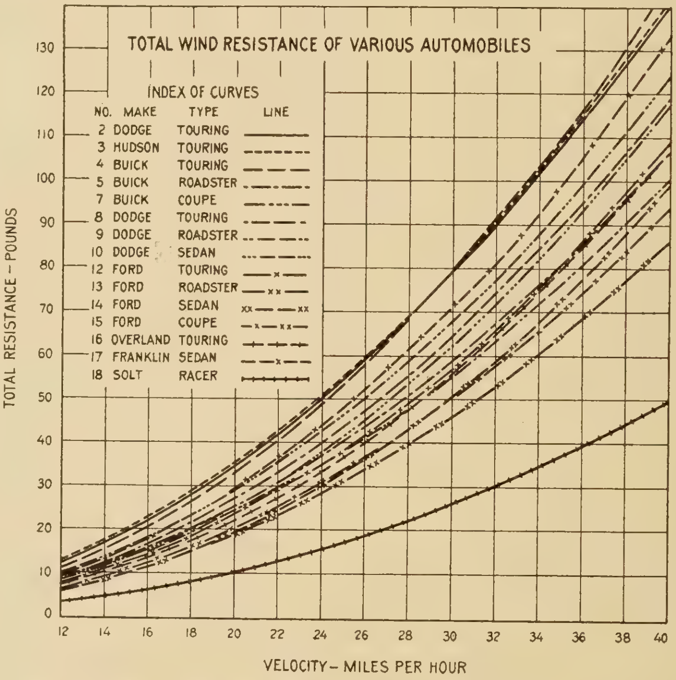

FIG. 3.—Curves showing total wind resistance to automobiles at various wind velocities

The fan was started at its lowest speed; and immediately the platform swung toward the fan. The platform was then returned to its original position by tightening the spring balance adjustment; and when the pointer indicated that the platform was in its original position, the manometer and spring balance were

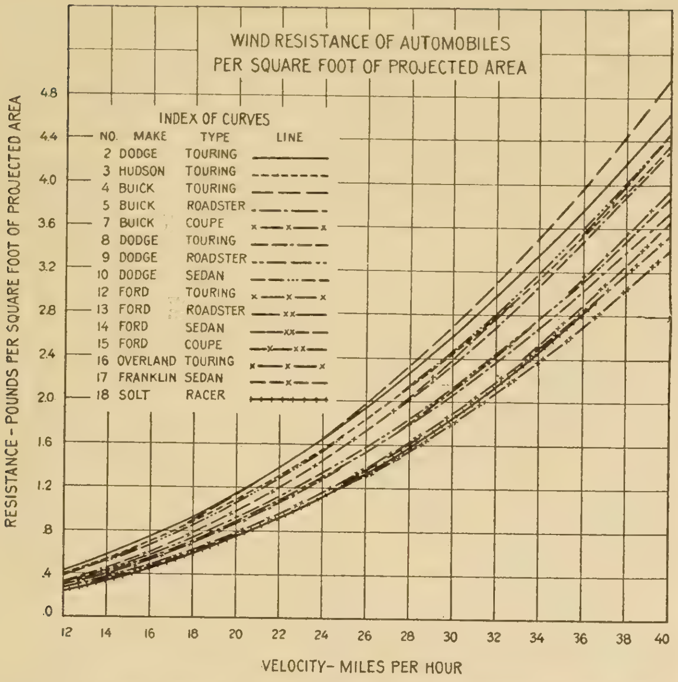

FIG. 4.—Curves showing unit wind resistance to automobiles at various wind velocities

read simultaneously. The process was then repeated for seven different air velocities, obtained by short circuiting out a portion of the armature resistance, and these data formed one test. At least two and usually three tests were run on each of the 15 cars.

The air velocity was recorded in terms of centimeters of alcohol and reduced to miles per hour in the usual manner. All velocities were reduced to an assumed standard atmosphere of 70° F. and 29 inches of mercury which represents a year-round average at Manhattan, Kans.

The spring balance was read in millimeters and reduced to pounds from a calibration chart, a correction being applied for any slight departure of the platform pointer from the zero position at the time the manometer was read. The resulting figure was multiplied by an air density factor to obtain the pull in terms of standard air, and from this value the platform resistance was subtracted, the result being the resistance of the automobile at the corresponding air speed.

The projected area of the car was next determined by tracing the outline of an enlarged photograph with a planimeter. All these photographs were taken at a distance of 200 feet, using a long-focus lens. The photograph thus obtained was enlarged about 10 times which magnified the image of the car 100 times. The relation between the size of the photograph and the size of the car was obtained from a scale which was photographed on the car.

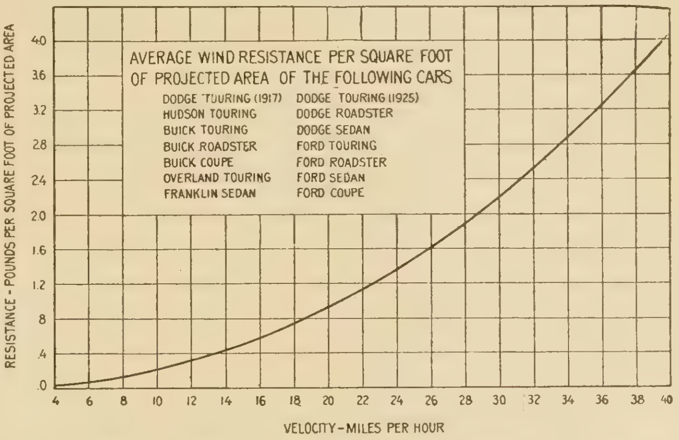

FIG. 5.—Curve of average wind resistance at various velocities for 14 stock cars

THE TEST RESULTS SUMMARIZED

The results of the tests run are summarized in Table 1, and are shown graphically by the curves of Figures 3 to 6. The equation representing the experimental data for each car was derived by the method of averages. These equations are all of the parabolic form and the exponents are not far from two, which has long been assumed to be the correct power of an equa-

TABLE 1.—*Summary of results of tests of wind resistance of automobiles*

Vehicle No.	Make of vehicle	Type of body	Model	Windshield	Top	Curtains	Projected area	Equations[1]		Protuberances, remarks, etc.
								Total pull on car	Pull per square foot of projected area	
							Sq. ft.			
2	Dodge	Touring	1917	Shut	Up	Off	30.52	$P=.0806\,V^{2.03}$	$P=.00264\,V^{2.03}$	No extras; no spare tire.
3	Hudson	do	1918	do	do	do	32.56	$P=.0880\,V^{2.00}$	$P=.00270\,V^{2.00}$	Motometer, vizor, bumpers, spot light, tool box on right running board, two spare tires on left running board.
4	Buick	do	1923	do	do	do	29.48	$P=.0550\,V^{2.14}$	$P=.00186\,V^{2.14}$	Motometer, vizor, bumpers, spare tire at rear.
5	do	Roadster	1923	do	do	do	28.42	$P=.0512\,V^{2.07}$	$P=.00180\,V^{2.07}$	Motometer, spare rim at rear.
7	do	Coupe	1922	do			29.48	$P=.0346\,V^{2.20}$	$P=.00117\,V^{2.20}$	Motometer, vizor, bumper at front, spare tire at rear.
8	Dodge	Touring	1925	do	Up	Off	27.44	$P=.0450\,V^{2.14}$	$P=.00164\,V^{2.14}$	Motometer, bumpers, balloon tires, spare tire at rear.
9	do	Roadster	1925	do	do	do	25.90	$P=.0478\,V^{2.07}$	$P=.00185\,V^{2.07}$	Motometer, bumpers, balloon tires, spare rim at rear.
10	do	Sedan	1924	do			27.75	$P=.0585\,V^{2.08}$	$P=.00211\,V^{2.08}$	Motometer, vizor, bumpers, balloon tires, spare tire at rear.
12	Ford	Touring	1925	do	Up	Off	27.49	$P=.0326\,V^{2.20}$	$P=.00118\,V^{2.20}$	Balloon tires, spare tire at rear.
13	do	Roadster	1923	do	do	do	25.60	$P=.0275\,V^{2.18}$	$P=.00108\,V^{2.18}$	Spare tire at rear.
14	do	Sedan	1924	do			27.18	$P=.0191\,V^{2.32}$	$P=.00070\,V^{2.32}$	Motometer, vizor, bumpers, balloon tires, spare tire at rear, folded luggage carrier on left running board.
15	do	Coupe	1925	do			26.55	$P=.0289\,V^{2.19}$	$P=.00109\,V^{2.19}$	Vizor, balloon tires, spare tire at rear.
16	Overland	Touring	1923	do	Up	Off	27.04	$P=.0302\,V^{2.22}$	$P=.00112\,V^{2.22}$	Spare tire at rear.
17	Franklin	Sedan	1922	do			29.70	$P=.0422\,V^{2.18}$	$P=.00142\,V^{2.18}$	Bumpers, spare tire at rear, folded luggage carrier on left running board.
18	Solt	Racing	1923	None.	None.	None.	14.05	$P=.0126\,V^{2.25}$	$P=.00089\,V^{2.25}$	Motometer, 2 spot lights, no head lights, spare wire wheel on right side.

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[1] P=Pull in pounds. V=Air velocity in miles per hour.

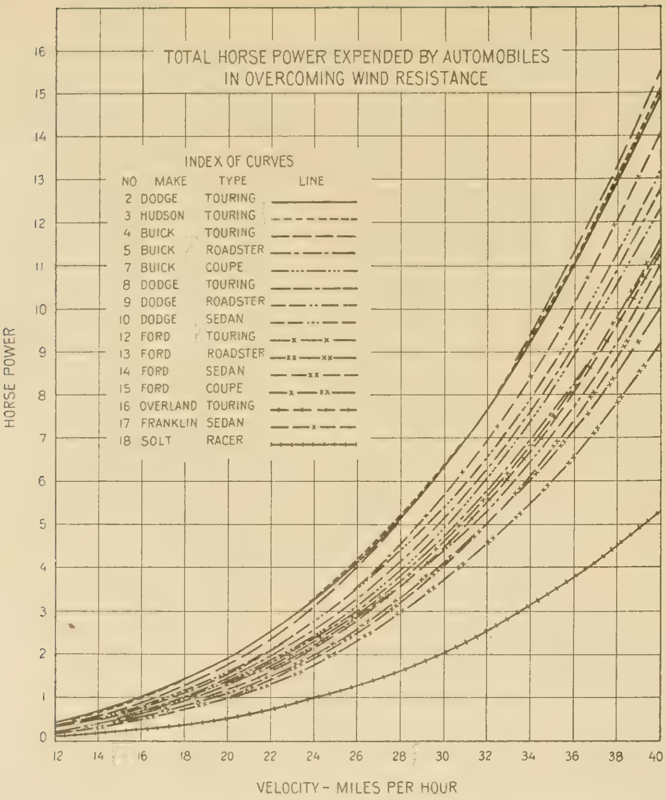

FIG. 6.—Horsepower required to overcome wind resistance to automobiles at various wind velocities

tion representing wind pressure. In one of the equations the exponent is exactly two, and in no case does it fall below that figure. The average value for the 14 stock cars tested is 2.14.

Figure 3 shows the curves for the total resistances of 15 different cars. The lowest one, No. 18, represents the resistance of a specially made racer without top, windshield, or fenders. The other 14 are stock cars which were borrowed for the tests from automobile dealers and private owners.

Figure 4 shows the curves for the unit resistances of the same cars. These were obtained by dividing the total resistance of each car by the projected area of the car in square feet. The highest of these curves, representing a Buick touring car, is approximately 50 per cent higher than the lowest, which represents a Ford roadster. In other words, the extremes vary only about 25 per cent from the average. This average curve is shown in Figure 5. The variation in unit resistance, apparently, does not accord with the make of car or type of body. The open cars are not consistently higher than the closed, as some experimenters have found.

The equation of the average curve (Fig. 5) is $P = 0.00149\ V^{2.14}$ where P is the pressure per unit area. In order to compare this with the values derived by other experimenters who assume the exponent to be 2, some definite velocity must be assumed. At 35 miles per hour, the equation would read $P = 0.00250\ V^2$. This is somewhat less than the pressure on a flat surface which is generally considered to be $P = 0.003\ V^2$. Experimenters heretofore have arrived at values of the coefficient for automobiles ranging from 0.00234 to 0.00340.

The horsepower required to overcome the air resistance of the cars tested is shown by the curves of Figure 6. These were calculated from the curves for total resistance by using the formula $H = \frac{PV}{375}$, where H = horsepower, P pressure in pounds, and V = velocity in miles per hour.

METHODS OF CURING CONCRETE IN A SEMIARID CLIMATE STUDIED

Studies of Methods of Curing Concrete in a Semiarid Climate, by Harrison F. Gonnerman and C. L. McKesson, has just been published as Bulletin 15 of the Structural Materials Research Laboratory, Lewis Institute, Chicago.

This investigation was conducted at Sacramento, Calif., as a cooperative research by the California Highway Commission and the Structural Materials Research Laboratory. The climatic conditions were quite unfavorable for the proper curing of unprotected concrete, but are typical of those encountered in semiarid regions.

The experiments were carried out on 7 by 10 by 38 inch Portland cement concrete beams made out of doors and cured in the open. Curing methods included:

1. Covering with wet earth.
2. Covering with asphaltic paper.
3. Surface application of flake calcium chloride.
4. Surface application of sodium silicate.
5. Air exposure.

Five hundred and eighteen beams were tested in cross-breaking with the cured surface in tension at ages of 3 to 90 days. The hardness of the cured surfaces of the beams was measured by a ball-indentation test. Compression tests were made on 175, 6 by 12 inch cylinders and prisms, in order to secure a measure of the quality of the concrete in a standard test.

In comparing the relative efficiency of the different curing methods, the strength of the concrete cured with earth wet 7 and 14 days (which showed practically identical results) was taken as the standard. The strength ratios for the different methods of curing were based on the following values of modulus of rupture of 1:.2 2:3.0 concrete: 7 days, 445; 14 days, 470; 28 days, 535; 90 days, 600 pounds per square inch. (The 28-day compressive strength was 4,000 pounds per square inch.)

The principal conclusions from the tests are—

1. A curing method is efficient which maintains the moisture content of the concrete during the early stages of hydration, about equal to the original quantity of mixing water. Wet-earth curing gave the best results; this method apparently supplied moisture in sufficient quantity to replace losses due to evaporation and to absorption by the subgrade. Curing methods which permitted high evaporation losses gave concrete of low strength.

2. The tests showed that concrete cured under earth wet for 7 or 14 days was only slightly stronger than when cured under earth wet for 3 days. In view of this and of the small rate of increase in strength after the fourteenth day it may be concluded that with temperature no lower than prevailed in these tests (70° F.) concrete pavements cured by covering with wet burlap

(Continued on page 212)

HIGHWAY RESEARCH PROJECTS TABULATED

AT THE request of the Bureau of Public Roads the highway research board of the National Research Council has recently completed a partial survey of research projects recently completed or now in progress under the auspices of State highway departments, universities and State experiment stations. The bureau desired information especially with regard to projects of which it would be desirable to obtain a motion picture record. Such a record of the outstanding researches is believed to be desirable and the bureau is considering plans for the purpose. By selecting a few of the more important investigations under way for picturization each year it is believed that a valuable photographic record of permanently interesting fundamental highway research will be gradually built up.

Questionnaires sent to the State contact men of the highway research board produced such a gratifying return that it has seemed desirable to compile and publish the data as a source of information in regard to current and recent projects. As it was emphasized in the request sent to the contact men that information was desired only with regard to projects suitable for picturization it is possible that some valuable information has been omitted from the reports.

The material is tabulated in accordance with the classification of the field of highway research arranged by W. K. Hatt, formerly director of the Highway Research Board.[1] Only those heads and subheads have been used which apply to the answers included in the questionnaire. Information was submitted by 39 State highway departments and 42 colleges and universities.

I. ECONOMICS:

1. Traffic studies—

United States Bureau of Public Roads in cooperation with States, etc.—Field work of traffic studies made in cooperation with the State and county highway departments has been completed in Connecticut, Maine, California, and Cook County, Ill. In cooperation with University of Tennessee and the State highway department a study has been completed in several counties of Tennessee. Studies are under way in Ohio and Pennsylvania in cooperation with the State highway departments. The data include traffic counts, net and gross loads of motor trucks, trip mileage, percentage of overloads, traffic in relation to population and other factors of value in determining highway budgets, selecting pavement types, and enacting traffic regulations.

California Highway Commission.—A traffic census is taken on all State highways at regular intervals, and this information is classified for future use. This work is under the immediate supervision of the maintenance engineer.

Colorado State Highway Department.—This State is now taking a traffic census on all the main highways. Counting stations are situated on the eastern and western slopes of the Rocky Mountain Divide.

Florida State Road Department.—This State has compiled a tabulation of traffic on the State highways.

Maine State Highway Commission.—A traffic census was taken during the period from July 1 to July 20, 1925, on the bridge between Kittery, Me., and Portsmouth, N. H. The object of this census was to determine the total amount of traffic coming in and going out of the State. The count showed the number of passenger cars, trucks, passenger busses, and horse-drawn vehicles. The registration by States was also taken.

Ohio Department of Highways and Public Works.—A comprehensive transport survey is now being conducted in cooperation with the Bureau of Public Roads. This work will cover a period of at least one year.

I. ECONOMICS—Continued.

1. Traffic studies—Continued.

South Carolina State Highway Department.—Traffic counts are being made at 117 stations for one day of each month. The object is to determine the most-used roads in order to select better types of surfacing.

University of Tennessee.—The department of highways and the University of Tennessee are engaged in making traffic studies throughout the State. Traffic counts are taken at typical stations four times each year.

Utah State Road Commission.—A traffic census is being taken this year. A count is being made on 13 days throughout the season beginning with May 6 and ending with December 1.

3. Cost of transport—

Vehicle—

Iowa State College.—Highway transportation costs. Engineering Experiment Station Bulletin No. 69.

4. Economics of location—

Iowa State College.—The Economics of Highway Grades. Engineering Experiment Station Bulletin No. 65.

North Carolina State College.—The determination of the power and cost of fuel required on State highways. Measurements are made on gasoline and electric trucks and cars with electric recording and integrating meters. The amount of the electric current and the speed are determined and from this the torque and power are calculated for different speeds on different roads and under different conditions. The test truck is calibrated for torque on the main driving shaft and on the driving wheels.

II. OPERATION:

1. Control of traffic—

Police regulations—

University of Pittsburgh.—The effect of automobile parking on traffic congestion. Observations are made of the speed of moving vehicles in the congested areas where different numbers of vehicles are parked.

7. Maintenance methods—

Routine—

Utah State Commission.—Field uses of bridge repair outfit. The unit consists of a 5-ton class B Liberty truck, on which is mounted a cement gun and an air compressor of 212 cubic feet capacity. The cement gun will be used for repairing concrete culverts and abutments which have been attacked by alkali. The truck also carries a compressed-air outfit for painting bridges and guard rails. Two jack hammers are part of the outfit. A car trailer hauls gas, oil, paint, tools, etc.

Replacement—

Colorado State Agricultural College.—A study is being made of joint fillers for use in maintaining concrete pavements.

Iowa State Highway Commission.—A study to determine the most satisfactory crack filler for use in concrete pavement maintenance. Observations were made on several sections of pavement on one road with the cracks in each section filled with a known commercial filler. The usual laboratory tests were made on each filler.

Michigan State College.—Laboratory tests are being made on 30 makes of bituminous fillers for cracks in concrete pavements. Observations are being made on 3 miles of road where these fillers are being used. The object is to secure information on which to base the revision of the specifications for crack filler.

Snow removal, etc.—

Michigan State Highway Department.—Work has been completed on an investigation of snow removal problems. The data show that a definite relation exists between temperature and snowfall. The effect of this relation is also shown on the length of the snow removal season and the amount of snow which actually remains to be removed after taking into account the amount which falls at a temperature at which no snow removal is necessary. A definite rating for the various counties in the State has been worked out and a comparison is possible between suitable equipment and a reasonable cost of carrying on the work. The report will be published shortly by the State highway department.

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[1] The Field of Highway Research, by W. K. Hatt. Public Roads, vol. 4, no. 5, Sept. 1921.

II. OPERATION—Continued.

7. Maintenance methods—Continued.

Snow removal, etc.—Continued.

Nevada Department of Highways.—The department has constructed a number of snow-removal units, one of them in particular being built on new lines. It is known that these plows and other lighter units are satisfactory in a depth of snow up to 18 inches. An attempt, however, has been made to build a snow plow that will handle easily 3 feet or more of hard snow. Since building units last year there has not been sufficient snow to make tests. If possible the tests will be made during the coming season.

Washington State Highway Department.—Various types of equipment are being tried out to determine the most economical method of removing the snow from the Sunset Highway in the Snoqualmie Pass through the Cascade Mountains.

Wyoming State Highway Department.—Investigations of the efficacy of elevating highway grades as a means of preventing the obstruction of roads by snow.

10. Safety—

Pennsylvania Department of Highways.—In 1924 guardrail tests were made. These are being continued this year. Loaded trucks are run into various types of guardrail to determine their resistance to impact and their capacity for saving life.

III. DESIGN (road):

1. Subsoil studies, properties—

Physical—

United States Bureau of Public Roads.—Intensive laboratory studies of the properties of subgrade materials are being made. These include studies leading to the proper classification of subgrade materials, investigations of their physical properties, and the development and standardization of tests for subgrade materials. Both laboratory and field tests are likewise being made in an effort to improve the supporting power of subgrades by manipulation or by the use of admixtures.

California Institute of Technology.—Tests are being made to determine the power exerted by confined adobe soils when the moisture content is increased from the dryness to saturation. The increases in volume from a dry condition to saturation are also being measured.

Colorado State Highway Department.—The department at this time is taking core-drill samples of pavements and samples of the underlying subgrade material. It is also sampling the subgrade soils on contemplated projects. These investigations are being made in cooperation with the Bureau of Public Roads.

Georgia State Highway Department.—Investigations are being carried on to determine the effective life of sand-clay, topsoil, and similar surfacing materials on the State highway system. Samples of surfacing material are taken annually from 29 Federal-aid projects which are under study. These samples are analyzed in accordance with standard methods and studies are being made on the several ingredients to determine the factors which control the stability of such soils under known traffic and weather conditions. Maintenance cost data are being kept on these projects and traffic counts are being made annually. These studies are expected to be carried on until the roads need to be reconstructed. At that time it is hoped that the combined economic and scientific data will be sufficient to determine the efficient use of these roads under known traffic density.

Iowa State Highway Commission.—An investigation to determine the cause and to devise a remedy for the subgrade failures occurring most frequently in cuts on earth and gravel roads in northwestern Iowa.

Michigan State Highway Department.—An investigation to determine the causes for the settlement of earth fills on unstable soils has been begun. An attempt is being made to determine the percentage of shrinkage probable on muck soil and the shape of the cross section of the earth fills in the muck. An attempt will also be made to determine the amount of muck beneath the fill which is compressed to such an extent that a comparatively stable support is provided for the fill above it.

Ohio Department of Highways and Public Works.—Soil investigations including laboratory tests are being made on experimental sections of pavements with specially prepared subsoils. The work is being carried on in cooperation with the Bureau of Public Roads and the Ohio Engineering Experiment Station.

III. DESIGN (road)—Continued.

1. Subsoil studies, properties—Continued.

Mechanical—

Iowa State Highway Commission.—The determination of the coefficient of friction of a concrete slab moving from rest and in motion on various soils. Concrete slabs, each 24 by 24 by 8 inches in size cast in place on the soil, are being studied. They are pulled with a hoist. The load is measured with a 1,200-pound spring balance and the movement observed and measured with a micrometer miscroscope.

Improvement by treatment—

Iowa State Highway Commission.—The effect of various finely powdered admixtures incorporated with the surface soil of earth roads. A total of 3½ miles of road was treated, one-half of the mileage on a tough, clay soil and the remainder on Missouri Valley loess. Portland cement and hydrated lime in various amounts were used on different sections of each road. They were mixed with the earth to a depth of 6 inches.

University of Illinois.—A laboratory investigation attempting to determine the basic principles involved in the construction of oiled earth roads. This includes a study of both the oils and the soils. Although considerable work has been done it has not yet reached the stage of publication. The work will continue during the coming year. A graduate research fellowship for the study of earth roads has been established. The work will cover a period of about two years.

University of Missouri Engineering Experiment Station.—A study to determine the effect of lime on earth roads. Commercial hydrated lime is incorporated in the top 6 inches of the soil of the road to determine the beneficial effect. It is hoped by this treatment that the maintenance of such roads will be made easier, particularly with respect to dragging and prevention of the formation of ruts. Some sections have been tried with a 2-inch depth of application of the lime and also with varying percentages of lime. Laboratory tests have been carried on in conjunction with field tests to determine how the soil is affected by the addition of the lime.

Effect of climate—

Minnesota State Highway Department.—A study of the occurrence of frost upheavals in the spring, the locations at which they are most likely to occur, and an investigation of methods of prevention.

2. Base course—

Ohio State University Engineering Experiment Station.—The method of maintaining the smoothness of a granular subbase beneath a concrete pavement while paving materials are being brought to the work, mixed, and placed.

3. Surface—

Character—

Alabama State Highway Department.—Determination of a clay-asphalt mixture for surfacing. It is desired to produce a serviceable and economical surfacing by the admixture of asphaltic oils with clay, sand, gravel, etc., adjacent to the roadway.

Connecticut State Highway Commission.—A study to determine an economical method of laying a bituminous surface on a concrete road with a pitted surface. Experiments are being carried out on sections of pavement surfaced with various kinds and depths of bituminous materials.

Michigan State Highway Department.—An investigation of the various types of rigid pavement now in service on the trunk-line and Federal-aid highway system in an effort to determine what methods of reinforcement of the slab, subgrade treatment, etc., have been particularly effective since their construction during the past five or six years. A number of projects are available on which experimental work has been done in the past few years.

Wear by elements—

Illinois Department of Public Works and Buildings.—An investigation to determine the temperature through pavement slabs and a study of the resulting stress and the curling action of the slab.

Wear by traffic—

United States Bureau of Public Roads.—Laboratory and field studies to determine the characteristics and properties of bituminous paving mixtures, especially with regard to the determination of the cause of longitudinal displacement or shoving. Field experiments

III. DESIGN (road)—Continued.

3. Surface—Continued.

Wear by traffic—Continued.

are being carried out on a circular track with concrete base surfaced with short sections of widely different mixtures. Traffic has been imposed by means of a loaded truck and the relative stability of the various sections obtained by recording the displacement of plugs set in the surface.

Laboratory tests have been made to determine the properties of materials used in the field test, and a new modified shear test has been developed which appears to measure the resistance to displacement of sheet asphalt and bituminous concrete mixtures.

Tractive resistance—

Iowa State College.—Resistance to the translation of Motor vehicles. Engineering Experiment Station Bulletin No. 64. Tractive resistance and related characteristics of roadway surfaces. Engineering Experiment Station Bulletin No. 67.

5. Impact—

United States Bureau of Public Roads, Society of Automotive Engineers, and Rubber Association of America.—The objects of this cooperative investigation are the determination of the effect of motor trucks operating on highways as influenced by various truck, tire, and road factors, such as type of tire, design of truck, and character of road surface; and the measurement of stresses in road surfaces as influenced by motor-truck wheel impact. Experiments so far include the determination of the cushioning of pneumatic, cushion, heavy-duty cushion, high-profile, non-skid, and regular types of solid tires. Tests have been made with both new and worn-out tires, and with new tires cut down to various heights to simulate the effect of partly worn tires. Both static load and impact tests have been made with trucks equipped with various tires, as well as tests on actual roads, one test road section being selected to represent a smooth and the other a rough surface.

8. Reinforcing—

Highway Research Board, National Research Council.—A nation-wide survey is being made to determine the value of reinforcing in concrete pavement. Pavements in good and bad condition are being compared to determine the relative value of the different types of reinforcement. In addition to differences in the subgrade conditions notes are being taken on the age, mix, traffic and cross-section variations.

IV. DESIGN OF VEHICLES (as related to the road):

1. Design of vehicle—

University of Kansas.—A study of the air resistance to motor vehicles. A wind tunnel is used in which the car to be tested is placed on a feebly swinging platform. As the wind is forced past the car its effect is observed and the force recorded

3. Surface—

Wear on tires—

University of Kansas.—A study to determine the relative effect of different types of pavement on the wear of motor-vehicle tires. A Dodge touring car and a laboratory apparatus using regulation-size tires are used in the tests.

4. Alignment—

Grades—

Michigan State Highway Department.—An investigation of the behavior of 1½-ton trucks on different types of surfaces and on various grades has been completed. This takes into account all factors at the various speeds. The factor which is new and which is believed never to have been considered before is that of the moment of inertia of the rotating part of the motor vehicle including the wheels, transmission system and engine.

6. Safety—

Iowa State Highway Commission.—The determination of various methods of securing satisfactory driving lights for automobiles and the regulation of the use of these lights.

V. CONSTRUCTION:

1. Materials—

Bituminous—

Iowa State Highway Commission.—The effect of various preservative treatments for wood posts used in guard-rail construction. Several sets of posts were treated by different methods and installed along the roads in three separate counties. Observations were made of ordinary installations, and laboratory tests were carried on for the various treating fluids.

V. CONSTRUCTION—Continued.

1. Materials—Continued.

Bituminous—Continued.

North Carolina State Highway Commission.—The determination of the proper thickness of a sand-asphalt wearing surface under various traffic conditions. The observations were made on pavement surfaces of 1½ and 2 inch depths under known traffic conditions.

South Carolina State Highway Department.—The observation of bituminous treatment of earth roads. Forty miles of experimental roads with various tar and oil treatments have been constructed. The object is to develop a satisfactory and economical surfacing for earth roads, such as topsoil and sand-clay.

Nonbituminous—

United States Bureau of Public Roads.—An investigation to determine how the character and type of aggregate affects the resistance of concrete road surfaces to wear produced by traffic loads. Sixty-two sections of cement-concrete surfacing were constructed in the form of a circular track 600 feet in circumference. Various types of coarse aggregate, such as crushed stone, gravel, and slag were employed, each of which varied in quality from the best obtainable to materials which have been considered of questionable value. These test sections have been subjected to the action of a motor-driven testing machine equipped with solid rubber tires designed in such a manner as to produce the same traffic effects as an actual motor truck. An amount of traffic equivalent to 300,000 applications of a single wheel load operating at a speed of 22 miles per hour and loaded to 600 pounds per inch width of tire, was first put upon the pavement. This was followed by a second test in which the testing machine followed an entirely different path and in which traffic was placed upon the pavement equivalent to 75,000 applications of the same wheel load, with the exception that the tires were equipped with nonskid chains.

A series of concrete tests is now being conducted in which the coarse aggregate varies both as to character and quality. About the same range of quality and character of aggregates is being employed in this test as was used in connection with the tests for wear-resisting properties of concrete. The specimens are subjected to alternate freezing and thawing in such a manner as to simulate the effect of actual frost action in the field. The effect of frost action is determined both by visual examination of the specimens and by subjecting them to flexure tests.

California Highway Commission.—A study to determine the efficiency and cost of calcium chloride for the prevention of dust on a heavily traveled gravel road has been made in one of the divisions of the State.

Colorado State Agricultural College.—A survey is being made to determine the location in the State of road materials for various types of highway construction. Samples of the materials are tested in the laboratory.

Another study is being made to determine the effect of beet pulp on concrete and mortar.

Iowa State Highway Commission.—A study to determine the effect of shale in various amounts in the aggregate upon the strength of concrete. This includes a study of rotten stone. Compression tests are made on 6 by 12 inch cylinders and transverse tests on 4 by 8 by 30 inch beams.

A study to devise methods of using poorly graded sands to produce concrete equivalent in workability and strength to normal materials. The mortar-void theory of proportioning was tried. The specimens consisted of briquettes and 2 by 4 inch cylinders.

A study to determine what physical characteristics of Iowa limestones affect the quality of concrete made by using these limestones as the coarse aggregate and to devise tests which would consistently indicate variations of those characteristics. Abrasion tests were made in the Deval machine with standard and slotted cylinders.

A series of tests of large-sized concrete pavement slabs constructed by the vibrolithic process and corresponding slabs constructed in the conventional manner. Both kinds of slabs were tested for modulus of rupture by means of a specially constructed testing machine. Various proportions of cement and aggregate were used in the slabs, one-half of which were tested with the top surface in tension, the balance with

V. CONSTRUCTION—Continued.
1. Materials—Continued.
Nonbituminous—Continued.

the bottom in tension. Tests are being made at the age of 28 and 90 days and one year.

Later this test was continued with a new operator to determine the durability of the limestone. Accelerated weathering tests and soundness tests were made. Particular studies were made of the steam-sulphate test and of the freezing and thawing tests.

Later this work was continued by making a particular study of the soundness, absorption, specific gravity, and standard Deval abrasion tests.

A study to determine the effect of varying ratios of fine and coarse aggregate in concrete mixes upon the strength and resistance to wear of the concrete. This is a corroboration of Crum's method of proportioning. Proportions were made by weight. The specimens made up in 6 by 12 inch cylinders and 4 by 8 by 30 inch beams were subjected to the usual tests. Both types of specimens were made in the field and in the laboratory.

A study to determine the serviceability of various paint mixtures under service conditions.

A study to determine the effect of the various chemicals found in the natural waters of the State upon the strength of the concrete mixed with these waters.

A study to determine the physical or chemical properties of a soil or clay which make it unsuitable as binding material for use in gravel road construction. Methods of tests were used as proposed in a paper on "Physical properties of subgrade materials," read by J. R. Boyd of the Bureau of Public Roads before the twenty-fifth annual meeting of the American Society for Testing Materials.

A study to determine the thermal coefficient of expansion of concrete made from different mixes.

An investigation of the characteristics of a serviceable paint film. Microscopic photographs of the surface and cross sections of the various paint films were made.

A study to determine the effect of the size and shape of concrete test beams upon the modulus of rupture. Beam specimens 4 by 8 by 30 inches and 4 by 4 by 60 inches in size were tested at different span lengths and in different positions.

A study to determine a method of using Platte River sand-gravel to produce concrete having strength equivalent to that produced by concrete made from a typical Iowa material possessing similar characteristics. The usual laboratory specimens were made. These consist of beams and cylinders and a special effort was made to develop a technique for measuring the workability of plastic concrete.

A study to determine the properties of the high alumina cement recently introduced into the United States. Tests were made on laboratory specimens consisting of standard briquettes and small cylinders.

John Hopkins University.—A study to determine the relation, if any, between static and impact strains in concrete. Concrete beams 6 by 8 by 4 feet long are subjected to impact loading by means of a rubber-cushioned weight which is allowed to fall upon the beams at their third points. The unit deformations are measured with graphic strain gauges inserted in both sides of the beams, six on each side arranged vertically one over the other at the mid point of the beams. The variable impact forces are determined by an accelerometer. Deflections of the beams are also measured. Corresponding measurements are also made for static loading which is applied by a standard testing machine.

Kansas State Agricultural College.—A study to determine the abrasive resistance of concrete with various kinds and proportions of aggregate. Nine-inch concrete spheres are cast and for 90 days are tested in a standard brick rattler. At the end of the test period, four ½-inch cores are drilled from each sphere and tested in compression.

Michigan State College.—A study to determine the effect of low temperatures on the time of setting and the strength of Lumnite cement. The compression specimens were exposed to cold weather of different degrees at various ages and with different coverings.

V. CONSTRUCTION—Continued.
1. Materials—Continued.
Nonbituminous—Continued.

A study to determine the bond between Portland cement and Lumnite cement. The bond was tested in shear and the effect of wear was observed on a top coat of the Lumnite cement on a pavement with a Portland-cement base.

Minnesota Highway Department.—A study to determine the effect of shale on the compressive strength of concrete. Concrete cylinders, 6 by 12 inches in size, containing varying percentages of shale were subjected to alternate freezing and thawing. The object was to determine the quantity of shale which should be permitted in coarse aggregate for Portland cement concrete.

A study of the limestone quarries in the State of Minnesota which are operated on a commercial scale. This report consists of geological descriptions of the various quarries in the State and physical and commercial tests and samples of rock taken from each quarry.

A study to determine the soundness of Minnesota stone. The tests were made in accordance with the methods described on page 8 of United States Department of Agriculture Bulletin No. 1216. Tests were made on 4 samples of trap rock, 5 samples of quartzite, 2 samples of granite, 14 samples of limestone, and 1 sample of sandstone. All samples were subjected to 20 immersions in copper sulphate. The fineness modulus was determined on each sample before and after tests were made. In this way the percentage of loss was determined.

A study to determine the effect of weather on the compressive strength of concrete. This involved alternate freezing and thawing, especially of concrete containing shaley or laminated limestone.

A study to determine the effect of moisture content on the volume of sand and the effect of the grading and character of the coarse aggregate on the percentage of voids.

A study to furnish comparative data on vibrolithic pavements and one-course concrete pavements constructed under similar conditions.

A study to determine the merits of the patented pavement known as "raw hide." The data were obtained from a short experimental stretch of this pavement constructed during the fall of 1924.

A study of the effect of time on the compressive strength of Lumnite cement concrete and observations on Lumnite cement concrete placed during freezing weather.

A study of the merits of Willite pavement. This investigation includes tests on the various grades of asphalt such as Texas, Mexican, Bermuda, Trinidad, etc., with and without copper sulphate. Tension, toughness, sag, and impact tests were made on sheet asphalt mixtures containing copper sulphate.

A study of an experimental road consisting of sections of Portland cement concrete with various kinds of aggregate and types of reinforcement. One section consisted of Lumnite cement concrete and another of sheet asphalt with an asphaltic concrete base.

A study to determine the value of marl as a binder on sandy roads. The experimental roads were built in 1922. A report of this test was published as Bulletin No. 1 of the Engineering Experiment Station of the University of Minnesota.

New Jersey State Highway Commission.—Deterioration surveys have been made of the concrete pavement on the State highways. The results will be compiled and compared with designs, construction conditions, and maintenance costs.

Purdue University.—The fatigue of concrete. Concrete specimens are subjected to repeated stresses or reversals of stress in a specially constructed apparatus. The object is to determine the fatigue limit of concrete under repeated loads.

Tennessee Department of Highways.—A study to determine the tensile and compressive strength of Lumnite-cement concrete at ages varying from 11 hours up to 12 months. The tensile and compressive specimens were 2 by 4 inches in size.

A field study to determine the behavior of rock asphalt as a road-surfacing material.

V. CONSTRUCTION—Continued.

1. Materials—Continued.

Nonbituminous—Continued.

Texas Agricultural and Mechanical College.—A study to determine the suitability of mudshell as an aggregate for bituminous pavements. Numerous specimens were prepared from various formulas and tested for stability by means of an improvised mold and plunger and by true punching shear. Comparisons were made with four other types of hot mixture.

University of California.—A study to determine the expansion of concrete due to the absorption of moisture. These tests have been under way since the first of the year. A room has been constructed in which the temperature and humidity may be maintained at any desired temperature and 3 by 3 by 40 inch specimens have been observed periodically to determine the rate of change in weight and length due to variations in the moisture content.

A study to determine the fatigue of concrete. Beam specimens, 4 by 6 inches by 6 feet, are subjected to repeated center loads up to 100,000 repetitions.

Tests are being inaugurated to determine the plastic deformations of concrete under continuing load. These tests will be made to determine a rate of flow of concrete in compression and also in flexure.

Fundamental mechanical properties—

California Highway Commission.—In order to determine the relative smoothness of various pavements, vialog records have been made of most of the existing pavements on the State highway system. New records are being made from time to time to determine what changes, if any, occur in the condition of the pavement. Records are also being made of new pavements to ascertain the relative efficiency of the finishing methods and construction operations.

Illinois Department of Public Works and Buildings.—A study to determine the effect of impact on pavement slabs by equivalent static loads through the medium of slab deflections.

Tests have been made with the Illinois fatigue machine to determine the fatigue stress in concrete.

Methods of tests—

U. S. Bureau of Public Roads.—Extensive laboratory and semifield tests are being conducted for the purpose of determining the most satisfactory method of measuring the consistency of Portland cement concrete. Comparative tests have been made, using the slump test, the flow test, and a special device known as the *plate test* developed by the bureau. All of these tests have been conducted with a view of developing a method which will control the water-cement ratio and, therefore, the strength of the concrete.

Illinois Department of Public Works and Buildings.—A number of pavement surfaces have been profiled with a profilometer in order to study the roughness of the slab.

Iowa State Highway Commission—A study to determine the effect of the number of pieces of rock used in the abrasion test for the French coefficient of wear.

A study to determine the effect of a standard shot rerun of the abrasion test.

A brief study to determine the effect of the number of revolutions in the determination of the French coefficient of wear.

An investigation of the various proposed methods for making quantitative analysis of the quantity of shale in gravel. Flotation in heavy liquids and separation by handpicking was tried.

An investigation of the various adaptations of the Deval test and others with the Deval machine.

Investigations of the abrasion tests of sand to determine the suitability of these tests for fine aggregates.

An investigation to devise a test for cement which will give consistent results in a shorter period of time than that required by the standard tests now in use. Standard briquets and 2 by 4 inch standard specimens were used.

An investigation to determine the adequacy of the standard Deval abrasion test for establishing the suitability of the mortar portion of the various concrete mixes used in highway work.

An investigation to devise laboratory tests which will consistently and accurately determine the characteristics which govern the behavior of a lubricating oil under known conditions of service. The work has consisted of a brief study of the methods now used for testing lubricating oils and a series of these tests was made upon a large number of commercial oils.

An investigation to devise a method of testing rotten stone, which, when used by different operators, will consistently differentiate this undesirable material.

Massachusetts Institute of Technology.—A study to determine the effect of slotted cylinders of the Deval machine.

Preparation and treatment—

Iowa State Highway Commission.—A study to determine the causes of and methods for controlling the hair cracks in concrete-pavement slabs. Small slabs were built upon various types of subgrade soil. Each soil was subjected to a similar set of conditions.

An investigation to determine the effect of varying sand ratio, varying consistency, and varying curing period upon the modulus of elasticity of concrete.

Wisconsin Highway Commission.—A study to determine the best method for the surface treatment of gravel roads from which has been developed the Wisconsin special-mix method which has been used in this State during the past three seasons.

Proportioning—

Illinois Division of Public Works and Buildings.—A study to determine the bulking effect of materials of different gradations by means of the Illinois bulkmeter.

Iowa State Highway Commission.—A study to determine the specific gravity of sand and gravel from a large number of deposits for use in the weight method of proportioning.

A study of the various methods for determining the cement content and the proportions of aggregate in cured concrete. Mechanical separation, chemical analysis and microscopic observation and measurement were used on prepared specimens wherein all the constituents were accurately known.

An investigation to determine the effect of the curing of the coarse aggregate upon the strength of concrete made in different proportions. Specimens consisted of 6 by 12 inch cylinders for the compression tests and 4 by 8 by 30 inch and 8 by 8 by 30 inch beams for the transverse tests. Workability of the plastic mix and shrinkage of the curing concrete were given special observation.

North Carolina State Highway Commission.—A study to determine the accuracy of proportioning fine aggregate by inundation. Several miles of concrete pavement were constructed with fine aggregates proportioned by loose volumetric measurements. Adjacent to this several miles of concrete pavement were built in which the same materials were proportioned by the so-called inundation method. Points observed are the effect on the cement, constant plasticity and workability of the concrete, and strength of the concrete as determined by cores taken from the completed pavement and broken in a standard testing machine.

University of Tennessee.—It is hoped that opportunity will be afforded to make during the next two years a study of fine dust as asphalt-pavement filler. It is hoped that the project will be under way by January of next year.

2. Mixing—

Efficiency of mixer—

Iowa State Highway Commission.—An investigation to determine the effect of the vibrolithic process as applied to the finishing of concrete-pavement slabs. Ten slabs, each 7 feet wide, 8 inches deep, and 75 feet long were constructed using five different proportions and 2 slabs for each proportion, 1 of plain and 1 of vibrolithic concrete. The slabs were divided into 750 beams 12 inches wide, 8 inches deep and 7 feet long. Transverse tests were made on the beams and compression tests on the cores drilled from the beams.

3. Placing—

California Highway Commission.—A field study is now being made to determine the relative efficiency of various periods of water curing. Sections of pavement were cured with earth covering kept wet for varying periods. Cores are being drilled at various ages. The last of these cores will be drilled in June 1926, at an age of 1 year.

V. CONSTRUCTION—Continued.

3. Placing—Continued.

North Carolina State Highway Commission.—A study of the methods of curing concrete pavements by moist earth and ponding, by calcium chloride sprinkled on the surface of the pavement and by calcium chloride (or Cal) used as an admixture. The points to be noted are the results of the core breaks, the visual inspection of the finished pavement surface and the character of concrete during construction.

A study to determine the necessity for joints in concrete pavements. A 10-mile plain concrete project will be built, 5 miles of which will be constructed without expansion joints and 5 miles with expansion joints. As an alternative to this method of construction, alternate sections 1-mile long may be built with and without joints. It is not known when this investigation will be begun.

4. Methods of testing roads—

Cores—

Minnesota Highway Department.—An investigation to determine the effect of capping concrete cores on the compressive strength of concrete, and also to determine what correction factors, if any, should be used for cores of various types.

6. Drainage (and drainage structures)—

U. S. Bureau of Public Roads.—In order to measure experimentally the distribution and intensity of abutment reaction in skew arches, a series of tests has been conducted on concrete arches, one-fourth actual size, constructed on 30°, 45°, and 60° skews. The arches were tested under a uniform load applied through 42 symmetrically placed loading points on the arch ring. Abutment reactions were measured by means of the soil pressure cells developed by the bureau, which were so placed as to take both the vertical and horizontal reactions at one end of the arch.

California Highway Commission.—A more or less elaborate study of corrugated-iron culverts is to be made during the latter part of this year with a view of determining, if possible, the relative durability of pure iron and of covered steel pipe.

Iowa State Highway Commission.—An investigation to determine the laws governing the behavior of steel rollers of varying temperature under loading when in compression. The preliminary work was done on rollers up to 48 inches in diameter. The project is now being carried on by the Engineering Experiment Station of the Iowa State College at Ames, Iowa.

A study of the factors affecting the design of concrete culvert pipe has been made in cooperation with the Engineering Experiment Station of the Iowa State College at Ames, Iowa. The station is now carrying on this work.

Maine State Highway Commission.—An investigation is being made of all classes of culvert installation. The study for the most part is being confined to culverts which have been installed at least seven or eight years or longer. The work will cover all sections of the State.

South Carolina State Highway Department.—The effect of sea water on reinforced concrete and vitrified-clay culvert pipe. The specimens are placed between high and low tide in the sea water at Charleston, S. C., and observations are made of the effect on the materials.

Tennessee Department of Highways.—A field study of the condition of several types of pipe culverts and also small concrete box culverts and stone culverts.

University of North Carolina.—A study to determine the vertical earth pressures on culvert pipes with varying heights of fill up to 20 feet. The completed tests will include both sand and clay as a filling material. Beginning in the summer of 1925 the tests will be continued using pipe of various sizes and kinds. In 1926 it is hoped to determine the radial pressure as well as the vertical pressure of the soil on the culvert pipe.

University of Pittsburgh.—Tests have been made on various sizes of concrete-culvert pipe to determine their strength. The pipes were tested to destruction and the work was done in cooperation with the Concrete Products Co.

8. Reinforcing, handling, and placing—

Illinois Division of Highways.—An investigation is being made as to the properties of rail steel and its reaction under impact when such steel is used for concrete-pavement reinforcement.

Iowa State Highway Commission.—A study of the behavior of reinforcing steel in concrete pavements. Special attention was directed to bond stress and the behavior of steel at cracks in the pavement. Preliminary work has been done on the testing of steel of different grades of hardness.

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for 16 to 24 hours and then with earth kept wet for 7 days may safely be opened to traffic in 14 days.

3. Curing with a surface application of flake calcium chloride, 2½ pounds per square yard, gave strength ratios of from 88 per cent at 7 days to 83 per cent at 90 days; with less than this amount and with 3 and 5 pounds there was a slight reduction in strength.

When the calcium chloride was washed off after 3 hours, the strengths were reduced perceptibly; washing off calcium chloride after one day gave essentially the same strengths as when left on the surface.

Surface hardness for calcium chloride cured beams was considerably less than for beams cured with wet earth or with asphaltic paper.

4. For beams molded and cured in concrete forms using calcium chloride, 2½ pounds per square yard, the strength ratios ranged from 100 per cent at 14 days to 89 per cent at 90 days. The strengths in this case were about 12 per cent higher than for beams molded in wood forms and cured with a similar amount of calcium chloride.

5. Asphaltic paper curing gave average strength ratios ranging from 92 per cent at 7 days to 78 per cent at 90 days; surface hardness was almost as high as for wet-earth curing.

6. Both air curing and sodium-silicate curing showed low strength and surface hardness. The strength ratios for these methods of curing ranged from about 77 per cent at 7 days to 74 per cent at 90 days.

7. Indentation loads used in measuring surface hardness averaged 21 times the modulus of rupture; the greatest surface hardness was found for concrete of highest flexural strength. This method of test showed that calcium chloride, sodium silicate, and air curing produced a more friable surface than wet earth or paper curing.

EARTH AND GRAVEL ROAD BIBLIOGRAPHY PREPARED

On account of the great interest in secondary highways the Engineering Societies Library has prepared a bibliography of books and articles on earth and gravel roads, published between January, 1920, and June, 1925.

The list, designated as S. 4085, contains 140 references with brief annotations. Mimeographed copies may be obtained for $1.50 each by writing to the Engineering Societies Library, 29 West Thirty-ninth Street, New York City.

HIGHWAY LANTERN SLIDES AVAILABLE

The Bureau of Public Roads has recently placed in its district offices at Portland, Oreg., San Francisco, Calif., Ogden, Utah, and Denver, Colo., sets of lantern slides illustrating the methods of constructing the principal types of roads. The slides are in six sets and are intended for use in engineering schools and colleges. Complete information with regard to the slides and how to obtain them can be secured from the Washington office or the above district offices of the bureau.

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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.

ANNUAL REPORT

Report of the Chief of the Bureau of Public Roads, 1924.

DEPARTMENT BULLETINS

No. 105. Progress Report of Experiments in Dust Prevention and Road Preservation, 1913.
*136. Highway Bonds. 20c.
220. Road Models.
257. Progress Report of Experiments in Dust Prevention and Road Preservation, 1914.
*314. Methods for the Examination of Bituminous Road Materials. 10c.
*347. Methods for the Determination of the Physical Properties of Road-Building Rock. 10c.
*370. The Results of Physical Tests of Road-Building Rock. 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.
390. Public Road Mileage and Revenues in the United States, 1914. A Summary.
407. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1915.
*463. Earth, Sand-Clay, and Gravel Roads. 15c.
*532. The Expansion and Contraction of Concrete and Concrete Roads. 10c.
*537. The Results of Physical Tests of Road-Building Rock in 1916, Including all Compression Tests. 5c.
*583. Report on Experimental Convict Road Camp, Fulton County, Ga. 25c.
*586. Progress Reports of Experiments in Dust Prevention and Road Preservation, 1916. 10c.
*660. Highway Cost Keeping. 10c.
670. The Results of Physical Tests of Road-Building Rock in 1916 and 1917. 5c.
*691. Typical Specifications for Bituminous Road Materials. 10c.
*704. Typical Specifications for Nonbituminous Road Materials.
*724. Drainage Methods and Foundations for County Roads. 20c.
*1077. Portland Cement Concrete Roads. 15c.
*1132. The Results of Physical Tests of Road-Building Rock from 1916 to 1921, Inclusive. 10c.
No. 1216. Tentative Standard Methods of Sampling and Testing Highway Materials, adopted by the American Association of State Highway Officials and approved by the Secretary of Agriculture for use in connection with Federal-aid road construction.
1259. Standard Specifications for Steel Highway Bridges, adopted by the American Association of State Highway Officials and approved by the Secretary of Agriculture for use in connection with Federal-aid road work.
1279. Rural Highway Mileage, Income and Expenditures, 1921 and 1922.

DEPARTMENT CIRCULAR

No. 94. TNT as a Blasting Explosive.

FARMERS' BULLETIN

No. *338. Macadam Roads. 5c.
*505. Benefits of Improved Roads. 5c.

SEPARATE REPRINTS FROM THE YEARBOOK

No. *727. Design of Public Roads. 5c.
*739. Federal Aid to Highways, 1917. 5c.
*849. Roads. 5c.

OFFICE OF PUBLIC ROADS BULLETIN

No. *45. Data for Use in Designing Culverts and Short-span Bridges. (1913.) 15c.

OFFICE OF THE SECRETARY CIRCULARS

No. 49. Motor Vehicle Registrations and Revenues, 1914.
59. Automobile Registrations, Licenses, and Revenues in the United States, 1915.
63. State Highway Mileage and Expenditures to January 1, 1916.
*72. Width of Wagon Tires Recommended for Loads of Varying Magnitude on Earth and Gravel Roads. 5c.
73. Automobile Registrations, Licenses, and Revenues in the United States, 1916.
161. Rules and Regulations of the Secretary of Agriculture for Carrying out the Federal Highway Act and Amendments Thereto.

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. 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. 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.

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* Department supply exhausted.

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL AID HIGHWAY CONSTRUCTION

AS OF

OCTOBER 31, 1925

GOVERNMENT PRINTING OFFICE

STATES	FISCAL YEARS 1917-1925			FISCAL YEAR 1926									BALANCE OF FEDERAL AID FUND AVAILABLE FOR NEW PROJECTS	STATES
	PROJECTS COMPLETED PRIOR TO JULY 1, 1925			PROJECTS COMPLETED SINCE JUNE 30, 1925			*PROJECTS UNDER CONSTRUCTION			PROJECTS APPROVED FOR CONSTRUCTION				
	TOTAL COST	FEDERAL AID	MILES	TOTAL COST	FEDERAL AID	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES	ESTIMATED COST	FEDERAL AID ALLOTTED	MILES		
Alabama	$ 5,970,097.71	$ 2,863,197.86	611.8	$ 5,290,651.84	$ 2,495,554.59	293.9	$ 10,322,000.26	$ 5,031,107.84	535.4	$ 378,592.64	$ 175,050.00	11.6	$ 2,243,745.71	Alabama
Arizona	9,580,133.43	5,016,119.94	613.8	237,926.80	145,397.06	7.1	2,051,812.12	1,308,811.30	166.1	176,977.10	108,150.70	26.7	1,982,862.00	Arizona
Arkansas	13,310,190.08	5,380,181.73	1048.9	2,641,387.65	1,118,078.04	93.2	5,904,602.02	2,825,489.13	381.9	1,164,378.38	549,903.60	96.4	464,244.50	Arkansas
California	22,346,175.99	10,719,249.61	894.8	1,758,210.30	782,842.66	40.4	10,448,983.86	5,251,917.12	319.5	1,203,924.54	489,986.35	39.3	2,344,113.26	California
Colorado	11,876,703.94	6,067,814.34	651.2	637,732.65	338,922.67	25.0	4,527,389.17	2,257,693.88	221.9	338,945.90	190,092.34	35.3	2,090,904.77	Colorado
Connecticut	4,558,639.29	1,819,368.66	101.6	750,965.91	250,212.14	13.4	1,713,128.78	549,559.48	26.9	204,505.29	48,608.15	2.3	1,192,504.57	Connecticut
Delaware	4,281,559.81	1,496,190.65	107.1	455,744.13	212,544.95	12.3	980,042.66	388,784.75	22.6				10,912.65	Delaware
Florida	2,959,273.72	1,405,487.97	96.3				8,970,318.13	4,370,709.60	251.7	1,991,337.04	650,530.77	41.5	761,040.66	Florida
Georgia	20,156,002.37	9,406,366.46	1478.3	2,039,093.60	991,054.44	121.0	11,092,111.41	5,226,115.36	705.1	1,170,995.66	483,749.27	87.9	343,478.47	Georgia
Idaho	9,394,676.80	4,815,332.26	600.1	176,117.58	101,367.48	21.0	2,750,264.23	1,733,255.24	177.0	933,074.03	562,087.44	41.2	410,995.58	Idaho
Illinois	40,010,481.10	18,640,076.28	1236.2	688,967.89	340,741.22	25.0	8,644,745.27	4,189,261.40	290.9				3,486,503.10	Illinois
Indiana	13,639,172.65	6,562,455.68	422.1	1,132,976.57	544,542.84	41.2	17,584,862.01	8,240,153.23	479.8	832,279.23	413,698.33	25.8	507,614.92	Indiana
Iowa	27,272,285.21	11,107,492.99	1996.9	722,462.52	320,365.06	36.5	7,272,120.64	3,265,326.98	457.5	1,480,053.73	699,848.90	144.3	2,032,060.07	Iowa
Kansas	26,399,695.77	9,755,273.32	831.4	2,784,450.08	1,213,748.87	146.4	10,670,447.84	4,512,216.72	517.9	1,787,131.43	505,704.68	104.6	1,405,301.41	Kansas
Kentucky	14,832,324.28	6,205,994.59	584.9	1,556,093.80	663,291.14	46.9	7,871,365.04	3,511,429.76	310.0	517,209.81	258,604.89	27.3	1,156,679.62	Kentucky
Louisiana	11,939,424.97	5,279,870.86	927.6	875,723.58	411,312.04	65.0	2,772,603.62	1,325,240.49	108.8	582,979.67	290,987.40	21.9	964,233.21	Louisiana
Maine	8,174,281.31	3,907,870.33	281.4	173,275.15	85,733.59	6.6	1,311,335.31	551,480.38	42.2	976,766.16	394,636.81	35.6	841,532.89	Maine
Maryland	8,132,506.90	3,849,383.15	294.4	368,826.12	177,191.15	14.7	2,814,750.06	1,244,591.15	126.3				19,267.55	Maryland
Massachusetts	14,047,656.22	5,467,661.28	300.6	505,080.98	165,015.60	11.0	6,155,325.67	1,629,813.05	86.9	523,237.49	173,035.13	8.1	1,584,145.94	Massachusetts
Michigan	16,234,000.80	7,328,316.91	612.6	5,227,433.17	2,405,657.00	208.7	12,044,705.07	5,523,127.94	328.5	433,069.40	158,370.99	0.3	2,709,474.16	Michigan
Minnesota	30,415,685.89	12,738,642.04	2721.2	3,560,542.83	1,506,322.07	279.5	7,353,175.06	2,888,700.00	608.9	1,023,293.92	171,600.00	44.9	156,347.89	Minnesota
Mississippi	10,292,285.79	4,988,702.73	803.4	1,134,270.59	566,407.24	83.6	8,337,386.37	4,162,437.53	437.0	1,083,118.42	541,559.18	61.1	575,708.32	Mississippi
Missouri	17,368,156.57	8,219,411.43	1118.9	2,830,765.80	1,363,795.71	121.5	25,921,368.10	10,264,311.41	763.8	1,362,237.84	115,523.89	32.3	416,546.56	Missouri
Montana	10,156,600.41	5,317,523.15	921.6	607,162.46	474,072.98	57.9	1,848,094.85	1,344,221.16	186.3	1,003,571.06	544,458.41	117.9	4,192,949.30	Montana
Nebraska	9,306,374.36	4,389,523.50	1570.6	1,362,105.81	660,957.40	117.0	8,761,990.25	4,347,216.75	887.7	2,420,926.59	1,190,961.25	213.4	2,458,438.10	Nebraska
Nevada	4,917,465.69	3,088,299.78	357.3	176,699.88	131,175.94	18.2	5,394,643.05	4,528,235.45	468.2	44,370.41	38,821.72	5.6	60,264.11	Nevada
New Hampshire	4,165,687.86	1,986,226.87	208.1	126,519.20	56,312.01	5.0	1,265,074.57	593,106.22	40.4				168,221.90	New Hampshire
New Jersey	11,961,357.45	3,820,679.99	219.1	870,702.97	207,502.78	10.3	9,870,567.74	3,453,916.40	81.2				50,612.83	New Jersey
New Mexico	8,717,999.18	4,914,070.61	1081.3	2,455,289.19	1,651,290.55	212.1	2,346,169.27	1,460,967.04	216.2	272,777.67	190,930.39	17.4	1,567,863.41	New Mexico
New York	28,597,769.67	12,229,076.53	831.5	3,991,290.54	1,562,381.59	100.1	33,598,825.75	10,621,551.55	661.6	7,123,300.00	1,746,285.00	116.5	4,238,734.33	New York
North Carolina	21,014,450.41	8,746,454.59	1119.8	2,371,883.81	1,007,858.84	67.1	8,215,648.74	3,469,733.08	199.4	1,787,907.60	762,380.84	45.0	22,224.65	North Carolina
North Dakota	10,829,263.82	5,268,930.47	1917.5	590,070.30	294,904.62	142.2	4,135,034.60	2,087,553.65	525.1	920,498.80	442,127.40	91.4	1,461,422.86	North Dakota
Ohio	41,572,252.81	15,244,993.93	1191.1	1,854,218.12	648,259.37	56.7	12,171,583.58	4,626,722.20	373.6	1,938,733.00	626,940.22	47.0	1,807,843.28	Ohio
Oklahoma	20,787,024.94	9,672,890.34	852.2	1,558,181.95	698,604.70	57.4	7,116,638.73	3,399,770.16	333.5	811,141.53	275,053.59	31.5	261,223.21	Oklahoma
Oregon	14,388,188.70	7,142,364.63	794.6	751,059.58	389,368.05	34.5	3,232,666.00	1,896,373.99	170.9	508,820.95	137,767.25	23.1	130,528.18	Oregon
Pennsylvania	43,054,835.19	16,222,023.97	850.3	2,657,611.93	834,606.72	49.5	36,004,538.70	9,640,406.67	651.5	2,463,989.12	826,309.13	61.8	468,514.51	Pennsylvania
Rhode Island	2,628,496.20	1,119,688.09	64.8				2,543,268.84	681,939.59	37.3	263,012.75	63,135.00	4.2	437,181.32	Rhode Island
South Carolina	11,163,347.84	5,121,267.54	1235.9	1,061,972.51	357,678.74	58.5	6,010,468.96	2,824,091.69	328.9	957,481.91	378,231.95	61.5	68,261.08	South Carolina
South Dakota	12,091,434.67	5,989,879.00	1447.9	1,535,493.16	743,311.55	192.2	6,588,931.26	3,107,824.85	936.1	86,427.58	48,425.04	14.0	55,151.56	South Dakota
Tennessee	13,789,140.98	6,732,079.77	497.9	2,555,128.53	1,261,638.03	84.4	9,992,630.24	4,427,733.01	337.8	241,502.80	119,851.60	11.3	1,120,869.59	Tennessee
Texas	54,120,970.93	21,057,940.12	3907.1	5,787,896.50	2,328,239.90	327.8	21,883,492.49	9,586,100.94	1265.6	4,914,240.46	2,212,696.79	323.1	994,536.35	Texas
Utah	6,259,159.41	3,818,836.91	423.1	132,178.99	99,880.35	5.9	3,224,624.68	2,193,626.23	255.5	325,575.07	246,654.73	16.9	611,529.78	Utah
Vermont	3,015,174.51	1,452,894.45	107.9	178,568.08	89,218.34	3.3	1,906,002.42	841,367.56	43.0	77,750.79	38,875.39	3.3	480,526.26	Vermont
Virginia	13,099,720.01	6,271,998.20	676.2	4,061,685.06	1,923,691.84	162.2	7,223,621.89	3,162,898.69	229.9	1,415,814.00	607,931.27	51.7	89,142.00	Virginia
Washington	13,352,504.18	6,117,211.87	526.7	1,964,825.31	855,987.39	87.7	2,426,786.31	1,115,400.00	74.9				927,196.74	Washington
West Virginia	7,343,200.86	3,230,293.33	326.7	252,664.30	123,013.89	12.8	6,774,986.54	2,719,659.25	179.1	981,982.41	367,090.29	35.2	118,518.24	West Virginia
Wisconsin	21,807,140.91	8,919,640.62	1451.7	107,355.47	53,526.17	6.6	5,850,782.11	2,876,686.58	281.4	621,435.40	312,333.00	40.6	3,406,366.63	Wisconsin
Wyoming	8,809,819.33	4,739,096.67	982.0	854,988.57	521,673.58	80.3	3,408,827.94	2,141,606.24	221.4	73,606.61	47,255.00	9.9	181,048.51	Wyoming
Hawaii							342,277.22	97,440.00	6.5				637,088.00	Hawaii
TOTALS	740,140,790.92	325,654,346.00	41898.3	73,404,251.66	33,175,152.79	3663.6	389,653,019.33	167,497,682.59	16359.6	47,418,974.29	18,206,344.08	2230.7	53,716,474.54	TOTALS

* Includes projects reported completed (final vouchers not yet paid) totaling: Estimated cost $ 96,991,426.65 Federal aid $ 43,376,227.96 Miles 4172.4