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A MODEL STUDY OF SLAB ACTION IN CONCRETE PAVEMENTS

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RES. REPORT #80

SYNOPSIS

An attempt has been made to study the effect of wheel loads upon concrete slabs by the use of models. A slab of dimensions 33 in. by 15 ft. by 2 in. was cast in a laboratory upon a soil subgrade. SR-4 electric strain gages were cemented to the concrete and deflection dials were supported at strategic locations. Shoes representing wheel contact areas were constructed and loads applied through these areas in a variety of arrangements.

Results of the test on this model show that a given load on an axle with four or six wheels will cause almost as much strain in the concrete as one with only two wheels. However, if the load is distributed over two axles there is an optimum axle spacing such that more than twice the single axle load may be supported by the system without producing a strain greater than that caused by a single axle. Likewise for three axles the system may carry more than three times the single axle load without increasing the strain, providing the axles are properly spaced.

The prototype for this study is now being studied and final evaluation of the model as a means of determining pavement stresses will be made when the investigation is completed.

A joint research project between the engineering research laboratories of the University of Michigan and the Michigan State Highway Department was initiated in June 1944 to determine the destructive effects of loading upon concrete pavements. The sponsors were particularly concerned with the effects produced by heavy loads upon single, dual, and triple axles supported by single and multiple wheels. Secondary considerations were an evaluation of the SR-4 electric strain gage as a reliable indicator of the state of stress in concrete slabs, and a model-prototype comparison for concrete pavement investigation.

Previous studies on pavement slabs have shown that variations in temperature and moisture cause internal stresses which complicate the analysis of the effects of loading alone. For this reason it was proposed that the study be conducted in a laboratory under controlled conditions. Because of limitation of space the investigation was made upon a model slab. It was agreed that a model would be satisfactory for preliminary work. It would serve as a means of developing technique and also it should indicate trends which could be verified later in a full sized slab.

A summary of the tests made on the model and the purpose of each is as follows:

1. A single axle was equipped with two, four, and six wheels and loaded to determine the reduction in strain due to an increase in the number of wheels.
2. Two axles were spaced at various distances in an effort to find a spacing which would allow the system to be loaded beyond the single axle load without increasing the strain.
3. Three axles were spaced at various distances to determine the effect of each axle upon the strains under the other axles.
4. Loads were applied at the interior of the slab, at a longitudinal edge, at an end or transverse edge, and at a corner. The object was to find the relations between strains and deflections of these positions.
5. Single loads on very small areas were applied at a corner, an edge, and at an interior point to obtain data which could be compared with the theoretical values obtained from Westergaard's equations.
6. Strain gages were attached to the under side of the slab for the purpose of comparing the tension there with the compression above.
7. Subgrades were changed in an attempt to observe the effects of stiff and soft subgrades upon the strain and deflection readings.
8. Overloads were applied at various positions in order to note the types of failures produced.

The model served the purpose for which it was constructed. It showed that the addition of wheels to an axle is not an expedient method of increasing the loading capacity. It showed that two axles could carry a load more than twice that of a single axle if the proper axle spacing were used. It gave a set of relations between the stresses at the center, edge, end, and corner.

From the study of this model, a better idea of the load-deflection-strain relationship was found. It was seen that strains under wheels at the edge of the slab are dependent upon axle length. Curves from which an optimum spacing for axles can be found were developed.

The slab has been useful in the development of technique for applying loads, for measuring deflections, and for the application and reading of electric strain gages. Results from this study are beneficial in the formation of further studies in the problem of loaded pavement slabs.

This is a progress report describing briefly the results of the various tests without detailed theoretical analysis or mathematical consideration. The report is devoted to the properties of the materials tested, discussion of the test equipment and loading technique, measurement of destructive effect and study of failures. Conclusions drawn from the test data are presented.

It is proposed in the course of the investigation to correlate test results with theory. The work will be continued on a full size slab upon which similar loadings are to be applied through actual truck and trailer wheel assemblies. The results from this work should enable analysts to evaluate constants for actual working conditions and determine the effect of many types of wheel-loadings on concrete pavements.

DESCRIPTION OF MODEL AND EQUIPMENT

A wooden form 18 ft. by 4 ft. by 18 in. deep was built upon a concrete floor in the laboratory. This was filled with a stabilized clay-gravel subgrade material which was compacted to desired density by vibration and tamping. Tests made with a 100-sq. in. bearing plate on the prepared subgrade material gave a modulus of subgrade stiffness of 2200 p.s.i. per inch at 0.05 in. deflection.

A concrete slab 15 ft. long by 33 in. wide and 2 in. thick was cast on this base. This was considered a satisfactory working model for the preliminary study. The aggregates used in the concrete mixture were composed of $\frac{3}{8}$-in. maximum size pea gravel and normal concrete sand. Cylinders and beams gave the following results:

Compressive strength at 14 days = 4500 p.s.i.
Compressive strength at 28 days = 4900 p.s.i.
Modulus of elasticity at 1000 p.s.i. = 4,800,000 p.s.i.
Modulus of rupture at 28 days = 700 p.s.i.

At the conclusion of the investigation on the stabilized subgrade the slab was removed. A 6-in. layer of concrete sand with 2 to 3 per cent clay added was placed on the old subgrade, the slab was replaced and loaded to obtain good bearing. The bearing plate test showed that the modulus of subgrade stiffness for the new subgrade was 350 p.s.i. per inch at 0.05 in. deflection.

The instrument used to indicate the strain in the slab was the SR-4 type A-1 strain gage. This is a resistance type gage and the strains are easily read directly in micro-inches per inch by means of a portable strain indicator. These gages were cemented to the slab surface and electrically connected to a selector switch. More than 100 such gages were used on the upper surface of the slab, and three rosettes of three gages each were cemented to the bottom. An array of strain gages used for the study of the effect of wheel and axle arrangements at the center of the slab is shown in Figure 1, and the strain gage layout for the corner study is given in Figure 2.

Deflections were measured with Federal one-thousandth dials. These were supported by portable wooden racks which were entirely free from contact with the slab, subgrade or forms. The dial pattern was adjusted to meet the needs of the investigation. Figure 3 is typical of the dial arrangement for center loading, and Figure 4 illustrates a method used in the longitudinal edge study.

Loads were applied to the model slab through wooden axle representations and tire contact areas reduced to approximately one-eighth scale. The actual dimensions and shoe arrangements are given in Figure 5. The center shoes represent an axle with two wheels;

the outer pairs, four wheels; and the inside shoes were attached for the six wheel study. These shoes, or tire representations, were notched to permit application of load immediately above the strain gages. This necessitated an oversize design in order that the actual contact area might be nearly equal to that of a one-eighth scale shoe without the recess for the gage.

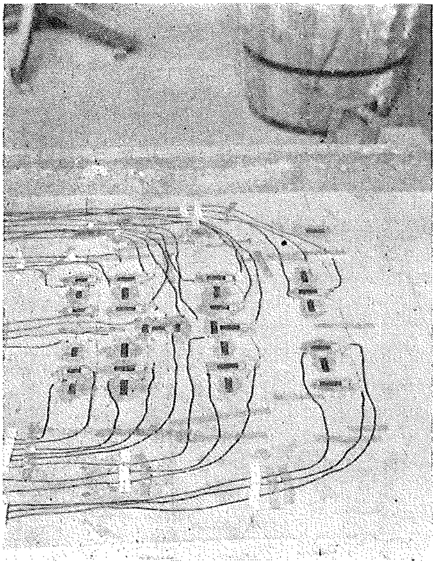


Figure 1. An Array of SR-4 Gages for the Study of the Effect of Several Wheel and Axle Arrangements at the Interior of the Slab.

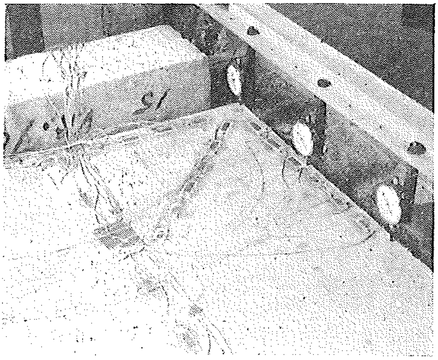


Figure 2. Strain Gage Layout for the Corner Study.

Force was applied to the axles by hydraulic jacks. (Fig. 6). A heavy wooden super-

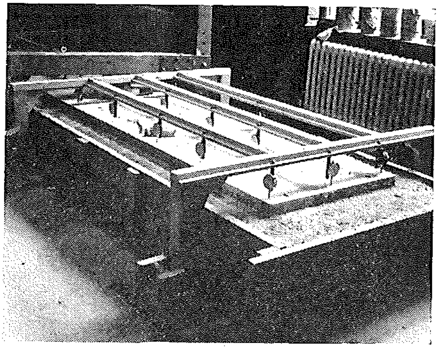


Figure 3. Dial Arrangement for Measuring Deflections at Interior of Slab.

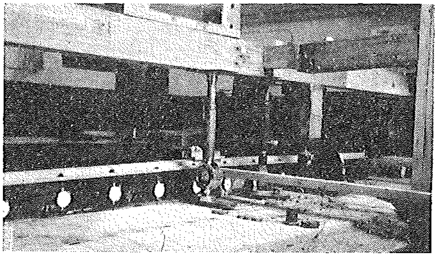
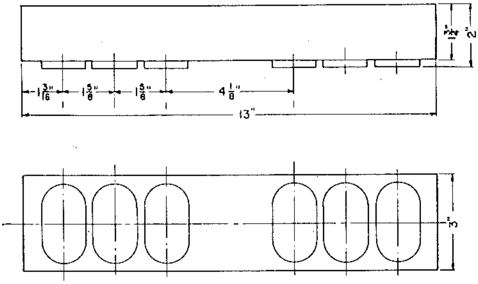
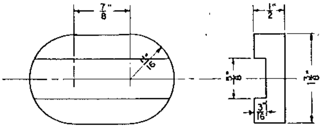


Figure 4. Linear Dial Pattern Used in the Measurement of Edge Deflections.



AXLE ASSEMBLY



SLOTTED SHOE

Figure 5. Wooden "Shoes" Representing Tire Contact Areas Assembled to "Axle." Lower sketch shows notch to straddle gage.

structure and loading beam were built above the slab to provide reaction for the jack when the load was applied. The jacks used to produce the load were the 10-ton Mohawk Portopower type. The intensity of the load was determined by dynamometer rings equipped with ten thousandth dials.

The greatest difficulty to overcome was the distribution of the load. As the loading patterns became more complicated by the addition of wheels and axles, the difficulties in alignment became more pronounced. Attempts were made in the initial stages to load several axles with a large metal plate. Results of these experiments were so inconsistent that better methods had to be devised. It was finally decided that each axle required a separate jack, and the problem then reduced to that of obtaining uniform pressure upon all of the wheels under the single axle.

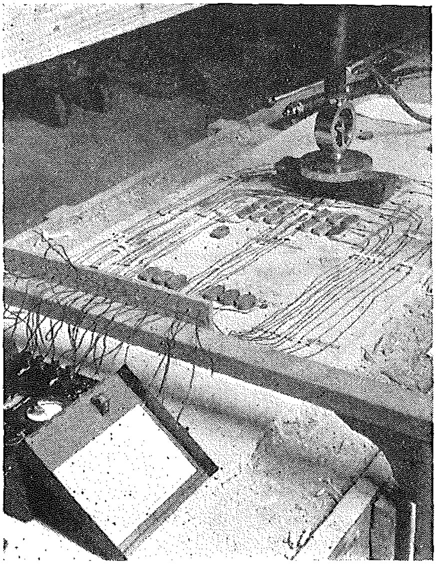


Figure 6. Method of Applying Single Axle Load. Note Hydraulic Jack and Dynamometer Ring.

The procedure finally selected was as follows The grooved shoes were placed over the gages to be read and rubber pads were placed upon them. Thin cardboard shims were then put on top of the rubber pads and the wooden axle assembly was carefully placed upon these. Pressure was applied to the axle block and the shims tested for tightness of fit. Additional shims were inserted above the loose ones until a snug fit was attained. A metal plate now covered the axle block, and the jack and dynamometer assembly was put into position.

Loads were kept to a value such that the deflection did not exceed 0.05 in. Excessive loads were required to get appreciable deflection when the slab was on the clay-gravel stablized base. However, good deflection readings at moderate loads were produced on the sand subgrade. A limiting factor in the loading was the compressive strength of the wooden shoes which would withstand about 1,000 lb. each without failure.

The rate of loading was not measured. However, the routine established a rather constant rate for all tests except the loads to failure. Deflections were always read at the end of a test after allowing the system to reach stability. The increase in strain readings resulting from the slow settling of the slab after loading during a single test was only 3 to 5 micro-inches. The increase in deflection due to a long period of maintaining a load was not more than 0.005 in.

MEASUREMENT OF DESTRUCTIVE EFFECT

Observations were made to determine the relative magnitudes of strain in the top and bottom of the slab directly beneath the load. Three sets of three gages each, one longitudinal, one lateral, and one at 45 deg. were attached to the bottom of the slab directly beneath corresponding sets on the top. When point loads were applied directly above these gage installations it was observed that the compressive stresses at the upper surface in each of the three directions were of about the same magnitude, and further, that the longitudinal tensile stress on the lower surface of the slab exceeded the corresponding compression stress on the upper surface by less than 10 per cent. This latter fact seemed to warrant the use of gages on only the upper surface to indicate the destructive effect of the load.

The direction of maximum strain under an axle supported by two wheels was the next consideration. The wheel representations could not be placed upon the gages, and this precluded use of rosettes. An alternative method was to cement single gages to the slab along the principal lines of action. Tests by this method showed that strains in a lateral direction were never more than 50 per cent of the longitudinal strains. Further studies with two and three axles gave increased lateral strains up to 70 per cent of the longitudinal value. Since the longitudinal strain was always the larger, it was used to represent destructive effect even though it may never have been actually a measure of maximum strain.

Early in the investigation it was found that the stress reduction due to the addition of wheels was dependent upon the stiffness of the subgrade. When the slab rested upon the stiff base, the strains caused by a load upon an axle with four wheels at interior of slab were 32 per cent less then those produced by two wheels on a single axle, and the six wheel array on a single axle gave a reduction of 23 per cent. However, similar tests when the sand subgrade was used showed reductions for four wheels of only 3 per cent, and an increase in strain of 6 per cent for six wheels. Since bearing tests on the sand indicated approximately field conditions, the latter figures are more indicative of the effects experienced on the road. Figure 7 shows a comparison of strain data from these single axle tests at the center of the slab for these two base conditions.

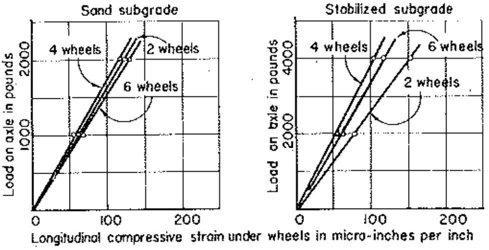


Figure 7. Comparison of Strains Under a Single Axle at Interior of Slab.

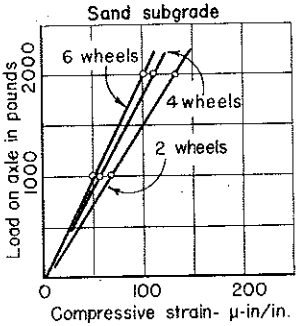


Figure 8. Load on Single Axle at Longitudinal Edge. Slab on Sand Subgrade.

The Effect of Multiple Wheels

Because of the present day trend to add additional wheels to trailer axles to allow transportation of heavy loads, a study was devised to evaluate the benefits derived from this practice. Axles with 2, 4, and 6 wheels were located at the interior, longitudinal edge, and corner of the model. Figure 6 is typical of the arrangement for leading at the interior.

The data from these tests are presented in Figures 7, 8 and 9. These graphs show first, that doubling or even tripling the loading area by adding wheels to an axle does not greatly effect the strain in pavement, and second, the tests at the longitudinal edge were the only ones which showed strain reductions in the order in which they were anticipated. Even at this position, four wheels per axle reduced the strain below the two-wheel value by only 15 per cent, and six wheels caused a 23-per cent reduction. If this test is indicative of conditions on full size slabs, the practice of doubling and tripling the load by changing from single to dual or triple wheels on a single axle is not warranted.

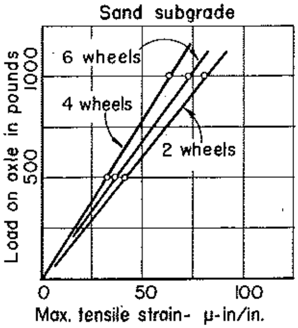


Figure 9. Load on Single Axle at Corner. Slab On Sand Subgrade.

Deflection and strain curves for a 2,000 lb. load on a single axle with four wheels are shown in Figure 10. The deflection curve extends over a large portion of the slab, the distance between points of zero deflection being about 8 ft. The influence of the load extends beyond this distance because of the small upward deflection outside of these zero points. However, the upward deflection is very small so that the slab is not greatly affected beyond a point 4 ft. each side of the load.

The stress curve shows that the top of the slab is in compression within a region 2 ft. wide and in tension beyond. Not enough gages were available to chart the complete curve, but the radius of curvature of the deflection curve is large in this region of tension so it is expected that the values attained are relatively small. No measured strains on the tensile portion of the curve exceeded 25 percent of the maximum compressive strain under the load.

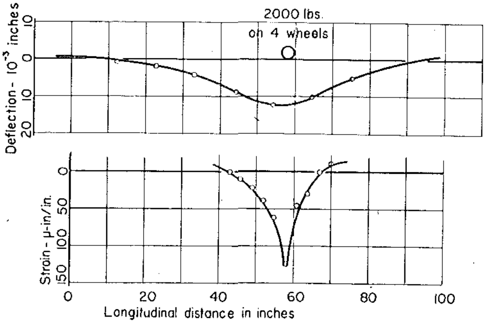


Figure 10. Deflection and Strain Curves for a Single Axle at Slab Interior.

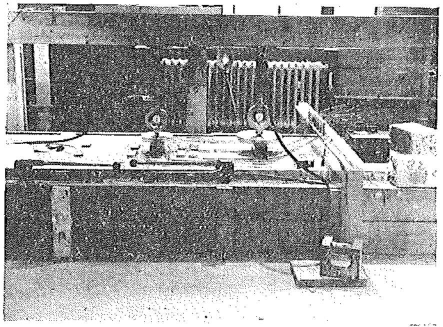


Figure 11. Method of Loading Two Axles.

Two Axles at Interior

The alternative method of adding wheels to support heavy loads is to use an additional axle. A report by the Bureau of Materials of the Illinois Division of Highways[1] indicated that there is a critical axle spacing beyond which the strains under each axle, for a constant axle load, are slightly lower than they are when one axle is loaded alone. This result was corroborated by the experiments on the model slab.

Two axles with dual wheels were spaced at the extreme distance of 102 in. and this space was reduced by stages until a minimum spacing of 6 in. was reached. Figure 11 is an example of the method of loading. Deflections and strains were read both for a load on the first axle alone and for equal loads on each axle. By this method the strain and deflection patterns for one axle could be readily compared with the patterns for two axles, and any increase or decrease in strain under the first axle was easily observed.

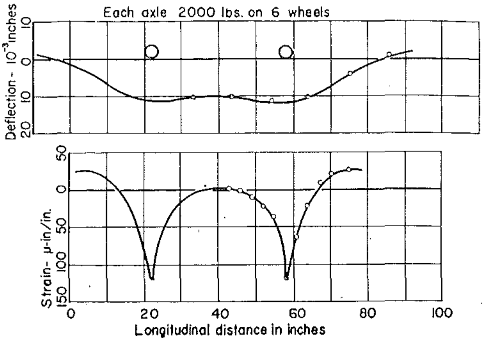


Figure 12. Curves for Two Axles at 36 in. at Slab Interior.

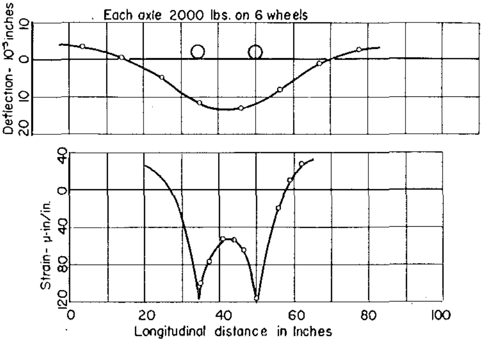


Figure 13. Curves for Two Axles at 15 in. at Slab Interior.

The curves obtained from the data on two axles with six wheels each and spaced at 36 in. are presented in Figure 12. At this axle spacing the deflection curve is practically flat at the bottom, and the strain curve shows only slight tension midway between the loads. Figure 13 shows the change in the deflection

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[1] Reference No. 1.

and strain curves produced by closer spacing. Here the axles are 15 in. apart. Although these curves were plotted from the six-wheel data, they do not differ measurably from the four-wheel case.

The curves in Figure 14 present a relation between stress change under the first axle caused by the application of the load to the second axle. These curves indicate that axle spacing under approximately 12 in. must be accompanied by a reduction in axle load if the strains are not to be increased beyond those caused by a load on a single axle. Apparently a spacing of approximately 25 in. will produce minimum strains. Since the axle lengths used in the project were about 12 in., it may be roughly stated that axles must be spaced at least one axle length apart if the two axle systems are to carry twice the load of a single axle. If the spacing is twice an axle length it is apparent from Figure 14 that the total load could be increased about 10 per cent.

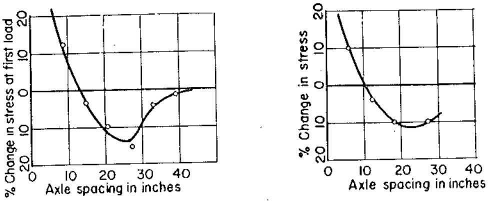


Figure 14. Effect of Second Axle upon Strain Under First Axle.

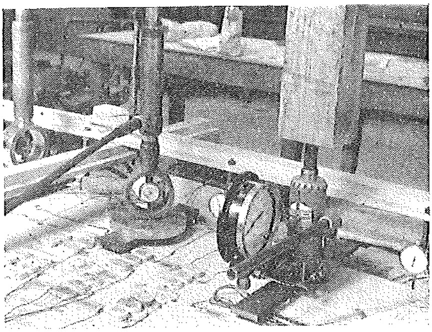


Figure 15. Three-axle Load at the Edge of the Slab.

Three Axles at Interior

A third axle was added to the system in order to ascertain whether or not the trend found in the two axle studies continued when additional axles were added. Figure 15 illustrates how three-axle loading was accomplished. Deflection and strain curves for 32-in. and 12-in. axle spacing for loads at the interior of the slab are presented in Figures 16 and 17.

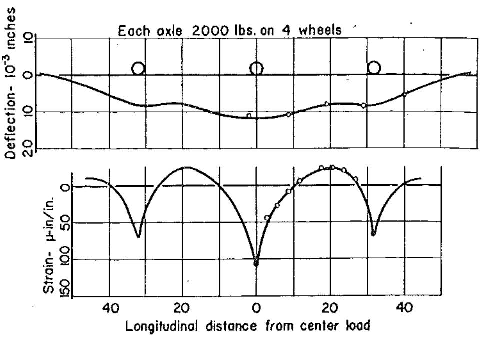


Figure 16. Curves for Three Axles at Interior of Slab. 32-in Spacing.

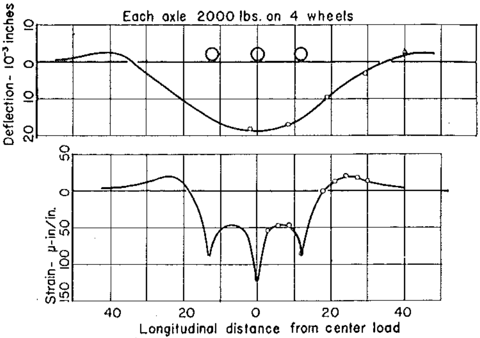


Figure 17. Three Axles at 12-in Spacing

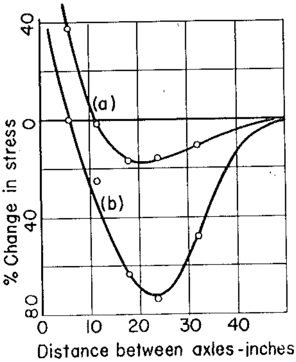


Figure 18. Stress Change Under (a) Middle Axle and (b) Outside Axle Due to Loads on Other Two Axles.

It is seen that the strains under the middle axles are greater than the strains under the outside axles in the two instances. There is a slight reversal in curvature in the deflection curve for the 32-in. spacing accompanied by a corresponding section of the strain curve registering tension. Closer spacing of the axles eliminates this effect.

The investigation at the slab center shows that the largest strain reductions occur under the inner axle when the spacing is about 22 in. (see curve (a) Fig. 18) and a corresponding maximum reduction is found at 23 in. for the outside axles, curve (b). These values support the results of the two axle study in which it was shown that a spacing of about two axle lengths produced minimum strain. If no other factors are involved, curve (a) suggests that in the case of three axles spaced at 23 in. the axle load might be increased 15 per cent over the single axle load without increasing the strain beyond that produced by one axle.

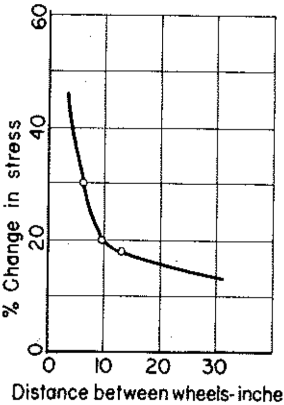


Figure 19. Effect of Wheel Spacing upon Stress Under Outside Wheel on Slab Edge.

Longitudinal Edge Loading

Strain gages were cemented to the slab along a longitudinal edge and a deflection dial pattern was arranged to permit a study of conditions at the edge of the slab. The strain and deflection patterns for this location were similar in appearance to those found at the slab center with the qualification that the amplitudes of the curves were greater. The strains at the edge exceed those for the center by 25 per cent.

The axle spacing effect for the longitudinal edge was exhibited by Figure 14. The critical spacing is seen to be 10 in., and the spacing for minimum stress is 23 in. These values are in fair agreement with the results of the center study.

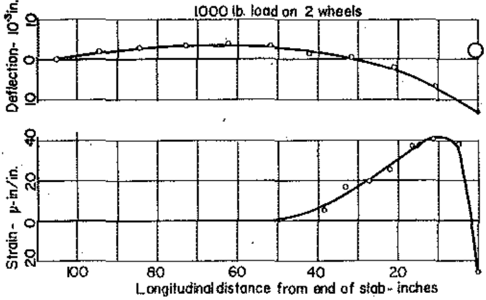
In order to study the effect of the inner wheel upon the strains under the wheel at the edge in a single axle two-wheel system, the loading jacks were arranged so that each wheel could be loaded separately. The magnitude of the strain caused by loading the outer wheel alone was found. The inner wheel was then loaded an equal amount and the increases in strain under the wheel at the edge noted. The size of this increase was dependent upon the distance between wheels, being about 20 percent for the regular axle length. At this axle length there was a noticeable difference between the strains under the outer wheel and the wheel near the interior of the slab the magnitude of the strain under the outer wheel exceeding that under the inner wheel by 75 percent. The effect of other transverse wheel spacings upon this strain relationship are shown in Figure 19. It was found that axle lengths under 9 in. yield rapid increases in strain under the outside wheel.

Loading at Transverse Edge

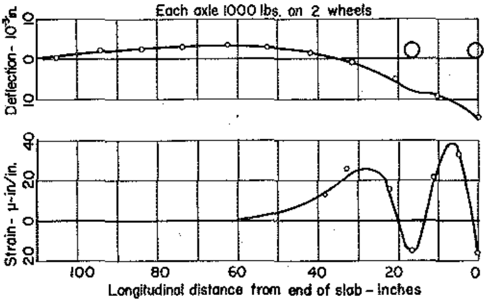
Usually concrete road slabs are joined at the ends by some load transfer device such as slip dowels. However, much wartime construction has been done without this steel. The model upon which these tests have been conducted simulates such construction, since there were no supporting dowels at the end.

Loads at the end of the slab produced strains of nearly equal magnitude in two directions: (1) tensile strains along the slab center line with a maximum a few inches inward from the load, and (2) compressive strains under the load in a lateral direction. The latter case is very similar to edge loading, but the amplitude of the strain curve was less than that for the edge because of the flat deflection pattern resulting from the narrow slab width. The longitudinal strains and deflections for a single axle and for two axles at 16 in. are exhibited in Figure 20. These curves show that the maximum strain is somewhat reduced by the application of a second axle, while the deflections remain about the same. The amount of such stress reduction is dependent upon the axle spacing.

Figure 21 shows the effect of the distance between axles. This curve reveals a critical axle spacing at about 9 in. and a spacing of 16 in. to produce minimum strain in the top of the slab due to loading near the transverse edge.



Curves for a Single Axle at Slab End



Curves for Two Axles at Slab End. 16-in. Spacing.
Figure 20.

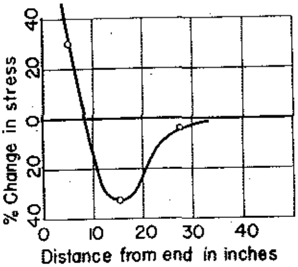


Figure 21. Change in Maximum Tensile Stress Along Slab Center Line Due to Transverse Edge Loading.

Loading at the Corner

Figure 2 shows the gage layout and dial arrangement along the longitudinal edge for the corner loading test. In addition to the gages along the slab edges, several gages were attached in the diagonal direction. The regular wheel and axle study was repeated here, and in addition tests were made for the case of a single wheel on the corner.

The direction of maximum strain for this study was dependent upon the type of loading. A single wheel on the corner produced maximum strain along the diagonal, certain two-axle systems showed greater strains along the diagonal than along the edge, while others gave larger strains at the logitudinal edge. The single-axle loading produced maximum strains along the longitudinal edge.

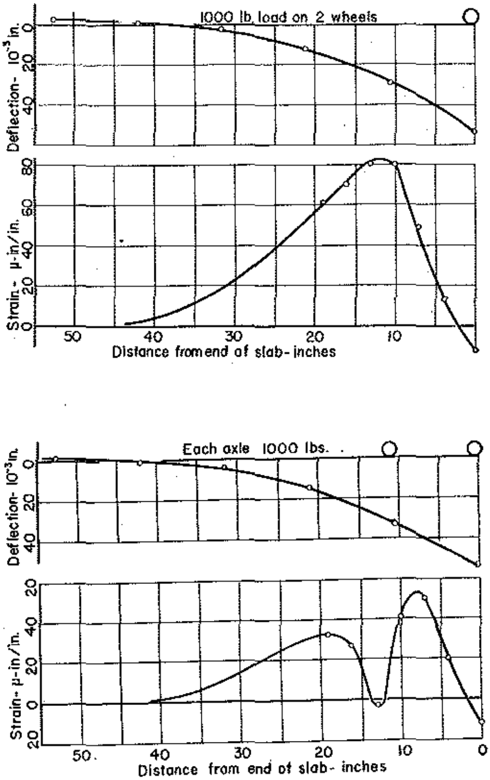


Figure 22. Curves for Single Axle and Two Axles Spaced 13 in. at the Corner of the Slab, Two Wheels per Axle.

Results of the single-axle study at the corner were shown on Figure 9. Strain and deflection diagrams for two wheels on one axle, and also for two axles with two wheels each at 13-in. axle spacing are shown on Figure 22. The stress reduction is noticeable for the axle spacing shown. Figure 23 shows that in the case of two axles the axle spacing of approximately 13 in. produces minimum stress along the longitudinal edge. The critical axle spacing is about 6 in.

Stresses due to corner loading exceeded those caused by any other type of loading. The stresses due to loads at the slab ends are only about 50 percent of the corner stresses, those due to edge loading were about 94 per cent, and when the loads were applied at the center the stresses were 75 per cent of the corner values. An axle at the corner produced a maximum stress along the longitudinal edge the value of which was about 70 per cent of the magnitude of the diagonal stress resulting from the single wheel load at the corner.

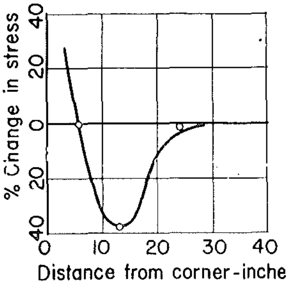


Figure 23. Change in Maximum Tensile Stress Along Longitudinal Slab Edge Due to Corner Loading.

A STUDY OF FAILURES

At the conclusion of the experiment several points were located on the slab and loads were applied through various devices at these points until the slab failed. Photographs of these breaks are shown and graphs are included for the presentation of load deflection data. Strain readings were taken at two positions.

Single wheel corner loading produced breaks across the corner perpendicular to the diagonal and a few inches inward from the load. Figures 24 and 25 show these failures. Load deflection and strain curves are presented in Figure 26. Curves a and a′ resulted from a load on a $1\frac{3}{4}$-in. disc. (Fig. 24 right foreground).

Loads on wheels in tandem caused a failure between the wheels (Curve b, Fig. 26 and Figure 25 left foreground). An axle with dual wheels broke the slab as shown in Figure 27. The corresponding deflection curve on Figure 26 is c. Another $1\frac{3}{4}$-inch plate test caused the crack in the left background of Figure 27. The accompanying curve on Figure 26 is d.

The edge breaks were of two types. Loads applied to a semi-circular area at the slab edge caused a local failure, but when the load was transmitted though the full area of the disc complete transverse cracks were formed. The first type breaks are shown in the foreground of Figure 24 and 29. The corresponding deflection curves are B and E of Figure 26. Breaks of the second type are seen on Figures 25 and 27. The curves are C and D on Figure 26.

Two breaks due to loads at interior points are shown. The failure caused when the load was transmitted through a $1\frac{3}{4}$-in. circular

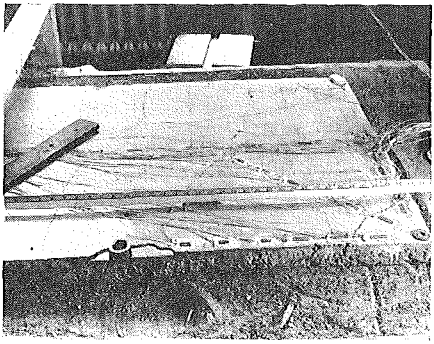


Figure 24. End of Slab Showing Failure Due to Single Wheel at Corner in Right Foreground, Corner Break from Tandem Loading in Right Background and Edge Break Caused by Semi-circular Loading Area in Left Foreground.

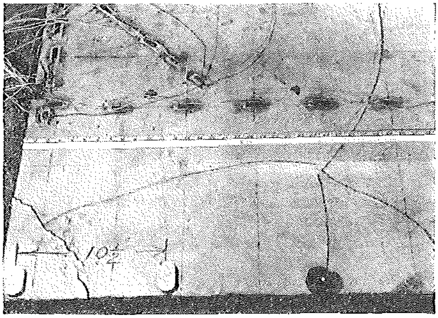


Figure 25. Left Foreground Break due to Tandem Load. Right cracks formed when load was applied on small circular plate at slab edge.

plate is seen in Figure 28, and the break for an axle with dual wheels is shown in Figure 29. The data are supplied by curves F, F′, G and G′ of Figure 26. It may be noted that the breaks under the loading point were radial, with accompanying transverse cracks about 3 ft. apart when the disc was used, but a transverse crack appeared immediately beneath the loading area when an axle was used.

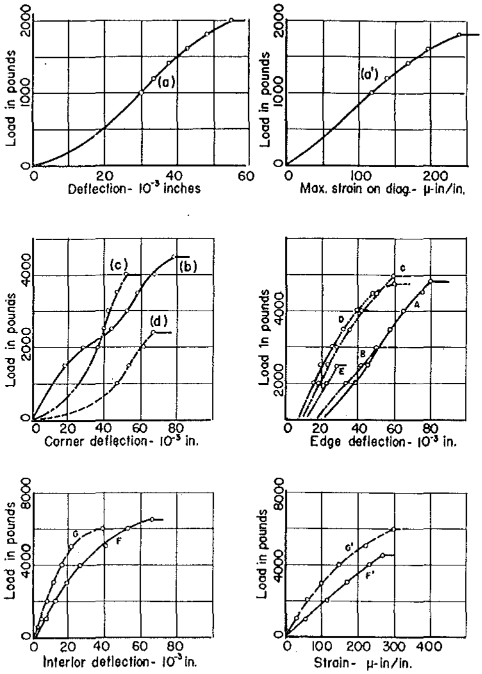


Figure 26. Curves Resulting from Loads to Failure

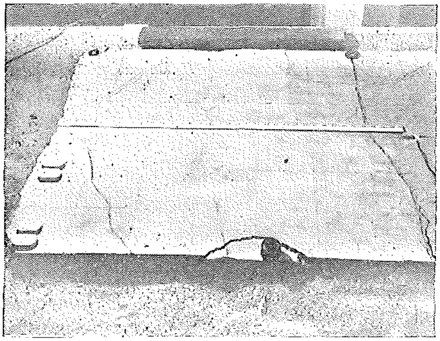


Figure 27. Corner Break from Axle Loading in Left Foreground, Edge Failure Due to Load on Semi-circular Plate in Center Foreground. Corner Break Caused by Single Wheel Load in Left Background, and Failure from Edge Load on Small Disc at Right.

Inspection of the curves on Figure 26 reveals the following: An ultimate load of 4,500 lb. was required to cause failure for the single wheel at the interior of the slab. The value at the edge was the same for the full disc area, but reduced to about 50 per cent of that value when the disc was on the extreme edge with only half the area on the slab. The load to cause failure at the corner was 40 per cent of the value for the center break.

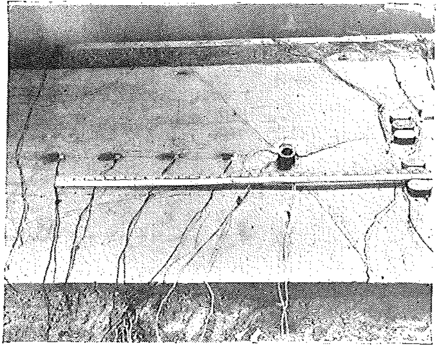


Figure 28. Radial and Transverse Cracks in Center of Slab Caused by Load on Small Plate. There was apparently some shear failure at point of load.

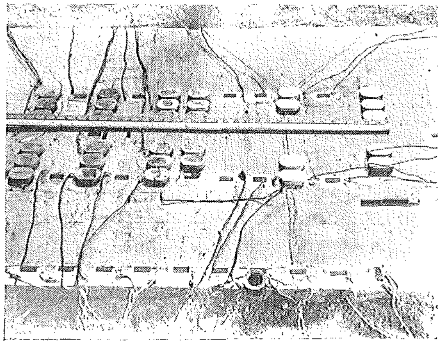


Figure 29. Foreground Failure from Load on Semi-Circular Area at Slab Edge. Center cracks formed when excessive load was applied on axle with four wheels near slab center.

An axle with four wheels caused failure at the center when the load was 6,000 lb. Although the loading area was increased 300 per cent, the ultimate load was only 33 per cent larger than the value for the single wheel. The corner failure in this case required a load of 4,000 lb. This is a reduction of 33 per cent below the value for the interior, but is twice the value for the single wheel at the corner.

SUMMARY

The results of the loading tests on the model concrete slab may be summarized as follows:

1. Strains in the slab caused by single axle loads were always larger in the longitudinal direction than in the lateral direction. This was true for loads at the corner as well as loads at the logitudinal edge and the interior. When two axles were loaded simultaneously at the corner, certain spacings produced strains along the diagonal which were slightly larger than in any other direction. Loads on a single wheel at the corner caused largest strains in the diagonal direction.
2. Maximum measured strains produced by loads at the interior and longitudinal edge of the slab were beneath the loaded areas, while those caused by corner loading and loads at the transverse edge were largest a few inches inward from the position of load application.
3. Tensile strains on the underside of the slab caused by loads directly above the gages were approximately equal in magnitude to the compressive strains in the upper surface directly beneath the load.
4. Deflection and strain curves had much greater amplitude when the slab rested upon the subgrade with modulus equal to 350 p.s.i. than they did when the stiff subgrade was used.
5. When the axle load was held constant the pavement strain produced by single axle loading was not greatly reduced when the loading area was increased.
6. When a two axle system was loaded with twice the single axle load, a critical axle spacing was found such that the strains in the slab were equal to the strains observed for the single axle loading, and axle spacings above this critical distance resulted in reduced strains while spacings below this value caused increases in the strains.
7. When a three-axle arrangement at the slab interior was loaded with a total load three times that of the single axle two facts were noted:
   a. The largest strain was under the middle axle.
   b. A critical axle spacing was found such that spacings above this distance caused strains under the loaded areas which were below those in the single axle case; and distances between axles less than this critical value produced strains greater than the single axle values.
8. For a given single axle load the order of magnitude of the resulting stress with reference to loading position on the slab was: corner, longitudinal edge, interior, and transverse edge.
9. Failures due to overloads at the edge caused small edge breaks for semi-circular areas on the extreme edge, and full transverse cracks when the full tire contact area rested upon the slab edge. Single areas on the corner produced the conventional corner break. A similar break between the wheels was the result of tandem loading. At the interior, a single area caused a combination of radial cracking and transverse cracks at some distance from the load, while axle loading produced transverse cracking directly beneath the loaded area.

CONCLUSIONS

The data resulting from the investigation seems to support the following conclusions:

1. Loads supported by single axles cannot be increased in proportion to the number of wheels added to the axle.
2. The load supported by two axles can be twice that carried by a single axle without increasing the strain above that recorded for one axle loading providing the two axles are properly spaced.
3. A three axle system permits loadings of three times the single axle load for axle spacings about the same as those in the two axle case.
4. Deflection and strain values are dependent upon the subgrade stiffness.

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DISCUSSION

MR. L. W. TELLER, *Public Roads Administration:* This interesting paper describes one of the most important attempts that has been made to study the conditions of stress caused by loads in a concrete pavement slab through the use of a scale model. The care with which the problem has been approached is evident and the instrumentation that has been applied to the problem is of interest to all concerned with the load testing of concrete pavements. The enconomies that are possible through the use of scale models in research of this kind are very great but the use of scale models entails factors that must be given careful consideration if the data obtained are to be correctly interpreted. If these scale effects are not properly evaluated the analysis of the data may lead to conclusions which, if applied to the prototype, will not be correct. It is gratifying, therefore, to note that the investigation will be continued with tests on full size slabs and with loads applied through actual truck and trailer wheel assemblies.

An earlier report of this investigation, Report No. F-72, dated July 16, 1945, showed data for strains measured transversely and longitudinally under an elliptical bearing area for a single wheel in the interior of the slab. The strains along the minor axis of the ellipse were about one third greater than those in the direction of the major axis. This is in general accord with Westergaard's mathematical analysis of this case[1] and with certain experimental data obtained in load tests with single elliptical plates of several sizes in the Arlington tests of the Public Roads Administration.[2]

In the present report the summary states that strains from the single axle loading were always greater in the longitudinal direction than they were in the transverse (or lateral) direction. This would indicate a strong influence of the tangential stress from the adjacent wheel. In the body of the report it is stated that "The stress reduction due to addition of wheels was dependent upon the stiffness of the subgrade." This is in accord with theory since the radius of relative stiffness, l, is dependent on 'k' the subgrade modulus and the value of 'l' determines the extent of stress distribution.

In the present experiments while the loads, bearing areas and slab dimensions were scaled down, the values of 'k', E, the modulus of elasticity of the concrete, and hence 'l' were not. Thus the distribution of strain and consequent magnitude of the effect of adjacent wheel loads may be quite different in model tests than it would be on the prototype.

It is stated in the report that in multi-axle loadings the axles must be spaced at least one axle length apart if the two-axle system is to carry twice the load of a single axle. Assuming that the axle of a conventional heavy truck is about 7 feet in length it is apparent that such a conclusion if applied to actual vehicle operating conditions would call for radical change in the design of many large motor vehicles. Before any attempt is made to draw conclusions on this point it should be carefully verified in the testing of the prototype.

Data obtained in load tests on full size pavement slabs many years ago[3] indicated that with the 3-axle, 6-wheel type of motor truck being investigated at that time the two rear axles could be considerably less than one axle

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[1] "Stress Concentrations in Plates Loaded Over Small Areas," by H. M. Westergaard. *Transactions* A.S.C.E., Vol. 108, (1943) p. 831.

[2] Discussion of the above paper by L. W. Teller and Earl C. Sutherland, p. 864.

[3] "The Six-Wheel Truck and the Pavement," by L. W. Teller. *Public Roads*, Vol. 6, No. 8, October 1925.

length apart before any significant increase in pavement stress was observed.

Strain measurements on the surface of pavement slabs of usual thicknesses[4] have shown that strains decrease very rapidly with distance from the loaded area. For example, with a 9-inch thick slab loaded with 18,000 pounds on a circular area 8 inches in diameter the radial strains were found to reach zero value at a distance approximating, l, the radius of relative stiffness which in this particular case was about 36 inches. The tangential strains reached zero value at about 1.6 l.

It is obvious that this matter of stress distribution is a very important one in any consideration of the effect of multiple wheel loadings since the strain under a given wheel is the algebraic sum of the strain contributions from all wheels. In model slab tests if the distribution is not to scale the observed strains cannot be used for conclusions applicable to a full scale slab without a knowledge of scale factors.

It is of interest that in the tests of the model slab in bending it was found that the tensile strains on the underside of the slab were approximately equal to the compressive strains on the upper surface. This is in accord with data obtained in certain of the Arlington experiments in which simultaneous strains were measured on the upper and lower surfaces of a slab supported on an earth subgrade. It is an important relation to establish since it permits the use of strain data obtained on the upper surface of a pavement slab in a study of the state of strain in the lower surface. It has made practicable much of the research work that has been done in this field to date.

The emphasis placed on the importance of scale effects in the above discussion is intended as no reflection on the report discussed nor on the work that has been done on this valuable research project. The author describes this as a progress report of preliminary work. As such it is both interesting and useful. It is hoped that the future program will include investigations of the importance of scale factors to the end that the possibilities and limitations of stress studies with scale models of pavement slabs may be established.

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[4] "The Structural Design of Concrete Pavements. Part 5.—An Experimental Study of the Westergaard Analysis of Stress Conditions in Concrete Pavement Slabs of Uniform Thickness," reported by L. W. Teller and Earl C. Sutherland. *Public Roads*, Vol. 23, No. 8 April–May–June 1943.