A STUDY OF SLAB ACTION IN CONCRETE PAVEMENTS UNDER STATIC LOADS

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SYNOPSIS

Earlier studies of the effects of axle loads on a concrete slab resting on a subgrade resulted in conclusions that two axles could be spaced so that for a given axle load the strains induced by the two-axle system were less than those caused by one axle, and similarly three axles could be so placed that the resulting strains were less than those produced by a single axle. Such conclusions needed substantiation, and primarily for that purpose this study was followed by similar investigations on a full-size concrete highway slab.

The slab was cast inside the laboratory. It was 9 inches thick by 11 feet wide by 28 feet long and rested upon a sand subgrade. Loads were applied through actual trailer axles and 10.00–20 truck tires. Strains were measured with SR-4 gages and deflections by Federal dial-indicators.

One, two, and three axle systems were placed at the edges and at the corners of the slab and loaded to full legal capacity. The axle spacing in the two and three-axle systems was varied, and the tests were run under two subgrade conditions.

No inconsistencies between the model results and those from the large slab were found. For a subgrade modulus of 60 lb. per cu. in. the strains caused by a single axle under 18,000-pounds load were greater than those caused by any two-axle or three-axle system tested at the same load per axle. At k = 110 lb. per cu. in. two axles closely spaced at the corner produced strains slightly larger than those found under other arrangements, but at axle spacings over five feet the single axle load proved to be most severe.

The magnitude of the experimental strains was affected by a curled state of the slab, but computations by formulas developed by Westergaard and those modified by the Public Roads Administration gave stress values commensurate with those found by experiment.

Early in 1944 an investigation was begun to determine the destructive effect of axle loadings upon concrete slabs. The Department of Engineering Research of the University of Michigan and the Michigan State Highway Department were the participants in this project. Preliminary tests were made upon a small model and these results have been published (1).[1]

Briefly, the model study indicated that under static conditions the addition of wheels to an axle is not an expedient method of increasing the loading capacity; that two axles in tandem arrangement could carry a standing load more than twice that of a single axle if a proper axle spacing were used; and, that a three axle system could be spaced so as to support static loads three times the single axle values.

[1] Italicized figures in parentheses refer to list of references at the end of the paper.

Although the model served very well to indicate the relative effects of various loading arrangements and locations upon the slab, it was necessary to repeat certain experiments upon a full scale slab in order to determine absolute values which could be used in slab and vehicle design. With this purpose in mind a 9-in. uniform slab 11 ft. wide by 28 ft. long was cast and tested in the Highway Research Laboratory at East Lansing.

Loads corresponding to full highway loads were applied through actual trailer axles with dual 10.00–20 tires at 70 psi. air pressure. The loading positions were midway between the ends of the longitudinal free edge and also at the corner of the slab. Single axles, two axles spaced from 3½ to 9 ft., and three axles spaced from 4 to 7 ft. were loaded and the slab strains and deflections measured.

Results of the tests on the full-size slab correlated quite well with those of the model. At a full 18,000-lb. load per axle, greater stresses were produced in the slab by a single axle than by two or three axle combinations with 4- to 8-ft. axle spacings. At the usual 4-ft. spacing between axles the three axle combination caused considerably less stress than either a two axle system or a single axle when the loads were applied at the corner of the slab.

This report includes a description of the materials and equipment used for this study, a discussion of the method of application of the loads and a graphical presentation of selected data. A comparison is made between the model study and the full scale investigation. The results of other investigations and theoretical computations are shown to corroborate certain data, and a bibliography of these sources is included.

DESCRIPTION OF EQUIPMENT AND TEST PROCEDURE

Materials and Equipment—The laboratory at East Lansing was chosen for the site of the test slab because there was sufficient space for the construction of a large slab and facilities for applying the loads. Other investigators had performed tests upon slabs cast out of doors, but the results were affected by warping due to changes in temperature and moisture. It was hoped that laboratory control would minimize this unfavorable condition.

A wooden form 15 by 32 by 2 ft. was built upon the concrete floor of the laboratory. Tie bars were placed at the corners and at inner points to prevent spreading when the form was filled with subgrade material. A system of perforated pipes was laid upon the floor and connected to the water supply for the purpose of controlling subgrade moisture, thereby giving some control over subgrade modulus. This stage of construction is shown in Figure 1.

Six inches of gravel were then placed in the bottom of the form and the remainder filled to within two inches of the top with a selected bank run sand. This sand was chosen because of its similarity to that used as a cushion under highway slabs and because of its bearing capacity. Table 1 is a summary of the properties of the sand.

In order to maintain a minimum temperature gradient in the slab some method of control had to be devised. Preliminary investigation showed that the difference in temperature between the top and bottom of the slab would be small, but that the lower surface of the slab would likely be cooler than the top. Of the various methods proposed for heating this lower surface, the one which appeared to affect the subgrade bearing capacity the least was an electrically heated wire grid. This was installed as shown in Figure 2 and it was

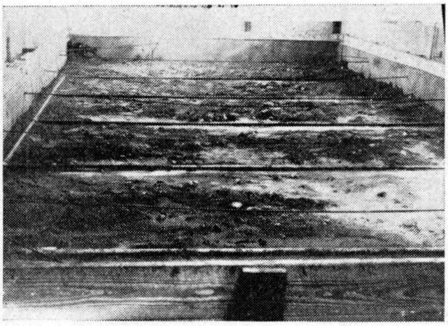


Figure 1. Form for Subgrade Showing Tie Rods, Waterproofing, and Moisture Control Pipe Layout

TABLE 1
CHARACTERISTICS OF SUBGRADE SAND

Sieve Analysis							
Sieve No.	10	20	40	60	100	200	
Percent Passing	99.43	97.57	85.90	43.15	7.80	1.55	
Density Values							
Percent Moisture	1	3	5	7	9	11	13
Density, *lb. per cu. ft.*	98	104	107	104	102	101	92

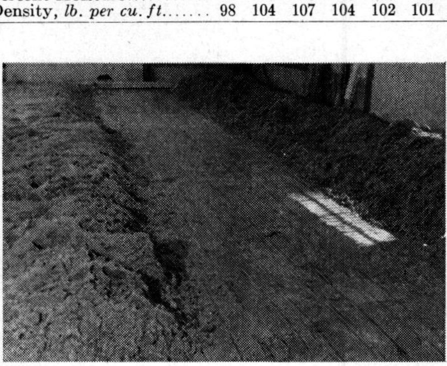


Figure 2. Wire Heating Grid Placed in Subgrade to Control Temperature Differential in Slab

covered with a 2-in. thickness of subgrade sand.

A wooden form 11 by 28 ft. by 9 in. was built upon the prepared subgrade. It was carefully leveled and securely fixed. The subgrade was planed and auxiliary equipment incidental to the tests was installed.

For the purpose of measuring strains on the bottom of the slab, SR-4 gages were attached to mortar blocks and those blocks were placed on the subgrade in such a way that the gages would be in the plane of the lower surface of the slab. Unfortunately these gages were not sufficiently insulated to give reliable results after a few weeks time.

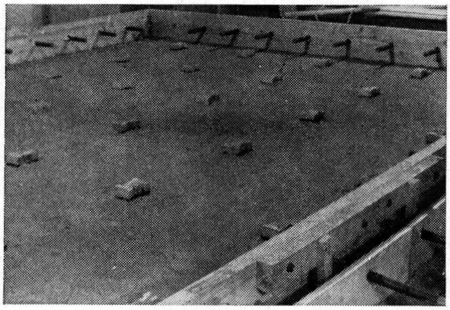


Figure 3. Form for Test Slab With Mortar Blocks and Dowel Bars in Place

TABLE 2
MIX AND TEST DATA FOR CONCRETE SLAB

Material	Type	Weights per Cu. Yd. Concrete *lb.*
Cement	Peninsular V.R. (Raw)	517
Fine Aggregate	Boichot 2NS	1182.5
Coarse Aggregate	American Aggregate Green Oak-10A	1892.0
Water		311.8

Fine Aggregate Gradation:

Sieve Size No.	4	8	16	30	50	100	200
Percent Passing	100	94	75	51	17	1	0

Coarse Aggregate:

Sieve Size, *in*	1	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{3}{8}$	No. 4
Percent Passing	100	93	59	34	1

Average slump = $7\frac{1}{8}$ in.
Average air content = 7.5 percent
Average 28-day compressive strength 9 6- by 12-in. test cylinders = 3660 psi.
Average 28-day modulus of rupture 6 6- by 8- by 36-in. beams = 585 psi.
Average 28-day modulus of elasticity of 6 cylinders at 400 psi. = 5.25×10^6 psi.

For a seqarate study, incidental to the loading investigation, dowel bars of various sizes and lengths were installed at one foot intervals on all edges of the slab. These bars and the mortar blocks are seen in Figure 3.

The test slab was cast using a carefully designed transit mixed air entrained concrete. Table 2 gives the mix and strength data. At this time five installations of thermocouples and Bouyoucos moisture cells (*2*) were made for the purpose of keeping accurate record of temperature and moisture differential throughout the slab and to aid in their control. A diagram of the slab and the location of measuring equipment is given in Figure 4.

Curing was accomplished by applying a membrane curing compound to the slab four hours after pouring. The relative humidity of the room was maintained at about 70 percent and the temperature held at 75 F. for 28 days. During this period moisture and temperature measurements were made and comparator readings were taken for length change and warping. Flat surfaces were ground on the slab surface according to the plan of Figure 4 and $\frac{1}{2}$ in. circular brass discs 1/6 in. thick were cemented to the slab for elevation and deflection measurements. SR-4 strain gages were applied and wired to junction boxes for facility in reading. The method of grinding smooth surfaces for these installations is shown in Figure 5.

Measuring Devices—The apparatus necessary for the measurement of moisture in the subgrade and concrete is thoroughly described in the technical bulletin (*2*). Temperatures were found by reading on a standard potentiometer the small emf. generated by iron-constantan thermocouples. Strains were measured by resistance changes in bonded wire SR-4 type A-1 and AR-1 strain gages. These resistance changes were read directly as unit strain by a Baldwin Southwark SR-4 strain indicator. Federal one-thousandth dials at the slab edges and corners indicated deflections, while one-ten thousandth dials were used in calibrated rings to determine the load intensity. A special comparator was constructed to measure length change and warping. This is illustrated in Figure 6.

Application of Loads—All loads were applied by means of hydraulic jacks reacting against an *I* beam on the laboratory ceiling. Calibrated dynamometer rings served to indicate the load intensity. Although loads of any value up to 20,000 lb. could be applied, most of the tests were made at 10,000-, 13,000-, 16,000-, and 18,000-lb. axle loads.

MEASUREMENT OF DESTRUCTIVE EFFECT

Subgrade Modulus—In order to make a comparison of test results with theoretical values it was necessary to determine the modulus of subgrade stiffness. This was done by two methods. First, before the slab was poured a number of loading tests were made using a 30-in. plate. Figure 7 exhibits the apparatus, and data for two locations are shown in Figure 8. It is apparent that the modulus, k, is about 110 lb. per cu. in. under the existing conditions.

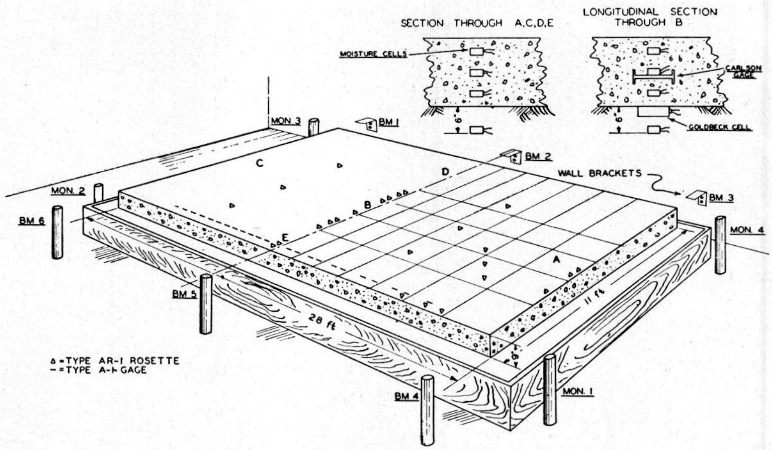


Figure 4. Plan of Test Slab

At the end of a 28-day curing period further tests were made by loading the slab in four locations. Having found the modulus of elasticity of the concrete, the subgrade modulus was computed from both load-deflection data and load-stress data by formulas developed by Westergaard (*3*) and by the modified equations from the Arlington tests (*4*). Figure 9 is an illustration of the apparatus used for these tests. The data are compiled and presented in Figure 10, and the accompanying table. There appears to be good correlation between these two methods of testing since the value 110 which was obtained by the bearing plate method also appears several times in the table. From these tests the subgrade modulus values for the two soil conditions which prevailed were chosen. For the first condition the value k = 110 lb. per cu. in. was used, and for the saturated condition k = 60 seemed to be a fair value.

In spite of rigid control of temperature and humidity there was some upward warping of the concrete slab. A continuous record of comparator readings and dial readings at the slab corners showed that the slab corners had raised about 0.2 in. Since the temperature differential was small the curling was attributed to moisture and fundamental differences in the concrete caused by the method of placement. In an attempt to rectify this condition

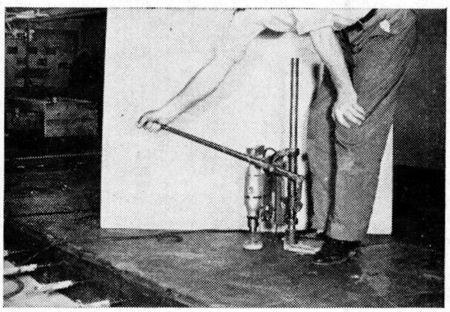


Figure 5. Method of Grinding Surface for Application of Strain Gauges and Deflection Targets

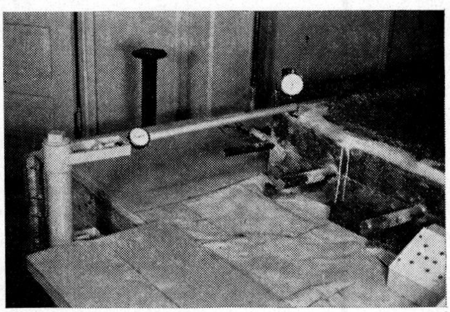


Figure 6. Length Change and Warping Measurements Being Made by Special Comparator

the upper surface of the slab was flooded with water and left in that state until there was no further downward movement of the slab. The recovery was about fifty percent. A heavy coat of membrane curing compound was applied as soon as the water was removed.

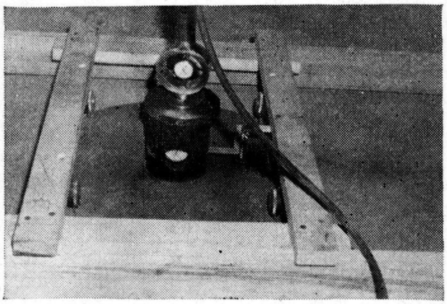
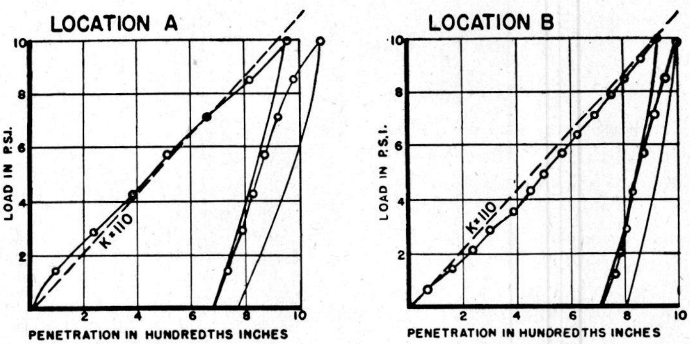


Figure 7. Arrangement of Dials, Calibrating Ring, and Jack for Tests on Subgrade with 30-in. Bearing Plate



Modulus of subgrade stiffness, $k = \frac{\text{unit load}}{\text{deflection}} = 110$ p.c.i. approximately

Figure 8. Thirty-Inch Bearing Plate Tests for Two Locations on Subgrade

The Loading Program—As soon as a series of slab elevation readings had been completed the loading program was begun. A preliminary series of tests were made at symmetric points with a metal plate for bearing area to determine the local differences in the slab and to attempt to attain good bearing between slab and subgrade.

A single 10.00-20 tire at 70 psi. inflation pressure was now located at several points on the slab and deflection and strain readings were taken. Figure 11 is an example of this test. The data curves are shown in Figure 12. A comparison of these curves with those of Figure 10 shows that the strains and deflections under the wheel are comparable to those under the metal plate. Apparently the greater contact area under the tire and consequent reduced unit pressure upon the slab does not cause any appreciable decrease in slab stresses below those produced under the metal plate.

This study was followed by similar tests on a single axle equipped with dual tires. Due to the small strain magnitudes and the difficulty in obtaining reliable deflection measurements at interior points of the slab, tests at these locations were discontinued, and the only data presented for these and subsequent tests are those for the edge and corner locations.

Next, two axles were placed with outer wheels on the free edge of the slab. One series of tests was run with the axles symmetrically

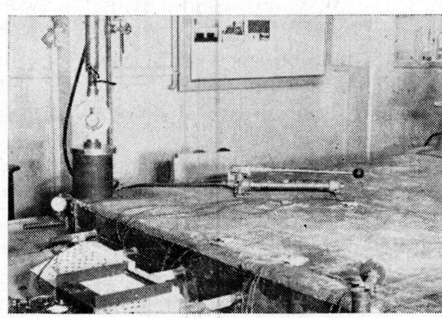
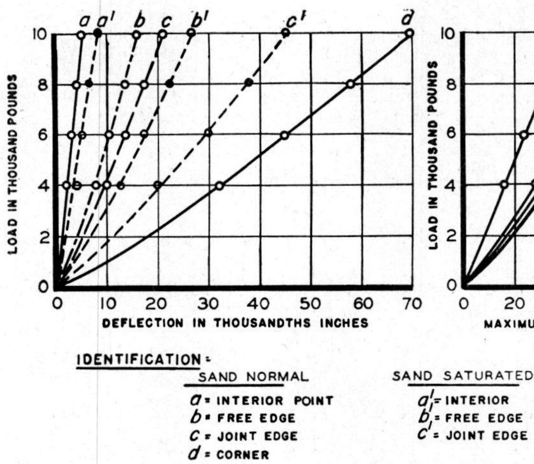


Figure 9. Method of Slab Loading for the Determination of Subgrade Modulus by Theoretical Formulas

placed about the middle point of the edge, and another series was made with one axle at the slab corner. A variety of axle spacings was used in each group of tests.



TABULATED VALUES OF SUBGRADE MODULUS K IN P.C.I.

LOCATION	1ST SUBGRADE CONDITION		2ND CONDITION	FORMULAS USED
	BY DEFLECTION	BY STRESSES	BY DEFLECTIONS	
INTERIOR	100	110	65	WESTERGAARD
FREE EDGE	110	110	65	WESTERGAARD
JOINT EDGE	80	95	40	B.P.R.
CORNER	55	60	—	B.P.R.

Figure 10. Data from Loads on 9-in. Slab Through 6-in. Diameter Plate

Finally three axles were loaded in the same test pattern as was used for two axles. The maximum axle spacing was necessarily limited because of the length of the test slab. For large spacings, the tests at the center were affected by the ends, and the tests at the end were influenced by the center. However, a fair comparison may be made between two and three axle systems for small axle spacings.

Free Edge Loading

Single Axle. An arrangement for measuring strains and deflections at the edge of the slab due to a load on one axle may be seen in Figure 13. Fifteen tests were made at edge locations for each of two subgrade conditions. In order to avoid eccentric results due to local conditions the axle was shifted to positions both sides of the lateral center line of the slab and all of these results were averaged for the presentation in Figure 14.

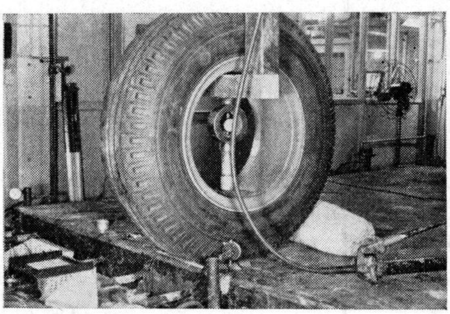


Figure 11. Load Being Applied Through a Single Tire

The strains from which the stresses were computed were measured longitudinally in a line on the top of the slab parallel to the edge and nine inches inward from the edge. This location was chosen because this line fell midway between the dual tires when the wheels were at the edge of the pavement. Although this is not the line of maximum strain it is sufficiently close for the purposes of these tests. It is also true that the longitudinal strains are not necessarily maximum, but calculations from 45-deg. rosette readings gave values within 10 percent of the longitudinal magnitudes and within a few degrees of the longitudinal direction.

Two Axles. A second axle was placed in tandem with the first, and strain and deflection readings were noted when these axles were loaded simultaneously. The distance between the axles was varied from the mechanical minimum of 3½ ft to a maximum of 9 ft. Figure 15 pictures one of these arrangements.

Since four feet is a standard spacing for axles on a heavy trailer, a number of tests were made at this spacing and the averages of these results are shown in Figure 16. The maximum stresses for this arrangement do not differ significantly from those due to the single axle. However, the deflections are greater under the two axle system than under one axle.

Three Axles. A third axle was added to the group and the loading tests were repeated for this system. The spacings for this group were from 4 to 7 ft. Again for comparative purposes the 4-ft. spacing was emphasized and averages of these tests are given in Figure 17.

The deflections increased over those of one axle and the two axle systems. The stresses, however, were only slightly less than the values under the single axle. The differences are not significant.

Corner Loading

Single Axle. Strains and deflections made by an axle at a corner of the pavement slab were measured at two corners at extreme ends of the slab. As in the case of edge loading, Figure 18 is a portrayal of average values.

An inspection of these data and a comparison with Figure 14 reveals that the corner deflections are much greater than the deflections at the edge at both high and low loads. For the softer subgrade, the maximum stresses also are greater at the corner than at the edge for corresponding loads. However, very little difference is noted for maximum stresses at the two locations when the subgrade modulus was 110 lb. per cu. in.

Two Axles. Loads were applied to a two axle system with one axle remaining at the corner and the second axle being inward from the first at distances from four to nine feet. Repeated tests were made at two corners and

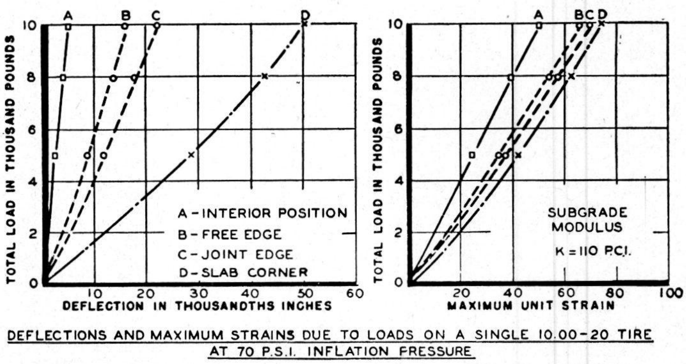


Figure 12. Single Wheel Loading Data

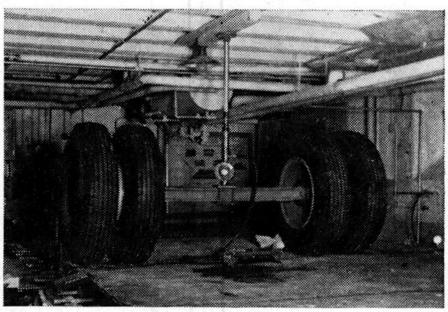


Figure 13. One Axle at Free Edge of Slab

averages of these data for the 4-ft. spacing are given in Figure 19.

those for one axle when the test was made upon the soft subgrade.

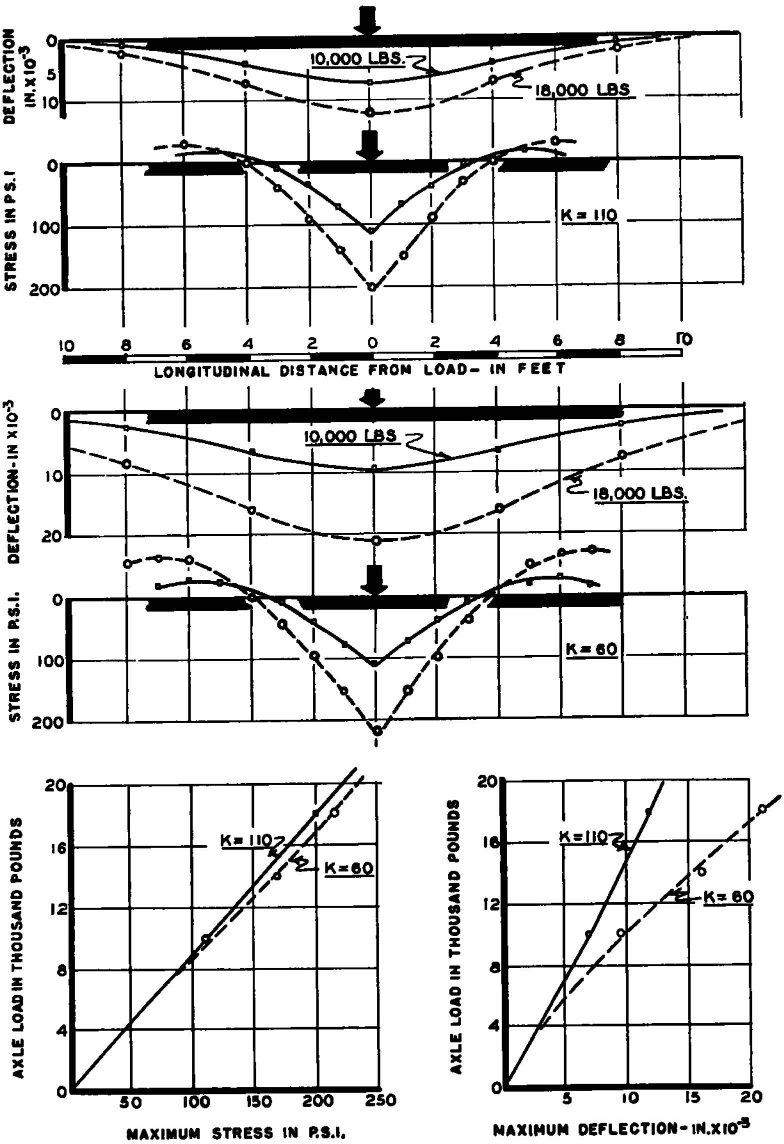


Figure 14. Stress and Deflection Curves for One Axle at Free Edge of Slab

Deflections for this case were larger than for the single axle. Although the maximum stresses were greater than those caused by one axle when the slab was supported by the stiffer subgrade, they were considerably less than

Three Axles. Finally, three axles were so placed that the first was on a corner and the others were equally spaced inwardly at distances of 4, 5, and 6 ft. The arrangement may be clearly seen in Figure 20. Average data from loading tests at the 4-ft. spacing are shown in Figure 21.

Although the deflections for the three axle system are greater than the corresponding deflections for the single axle and two axle arrangements, the stresses are less. Apparently the deflection curve is flattened to such an extent that larger subgrade displacement is obtained with a smaller slab curvature.

Comparative Tests

Effect of Multiple Axles. Although the previously described tests provided average values for stresses and deflections for the arrangements specified, it was noted that the differences in maximum stresses as produced by the three systems at the edge of the slab were not significant. The several tests made

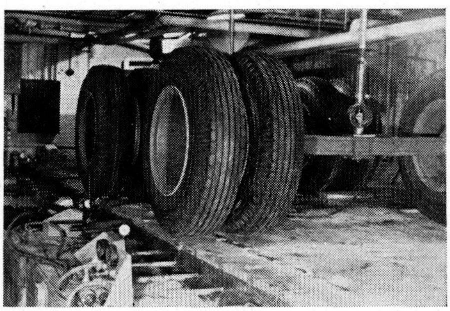


Figure 15. Two Axles Placed on Slab and Loaded Preparatory to Measuring Strains and Deflections

in each group gave maximum strain values which differed substantially from a mean value. However, repeated tests upon a system whose position on the slab was not disturbed usually produced results in close agreement. This fact led to the conclusion that some local condition in or below the slab, such as grouping or size of aggregate or perhaps subgrade bearing beneath the slab, influenced the strain readings.

With this thought in mind, and the object a direct comparison of the maximum stresses under the one, two, and three axle arrangements, the systems were tested in such an order that an axle once placed was not disturbed. The results of this method applied to the axles located at the slab edge are given in Figure 22.

A similar set of comparative tests was made at one corner of the slab. The curves are shown in Figure 23. It may be seen that the stresses are quite high for these tests. This fact may be explained by the warped condition of the slab at this time. The irregularity of the stress curve for one axle is evidence that warping affected the results.

Loads of 13,000, 16,000 and 18,000 lb. were used in this latter series of tests in order to make comparisons among the legal loading values. These data bring out the fact that from the standpoint of slab stresses, the single axle 18,000-lb load is more severe than any other loading system tested. The detrimental effect of large deflections under multiple axle loads has not been determined.

Effect of Axle Spacing. Although the stress and deflection curves for two axles shown in this report are drawn from data obtained when the axles were spaced four feet apart, other spacings were used in an effort to find the distances at which the slab strains would be the least. When the axles were located along the slab edge the minimum strain was found to occur at a 6-ft. spacing, while a 4-ft. distance between axles produced the least strain in the corner region. These figures may be easily verified by examination of Figure 24.

A COMPARISON OF THE MODEL INVESTIGATION WITH RESULTS OF THIS STUDY

Comparisons between curves from the model study (*1*) and the corresponding curves for similar loading on the full-size slab show a marked similarity. The strain curves for the model have several times the amplitude of the curves for the large slab. This indicates that the model was considerably overloaded. These excessive loads magnified the differences in deflections, however, and brought out fluctuations that are not apparent in the full-size slab study.

No conflicts are seen between data from the large slab and data from the model. The prototype study was necessary for the determination of working values for slab design, but the relative effects of different loading arrangements are brought out clearly in the model study and are corroborated by this later investigation.

RESULTS OF OTHER INVESTIGATIONS

Static load tests somewhat similar to those made in this study have been conducted by other investigators. A six wheel truck study was made by Teller (*5*) in 1925. A 6-in. plain study. In 1931 the Illinois Division of Highways (*6*) made tests on the edge of a 9–6–9-in.

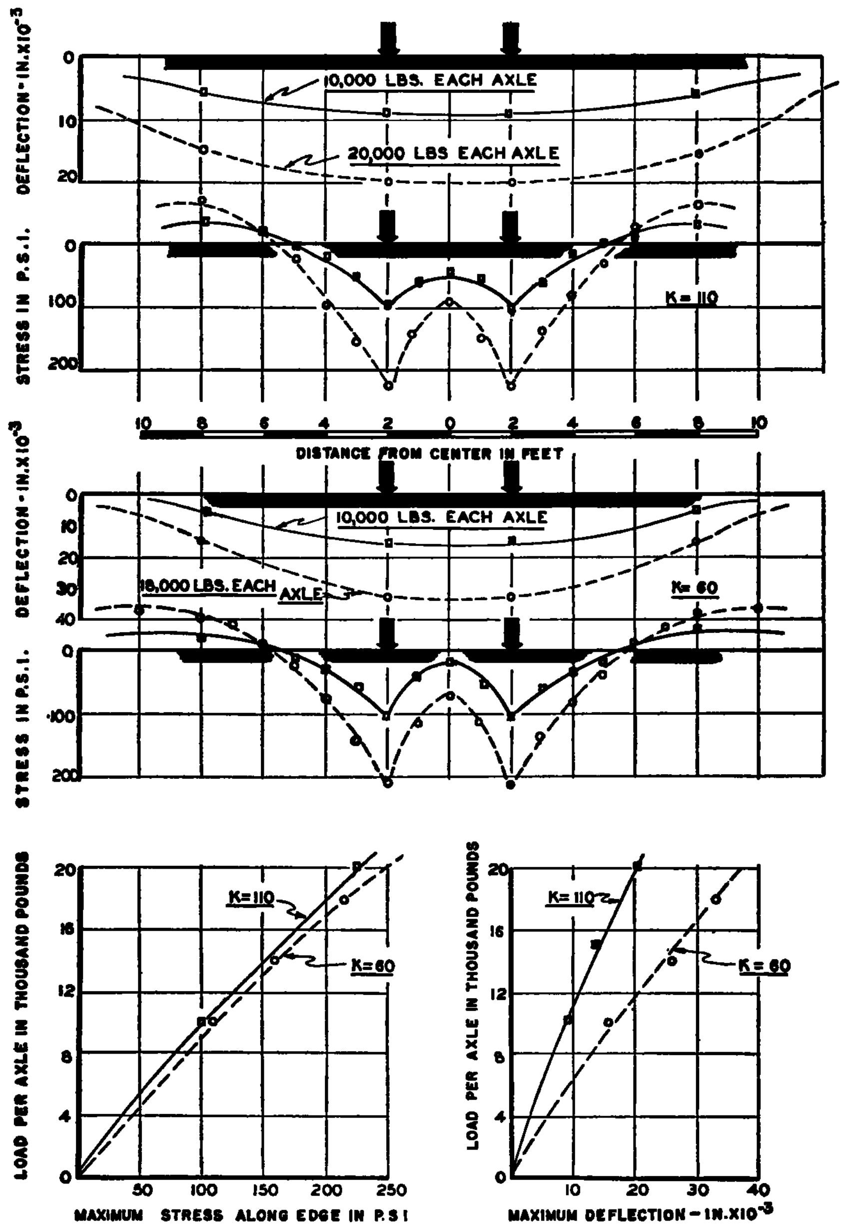


Figure 16. Stress and Deflection Curves for Two Axles on Slab Edge—4-ft. Spacing

concrete slab was tested, and deflection and strain curves for one and two axles were found. These were similar to those of the present pavement when it was subjected to loading by four and six wheel trucks. Again the one axle and two axle data compare well with the results of the present investigation. A thorough study of stresses in the corner region of concrete pavements was made by Spangler (7) in 1942. These results were used as a guide for gage placement in the present test.

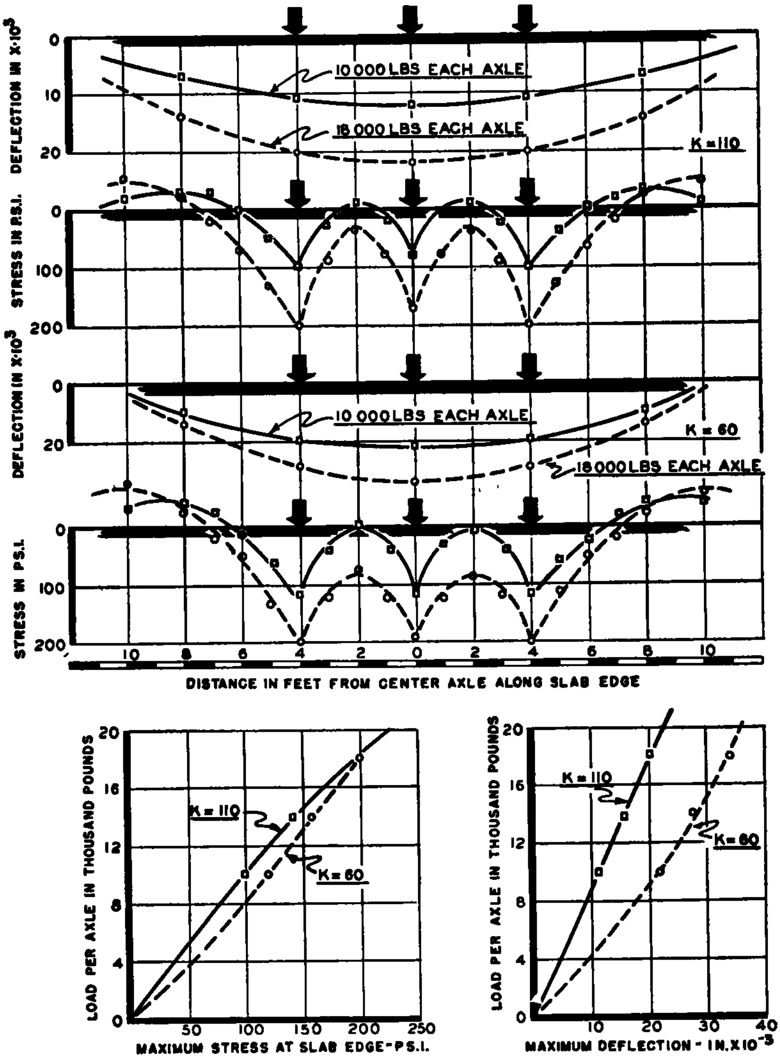


Figure 17. Stress and Deflection Curves for Three Axles on Slab Edge

Numerous other studies have been made where the investigators used actual vehicles and also loading plates to apply loads to the concrete slabs. The strains have been measured by mechanical gages of standard and self recording types. Investigations by O. Graf (10) and G. Weil (11) are particularly thorough.

LIMITATIONS OF THIS STUDY

Although the concrete slab under investigation was constructed in the laboratory, test conditions did not prove to be as ideal as anticipated. Lack of room precluded the possibility of making any study under moving loads, and a curling phenomenon which materially affected the stress values was encountered.

The extensometer shown in Figure 6 gave a record of slab warping at each corner. Figure 25 provides a typical curve. This upward movement of the corners and edges was verified by a precise level. The cause of this slab distortion cannot be attributed to a temperature differential, for continuous records showed little or no differences in temperature readings between the top and bottom of the slab. Further experimentation and analysis is necessary before a satisfactory solution to the causes of such behavior can be presented.

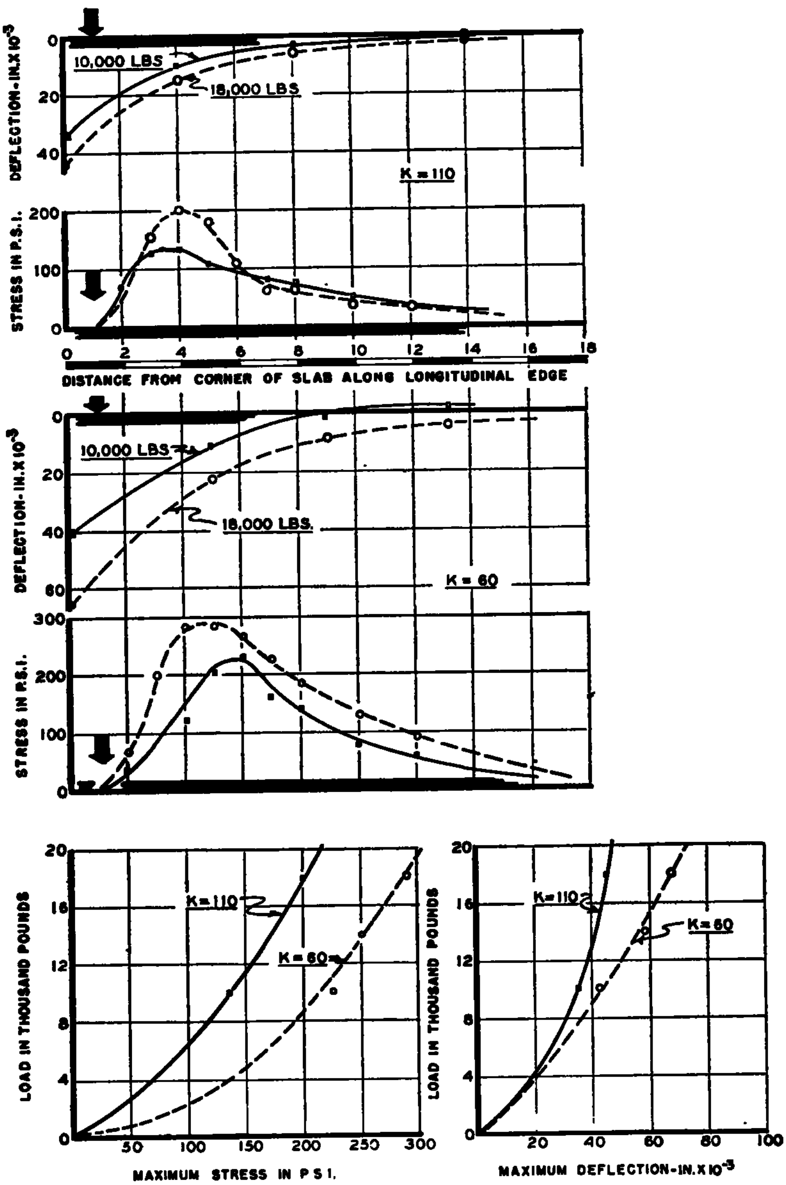


Figure 18. Stress and Deflection Curves for One Axle at Slab Corner

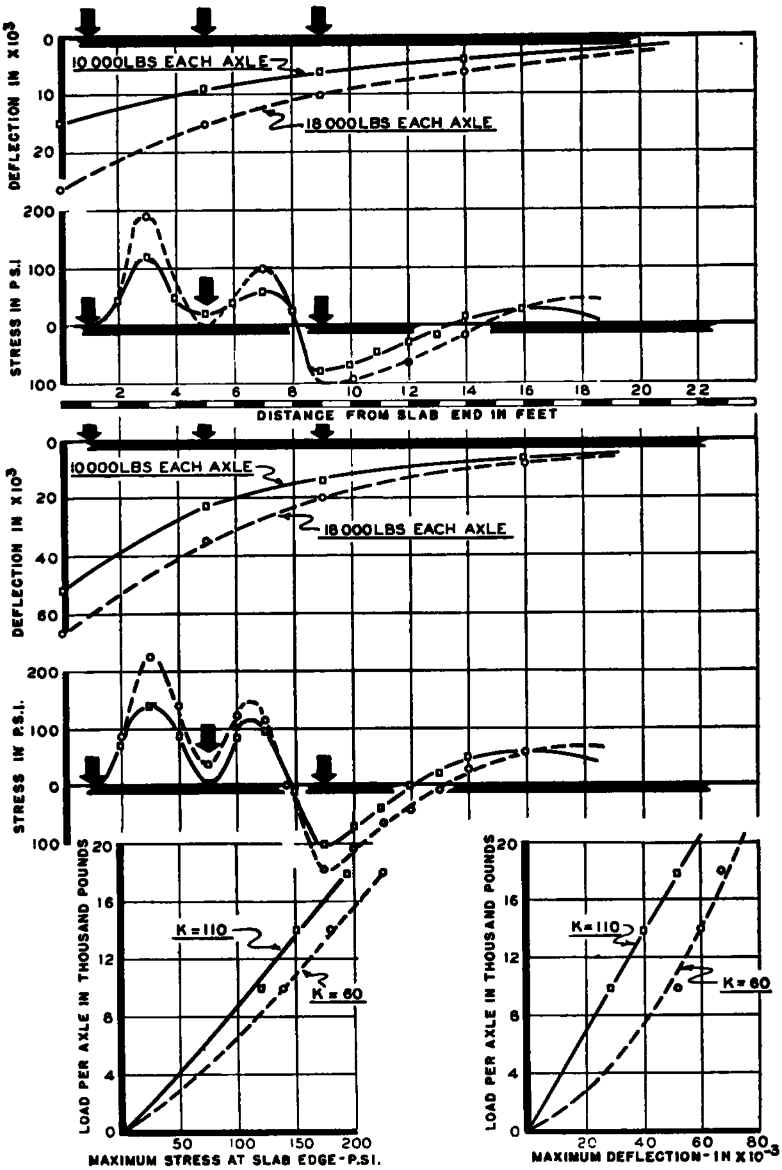


Figure 21. Stresses and Deflections Caused by Loads on Three Axles—Slab Corner

Similarly $S_x = +15$ psi., consequently the principal stresses at 1 expressed as functions of S_1 are,

Longitudinally: $S_1 + S_x = S_1 + 15$

Laterally: $S_1 + S_y = S_1 - 16$

Longitudinal Edge. The longitudinal stress S_e under load 1 due to the load at 2 when point 1 is on the longitudinal edge of the slab has been previously computed. The effect of load 2 at position 1 is found in a manner similar to that for an anterior location. Wheel 2 is at an interior point, and its effect on 1 will approximate the value found in the interior case, namely 15 psi. The longitudinal stress will then be $S_e + S_x = S_e + 15$ psi.

Transverse Edge: When the axle is at the transverse edge, the load at 1 produces

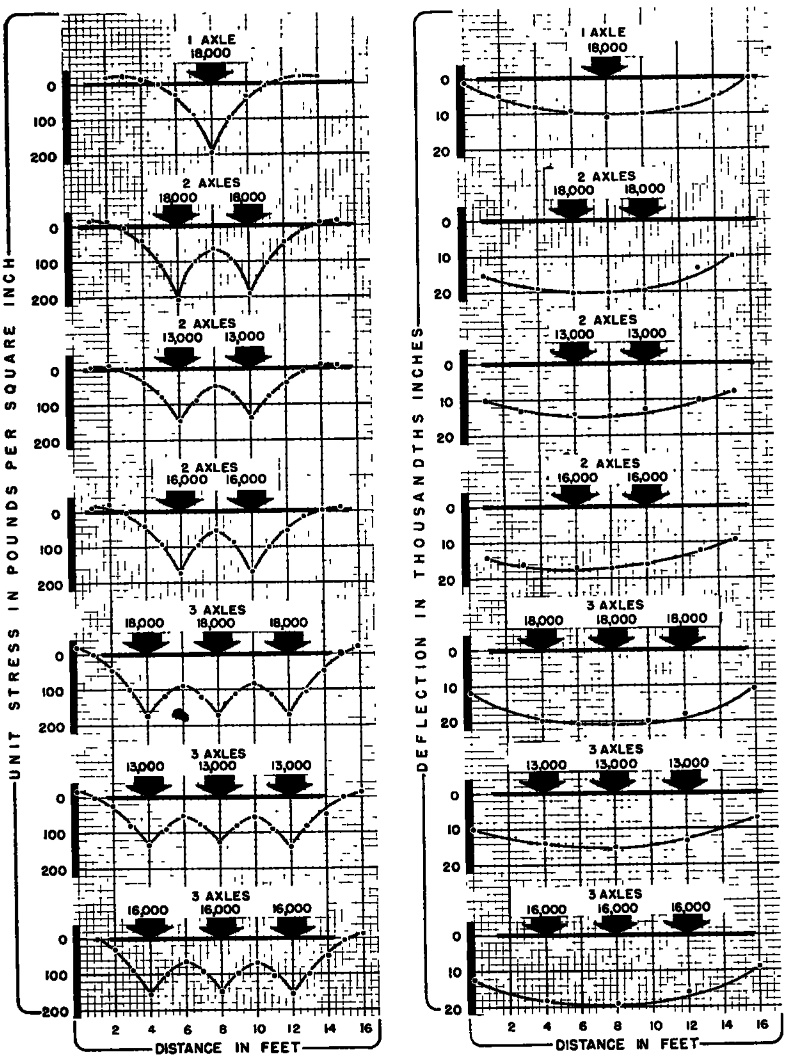


Figure 22. A Direct Comparison of Stress and Deflection at the Edge

stress S_e. The influence of load 2 is found by use of Figure 28, which is drawn by interpolation from Westergaard's graphs in order to obtain a direct reading curve for $\mu = 0.15$. At distance $1.74t$, the coefficient $\frac{M}{P} = -0.057$, hence $S_x = \frac{-0.057 \cdot 10,000}{13.5} = -42$ psi. Then the total transverse stress at 1 is $S_e - 42$ psi.

Loads on Four Wheels

Interior Location. Consider loads at interior positions 1, 2, 3 and 4. The accumulation of stresses due to loads at 1 and 2 have been found. We now find the effects of loads at 3 and 4.

Figure 26 shows load 3 to be 48 in. from 1. Since 48 in. = 1.156t, we find from Figure 27

The effect of the load at 4 upon position 1 is slightly more complex. In this case the

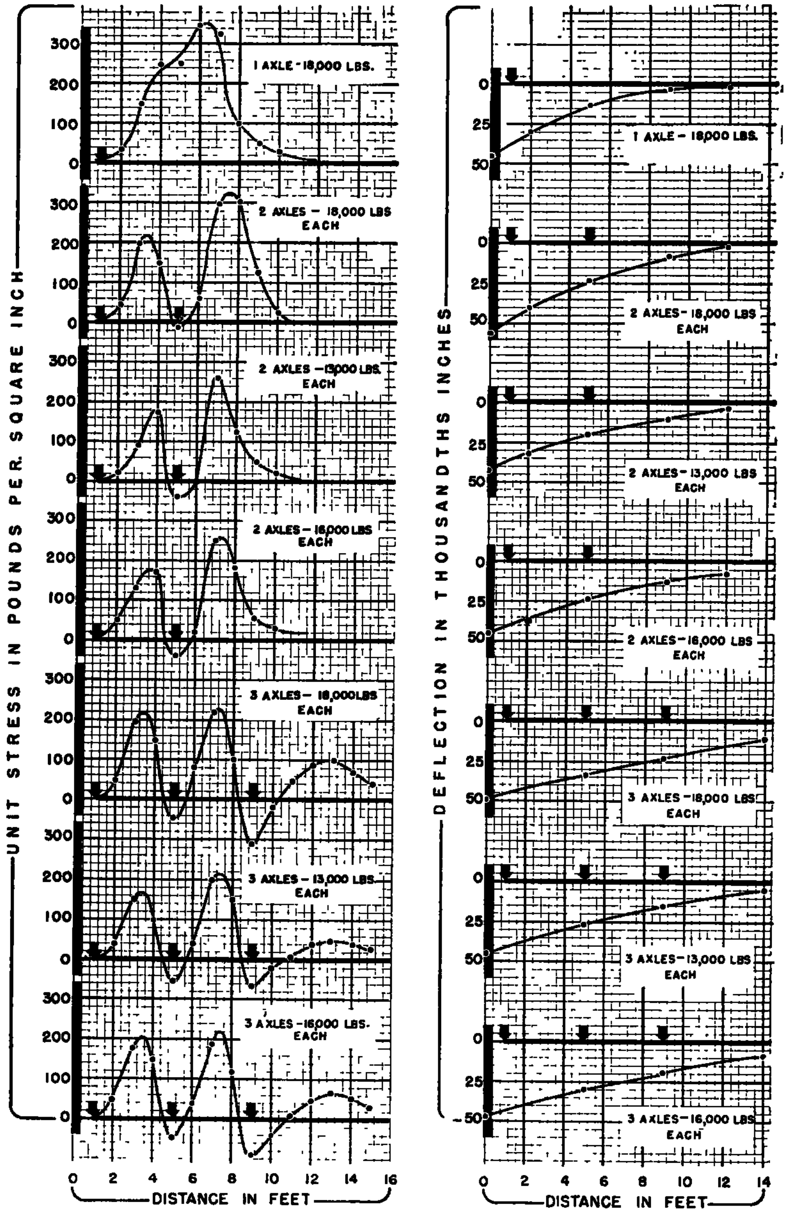


Figure 23. A Direct Comparison of Stress and Deflection at the Corner

that $\frac{M_y}{P} = \frac{M_t}{P} = 0.044$ and $\frac{M_x}{P} = \frac{M_r}{P} = -0.01$. Hence $S_y = 0.044 \cdot 10^4 = 33$ psi. and $S_x = \frac{-0.01 \cdot 10^1}{13.5} = -7.4$ psi.

tangential and radial stresses are not in the x and y directions but make angles of 34 deg. with those axes. Position 4 is 86.5 in. = 2.08t from 1 so by Figure 25 again $\frac{M_t}{P} =$

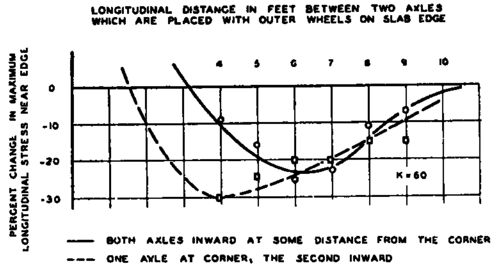


Figure 24. Effects of Axle Spacing on Maximum Stress Near Slab Edge

TABLE 3
STRESSES UNDER A SINGLE WHEEL WITH 10,000-LB. LOAD

	Westergaard Formulas	Arlington Formulas	Test Slab (Experimental)
	psi.	*psi.*	*psi.*
Corner	222	311	350
Interior	166	142	250
Longitudinal Edge.	194	238	330
Transverse Edge	234	271	350

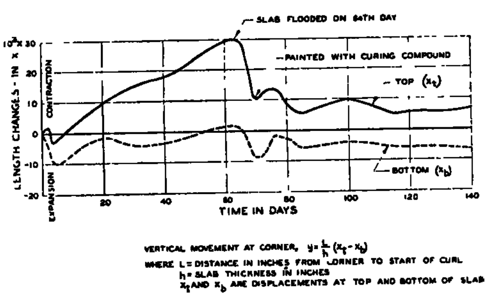


Figure 25. Extensometer Record at Slab Corner

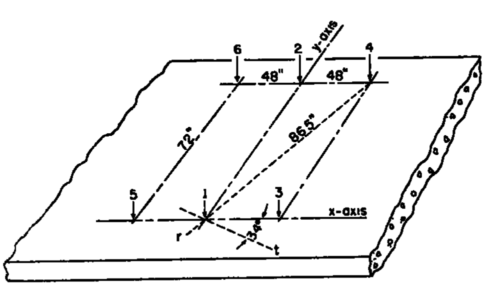


Figure 26. Load Spacing for Multiple Axles

0.012 and $\frac{M_r}{P} = -0.022$ whence $S_t = +9$ and $S_r = -16$. Since the principal stresses from positions 2 and 3 are on the x and y directions, the effects of S_t and S_r in these directions must be computed before the longitudinal and lateral stresses can be accu-

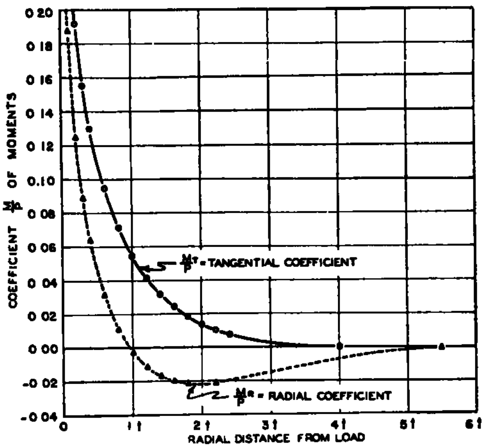


Figure 27. Bending Moment Coefficients for an Interior Load

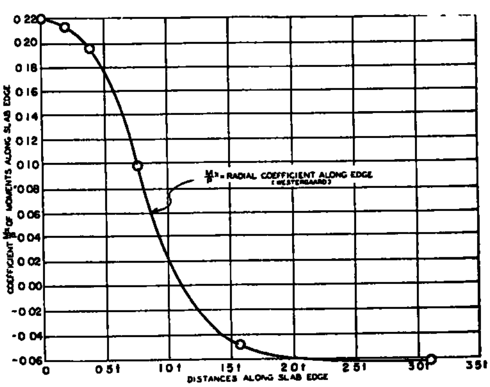


Figure 28. Bending Moment Coefficients for a Load at Edge of Slab

mulated. The stresses in directions x and y due to load 4 are:

$$X = 9\cos^2 34 - 16\sin^2 34 = 1$$
$$Y = 9\sin^2 34 - 16\cos^2 34 = -7$$

and shear $T = 1/2\,(-16 - 9)\cos^2 34 = -9$

The accumulated stresses in the x and y directions are:

$$S_x = S_1 + 15 - 7 + 1 = S_1 + 9$$
$$S_y = S_1 - 16 + 33 - 7 = S_1 + 10$$

and $T = 9$

The principal stresses are found by the formula

$$S_{max} = \frac{S_x + S_y}{2} + \frac{S_x - S_y}{2}^2 + T^2$$

$$S_{min} = \frac{S_x + S_y}{2} - \frac{S_x - S_y}{2}^2 + T^2$$

Whence $S_{max} = S_1 + 19$ and $S_{min} = S_1 + 0.5$

Longitudinal Edge. The longitudinal stress is necessarily maximum at the edge of the slab. The load at 2 adds 15 psi. as was shown in the two wheel case. Load 3 is at distance $1.156t$ from 1, hence from Figure 28, $\frac{M_r}{Y} = -0.012$ and $S = \frac{-0.012 \times 10^4}{13.5} = -8.9$ psi. The effect of load 4 is not determined, but from the computations above, for the interior, it is apparent that it is small. An approximate value for stress at the edge is then

$$S_x = S_e + 15 - 9 = S_e + 6$$

Loads on Six Wheels

Interior. When the load is distributed through six wheels, the greatest stresses are at positions 1 and 2 (Figure 26). Consider the stresses at point 1. Computations for stresses under four wheel loading may be used for this calculation. The stresses at 1 due to load 1 are S_1 in all directions. Load 2 contributes $+15$ psi. longitudinally and -16 psi. laterally. Loads 3 and 5 each affect 1 by longitudinal stresses of -7 and lateral stresses of $+33$. Loads at 4 and 6 produce tangential and radial stresses of $+9$ and -16 respectively, and the t and r axes make angles of -34 and $+34$ deg. respectively with x. These stresses, accumulated, are equivalent to $S_x = 2$, $S_y = -14$, and $T = -18$. Finally, the sum of all the stresses at 1 is:

$$S_x = S_1 + 15 - 14 + 2 = S_1 + 3$$
$$S_y = S_1 - 16 + 66 - 28 = S_1 + 22$$
$$T = 18$$

The principal stresses are:

$$S_{max} = S_1 + 31 \qquad S_{min} = S_1 - 6$$

Longitudinal Edge. For three axles at the longitudinal edge it is sufficient to compute the longitudinal stress under 1. The stress due to load 1 is S_e. By Figure 27 that due to 2 is $+15$. Loads at 3 and 5 each cause $\frac{M_x}{P}$ to be -0.012 from Figure 28, whence each $S_x = \frac{-0.012 \times 10{,}000}{13.5} = -8.9$. The effects of 4 and 6 must be approximated by the method used for interior loads. From above the effect of these two loads in the longitudinal direction was only 2 psi. Hence the total longitudinal stress due to all loads is:

$$S_x = S_e + 15 - 18 + 2 = S_e - 1$$

Tabulation of Computed Stresses—The foregoing computations were made in terms of a variable S_1 or S_e in order that we might make a comparison between the formulas for stress computation. Results are given in Table 4.

TABLE 4
STRESSES UNDER MULTIPLE WHEELS WITH 10,000-LB. LOAD PER WHEEL

Load Type	Position	Maximum Experimental Stress	Maximum Computed Stress	
			Westergaard	Arlington
1 axle	Interior		182	157
1 axle	Long. edge	220	209	253
1 axle	Trans edge		192	229
2 axles	Interior		185	161
2 axles	Long edge	230	200	244
3 axles	Interior		198	173
3 axles	Long edge	220	193	237

It is readily seen that the Public Roads formula yields greater stresses than Westergaard's except for the interior location, and in all cases of multiple wheel loading our experimental values lie between the values computed by these formulas.

OBSERVATIONS AND CONCLUSIONS

The greater part of this report has been limited to the effects of one axle, two axles at an axle spacing of 4 ft., and three axles at a 4-ft. spacing. Except where otherwise stated, all observations and conclusions given here are restricted to a discussion of results found under these limitations. The outstanding results are as follows:

1. A comparison of the curves presenting average values shows that the maximum stresses for a constant axle load are produced by a single axle on the corner of the slab.

2. Stresses due to corner loading by all

three systems were considerably greater when the slab rested on a subgrade with modulus $k = 60$ lb. per cu. in. than they were when $k = 110$.

3. At $k = 110$ stresses due to corner loading did not greatly exceed those due to edge loading for any of the three systems tested, but at $k = 60$ lb. per cu. in., corner loading produced greater stresses than edge loading.

4. The special comparative tests, the data for which were given in Figure 22, indicate the following relationships for edge loading:
   (a) The maximum stress for the two axle system under loads of 18,000 lb. per axle did not exceed that for the single axle at 18,000 lb.
   (b) The three axle system at 18,000 lb. per axle caused less stress than either of the other two systems.
   (c) The maximum deflection under the two axle system was twice that under the single axle, but the three axle system did not cause a corresponding increase in deflection.

5. The corner loading tests which furnished the data for Figure 23 showed the following:
   (a) The single axle produced a greater maximum stress than either other system.
   (b) Three axles at 18,000 lb. each produced less than 70 percent as great a maximum stress value as the single axle, and two axles at 18,000 lb each caused a maximum stress which was more than 90 percent of the single axle value.
   (c) The deflections under two axles were 20 percent greater than under one axle, but the three axle deflections were only ten percent greater than those for a single axle.

6. Upward warping of the slab at the ends affected the total stresses, but measured values were found to lie between those computed by the Public Roads and Westergaard formulas.

7. The results of this study are so nearly those that might have been predicted by the model investigation that model studies are recommended for further investigation in slab stresses.

8. Strains as measured by the SR-4 type A-1 and AR-1 gages vary somewhat due to local conditions. Strain differences as high as ten micro-inches per inch were found, and when the strains due to loading were small, these local differences caused decided irregularities in the curves.

9. The intensity of maximum stress caused by the two-axle systems was influenced by the axle spacing. The optimum distance between axles is about five feet.

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WYOMING METHOD OF FLEXIBLE PAVEMENT DESIGN

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SYNOPSIS

Design is based on California bearing ratio tests, or modifications thereof, used in conjunction with eight different CBR wheel load curves, some of which have been interpolated, within the range of 4,000 and 15,000 lb. Selection of the wheel load curve to be used on any one section of a project is indicated by the total empirical value obtained from evaluating job conditions and traffic within the section. The items evaluated are: (1) annual precipitation, including adjustment for irrigation, seepage or swampy conditions; (2) water table, in reference to depth below finished grade line elevation; (3) frost action, as regards degree of heaving induced and the resulting effect on subgrade support; (4) existing conditions, including surface drainage, subdrainage, and snow conditions; (5) traffic, in number of equivalent 5,000-lb. wheel load repetitions in one direction, as estimated for the next 20 years.

Tests are made on the preliminary soil samples, then preliminary design, and estimates, are entered on the soil profile. The soil profile is then submitted to the plans division to be used in completing plans for the project. Usually, projects as awarded in this State include grading, sub-base, base, and surface course. Samples of the finished subgrade, imported fill, and selected material surfacing are submitted as construction proceeds. Due to blending of soils on actual construction, as well as to some unforeseen job conditions that develop, changes from preliminary design are sometimes necessary. These construction tests, as well as the construction design, are entered on the soil profile. The engineer is kept fully informed of any changes, so that if there are variations of more than a few inches from the preliminary design the proper adjustments may be made in subgrade width. The completed soil profile, including preliminary and construction design, becomes a permanent record of a project.

The first systematic method of design for flexible pavements, based on soil characteristics, was adopted in this State in 1940. The method was based on a soil value formula developed by Keith Boyd (*1*)[1]. Some changes in the original formula were made, to fit local conditions more nearly, and under the revised formula, the total surfacing thicknesses ranged from 4½–3–4½-in. to 10½–9–10½-in. depending upon the soil value. In 1944, the soil value method of design was abandoned in favor of the group index method (*2*). As a result of a survey made throughout the State, of previously constructed projects, and a comparison of the group indexes of the soils and thicknesses of the total as constructed base and

[1] Italicized figures in parentheses refer to list of references at the end of the paper.