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HIGHWAY RESEARCH IN ILLINOIS*

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With Discussion by H. F. Clemmer, Assoc. M. Am. Soc. C. E.

Synopsis

In this paper are described a series of research projects carefully planned to give an insight and understanding of the unsolved problems of rural pavement design.

The principal problems investigated include the drainage of sub-grade soils, the effect of repeated bearing pressures on soils, the effect of temperature changes on pavement surfaces, the position of wheel loads as affecting stresses in pavement slabs, the impact resulting from moving wheel loads, and the fatigue effect of repeated loads causing bending stresses in plain concrete.

A test road was constructed so as to eliminate as far as possible the variable factor of sub-grade bearing power. Six groups of test sections were built, each representing a given type of pavement. Each group included a series of sections graduated in thickness and strength from light to heavy, and presumed to be comparable with corresponding sections of the other groups. The test road was subjected to a graduated artificial truck traffic, beginning with wheel loads of 2 500 lb. and ending with wheel loads of 13 000 lb.

In this paper are described briefly the methods used in the investigations, the data obtained, and the tentative conclusions drawn from these studies.

The highway research activities of the Division of Highways, Department of Public Works and Buildings of Illinois were started in 1920 with an ambitious program. This work centers about a test road constructed by the State near Bates, Ill., popularly called the Bates Test Road. The contemplated expenditure of about $100 000 000 for the paving of a primary road system was the inspiration that gave birth to the intensive research activities of the Department.

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* Presented at the meeting of the Highway Division of the Society, January 17, 1924.

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For purposes of discussion, this research work will be considered under two classifications:

First.—Carefully controlled special investigations bearing on the most important factors involved in the rational design of pavement surfaces. The principal problems were to determine (*a*) the path of wheel travel resulting in maximum destructive forces; (*b*) the impact effects of wheel loads; (*c*) the safe working stress for certain paving materials; and (*d*) the character of the support afforded the pavement by the sub-grade soil.

Second.—Traffic tests of a variety of pavement sections designed so as to give empirical data for use in confirming any fundamental laws developed.

Anticipating possible failure to develop a complete rational method for the design of pavement surfaces, the empirical data were expected to become a valuable guide for future construction. The Bates Test Road was planned with both these general forms of research in mind.

General Plan of the Research Project

In planning the road, an endeavor was made to include as comprehensive a series of test sections as might be necessary to bring out the traffic-supporting characteristics of each of the general types considered to merit a place in the large State paving program then contemplated. Each group of sections representing a given type included ranges of thickness varying from an arbitrary minimum considered suitable for the lightest traffic to a maximum considered as possibly being able to withstand the heaviest units of traffic permitted in Illinois.

As the test sections were completed, special investigations were undertaken, including observations of natural phenomena and a series of carefully controlled load tests designed to throw light on the rational design problem. It was then planned to subject all sections to an artificial truck traffic, beginning with truck loads no greater than those which might be expected on light traffic roads, followed by successive increases of wheel loads until the maximum permitted by law had been reached, or possibly exceeded. It was hoped that this plan of traffic testing would bring out at least roughly the relationship between wheel loads and thickness of pavement for each type used.

Description of Test Sections

Each of the following types was represented by a group of sections:

(*a*) Vitrified brick surfacing with bituminous joint filler on a macadam base;
(*b*) Asphaltic concrete surfacing on a macadam base;
(*c*) Asphaltic concrete surfacing on a concrete base;
(*d*) Vitrified brick with bituminous joint filler on a concrete base;
(*e*) So-called "monolithic" brick, or brick with cement grout filler laid on a concrete base before it had set; and
(*f*) One-course concrete, both plain and with various inclusions of embedded steel.

In Table 1 will be found details of the various sections included in the original construction, grouped by types. Sections 12 to 57, inclusive, were constructed in the fall of 1920. The base of Sections 1 to 11, inclusive, was laid in the spring of 1921. The asphaltic concrete surface on Sections 6 to 22, inclusive, was laid during the spring months of 1921, as was also the brick surfacing on Sections 1 to 5, inclusive, and 23 to 32, inclusive. Concrete Sections 57 to 63, inclusive, were laid in the spring of 1921. Sections 63 and 63B were not included in the original plan, but were added before the completion of the remainder of the sections, profiting by the results obtained from certain preliminary investigations, to be described later.

A length of 200 ft. was selected as standard for each primary test section. This dimension should be of such magnitude that in case of the complete failure of an adjacent section, thereby imposing undue stress on the end of the section in question, an additional length would still remain from which to judge the normal effect of traffic on a similar road of indefinite length. It was also considered that the test sections involving the use of concrete should be of sufficient length to include one construction joint and at least one natural transverse contraction crack before the artificial truck traffic was started.

In each section involving the use of concrete, a construction joint was placed at a distance of 25 ft. from the east end of the section. A number of Goldbeck pressure cells were placed in many of the sections as the pavement was laid. About 600 iron pipes of a length equal to the depth of the pavement were also set at various places, the tops being closed by water-tight plugs. The purpose of these pipes was to enable observers to secure samples of the sub-grade soil for moisture determinations and to facilitate observation of contact between the under surface of the pavement slab and the sub-grade soil.

Inasmuch as the soil throughout a large part of the State exhibits fairly uniform physical characteristics and considering the fact that the relative behavior of the various sections could not be judged if the nature of the foundation varied materially, a site was selected where sub-grade conditions would be as nearly uniform as possible. Practically all unprejudiced observers agree that the Bates Road site fulfilled these conditions as ideally as could be expected in a length of road of two miles or more. No visible variation in the character of the soil could be detected; on the other hand, no positive method of establishing beyond question the lack of variation in sub-grade soil could be found.

Impact Investigations

The wide variety of pavement designs on the Bates Road offered an ideal opportunity to observe the behavior of each under carefully controlled conditions. As rapidly as the sections were completed and aged, preliminary investigations as to their action under load were conducted.

A knowledge of the wheel loads imposed by highway traffic is a fundamental requirement for rational design. It is believed that until more is known regarding the design of the economical highway transport freight unit, wheel

TABLE 1.—DETAILED DESCRIPTION OF THE ORIGINAL TEST SECTIONS.

(a) VITRIFIED BRICK SURFACING WITH BITUMINOUS JOINT FILLER ON MACADAM BASE.*

Number of section.	Length, in feet.	Thickness of brick, in inches.	Cushion.	Base course thickness, in inches.	Total thickness, in inches.	Number of courses in base.
1 A	100	3-lug	2-in. sand	4	9	1
B	100	3-lugless	2-in. "	4	9	1
2	100	4-lug	2-in. "	4	10	1
3	100	4- "	2-in. "	4	10	1
4	100	4-lugless	1-in. mastic	8	13	2
5	100	3- "	2-in. "	8	13	2
....	600	....	....	..	..	..

(b) ASPHALTIC CONCRETE SURFACE ON MACADAM BASE.*

Number of section.	Length, in feet.	Wearing course.	Base course.	Total thickness, in inches.	Number of courses in base.
6	200	2-in. Topeka	10 in. Macadam	12	2
7	200	2 " "	8 " "	10	2
8	200	1½ " " / 1½ " Binder	5 " "	8	1
9	200	2 " Topeka	6 " "	8	1
10	200	2 " "	4 " Novaculite	6	1
11	200	2 " "	4 " Macadam	6	1
..	1 200	....	....	..	..

(c) ASPHALTIC CONCRETE SURFACE ON CONCRETE BASE.†

Number of section.	Length, in feet.	Wearing course, in inches.	Base course thickness, in inches.	Mix.	Total thickness, in inches.
12 A	200	2-in. Topeka	4	1-3-5	6
B	25	2 " "	5	1-3-5	7
13	200	1½ " " / 1½ " Binder	4	1-3-5	7
14	200	2 " Topeka	4	1-2-3½	6
15	200	1½ " " / 1½ " Binder	4	1-2-3½	7
16	200	2 " Topeka	5	1-3-5	7
17	200	2 " "	5	1-2-3½	7
18	200	1½ " " / 1½ " Binder	5	1-2-3½	8
19	200	2 " Topeka	6	1-3-5	8
20	200	2 " "	6	1-2-3½	8
21	200	2 " "	7	1-2-3½	9
22	200	1½ " " / 1½ " Binder	8	1-2-3½	11
....	2 225	....	..	....	..

* The coarse aggregate for the macadam base is crushed limestone.
† Crushed limestone used for coarse aggregate.

TABLE 1.—(*Continued*).

(*d*) Vitrified Brick Surface with Bituminous Joint Filler on Concrete Base.*

Number of section.	Length, in feet.	Thickness of brick, in inches.	Cushion.	Base course thickness, in inches.	Base mix.	Total thickness, in inches.
23 A	100	3-lug	1 sand	6½	1-2-3½	10½
B	100	3-lugless	1 "	6½	"	10½
24	100	3-lug	1 "	5½	"	9½
25	100	3-lugless	1 mastic	5½	"	9½
26 A	100	4-lug	1 sand	4	"	9
B	100	4-lugless	1 "	4	"	9
27	100	3-lug	1 "	4½	"	8½
28	100	3-lugless	1 "	4½	"	8½
29 A	100	3-lug	1 "	4½	1-3-5	8½
B	75	3-lugless	1 "	4½	"	8½
30	125	3-lug	1 "	3½	1-2-3½	7½
31	100	3-lugless	1 sand-cement	3½	"	7½
32 A	100	3-lug	1 sand	3½	1-3-5	7½
B	100	3-lugless	1 "	3½	"	7½
.....	1 400	....	....	...	....	...

(*e*) Monolithic Brick on Concrete Base.*

Number of section.	Length, in feet.	Thickness of brick, in inches.	Type.	Base course thickness, in inches.	Base mix.	Total thickness, in inches.
33	200	3	Monolithic	2	1-2-3½	5
34 A	200	3	Semi-monolithic	2	"	5¾ (¾-in. sand cement bed)
35	200	4	Monolithic	2	"	6
36	200	3	"	3	1-3-5	6
37	200	3	"	3	1-2-3½	6
38	200	4	"	3	"	7
39	200	4	"	4	1-3-5	8
.....	1 400	..	....	..	......	....

* Crushed limestone used for coarse aggregate.

TABLE 1.—(*Continued.*)

(*f*) PORTLAND CEMENT CONCETE.*

Number of section.	Length, in feet.	Thickness, in inches.	Mix.	Special features.
40	200	9	1-2-3½	None.
41	150	8	"	Corrugated transverse joint every 25 ft. Corrugated longitudinal joints full length of section†.
42	150	8	"	None.
43	150	7	"	Corrugated transverse joint every 25 ft. Corrugated longitudinal joints full length of section†.
44	150	7	"	None.
45	100	6	"	Corrugated transverse joint every 25 ft. Corrugated longitudinal joints full length of section†. Pavement reinforced with circumferential reinforcing in 25 by 9-ft. sections‡.
46	100*	6	"	Corrugated transverse joint every 25 ft. Corrugated longitudinal joints full length of section†. Pavement reinforced with circumferential reinforcing in 25 by 18-ft. sections. Transverse rods passed through longitudinal joints. No longitudinal rods adjacent to longitudinal joints‡.
47	100	6	"	Corrugated transverse joint every 25 ft. No longitudinal joints†. Pavement reinforced with circumferential reinforcing in 25 by 18-ft. sections.
48	100	5	"	Same as Section 45.
49	100	5	"	" " " 46.
50	100	5	"	" " " 47.
51	100	6	"	Wire mesh reinforcing§.
52	200	6	"	None.
53	100	5	"	Same as Section 51.
54	200	5	"	None.
55	200	5	"	"
56	200	5	"	4% calcium chloride incorporated in 125 ft. 2½% " " " " 75 ft.
57	200	5	"	Cemite cement used.
58	200	4	"	4-in. rolled-stone base course under slab.
59	200	4	"	Cemite cement used.
60	200	4	"	2½% calcium chloride incorporated.
61A	100	4	"	Hydrated lime, 7½%.
61B	100	4	"	None.
62	200	4	"	‖
63A	150	7	"	‖
63B	50	7	"	‖
....	3 800	....	....	

* Crushed limestone used for coarse aggregate in all sections, except Sections 55 and 63A, in which gravel was used.

† Transverse and longitudinal joints were formed by setting on edge strips of horizontally corrugated galvanized iron. The strips were 6 ft. long and had a width of 1 in. less than the thickness of the pavement. The width of the corrugations was 3 in. and the depth 1 in. The metal was 16-gauge and the weight of galvanizing was 2 oz. per sq. ft.

‡ All bar reinforcing consisted of ¾-in. round deformed dowel bars placed 2 in. from the top of the slab and 6 in. in from the edges of the section, with a 3-in. lap at intersections.

§ The wire mesh reinforcing weighed approximately 45 lb. per 100 sq. ft. The total effective longitudinal sectional area, in square inches per foot of width, was 0.093 and the sectional area of the longitudinals, in square inches per foot of width, was 0.087.

‖ Longitudinal joint full length of section; ⅝-in. deformed bars, 5 ft. long and spaced 10 ft. apart, were placed across longitudinal joint. A ¾-in. plain round painted bar was placed 6 in. from each outside edge of the slab and at one-half its depth. The longitudinal bar along the edge was continuous through Sections 62, 63A, and 63B.

loads must be arbitrarily limited by law, in order to safeguard the many millions of dollars already invested in pavements. In contemplating the design of a pavement, it is necessary either to assume the maximum expected wheel load or be governed by the limits set by the law. Whether or not an impact factor must be allowed is a matter of great importance. Research, therefore, was undertaken to determine this.

The impact effect of wheel loads on concrete pavements, and on pavements with concrete base only, was investigated. No suitable instrument could be found for determining the fiber deformation in the upper face of a concrete slab under moving loads; instead, an attempt was made to find a measure of the impact stresses by accurate observations of deflections. Records of rigid pavement failures seem to indicate that, in ordinary types, maximum stresses occur at corners and unbroken edges. Accordingly, impact observations were confined to such points.

Relation of Deflection Curves Due to Impact and to Static Loads.—It was thought that possibly a sudden blow, produced, for instance, by a truck wheel falling from an obstruction, might result in a deflection curve of shorter radius than that resulting from a static load giving the same total deflection at a certain point. In order to establish the relationship of deflection curves produced by impact and by static loads, the following plan was finally devised: At intervals along the edge of the pavement slab, Ames dials were located so as to indicate the deflection of the slab at distances of 0 in., 20 in., 4 ft., 7 ft., 10 ft., 13 ft., and 16 ft. from the point of observation. The dials were actuated by metallic lugs attached to the pavement edge, and were equipped with a friction device, by which the spindle and the index pointer, having moved to the point of maximum deflection, would retain that position after the load was removed and the pavement slab had recovered its original elevation. A small bulb at each dial, electrically connected, remained lighted as long as the lug and dial were in contact. The procedure was then as follows: The spindle of each dial was adjusted to contact with the lug, each bulb, therefore, being lighted. The wheel of a loaded truck was then lifted by a hydraulic jack and allowed to fall on the pavement edge or corner at a point immediately opposite the zero dial, the wheel load and height of drop being varied to represent impact conditions up to such extremes as the slab might be expected to resist without failure. Only such loads and drops were recorded as caused an impact deflection greater than that resulting from the load at rest. The fact that the dropping of the wheel extinguished all the lights, with no subsequent flicker, indicated conclusively that the dials recorded the impact deflection only, rather than any subsequent vibratory or static load deflection. After the dials were read, a gradually increasing load was applied at the same point on the pavement, using a hydraulic jack and a loadometer, until contact again was made at the zero dial. All the dials then were adjusted to contact and readings again taken. Thus, the first set of readings defined the impact deflection curve, and the second, a static deflection curve having an equal maximum.

Tests conducted during daylight hours were not reliable, owing doubtless to temperature effects. All such tests, therefore, were made at night during periods of least sub-grade support resulting from warping of the slabs due to change in temperature, a condition which will be discussed elsewhere.

In Fig. 1 are plotted the readings of the night test that resulted in the greatest variance between the impact and static deflection curves; the average results of these tests show a close coincidence of the two graphs. This may be appreciated from the fact that although a static load of 10 000 lb. might be necessary to effect a pavement deflection sufficient to light the first bulb, yet an increase of only about 200 lb. would cause contact at all the remaining dials. In many cases, several of the bulbs would light at the same instant. Often when the first bulb showed contact, a man jumping on the edge of the pavement could make or break contact at all the dials.

The close coincidence of the impact and static deflection curves indicates that the deflection method is reasonably reliable.

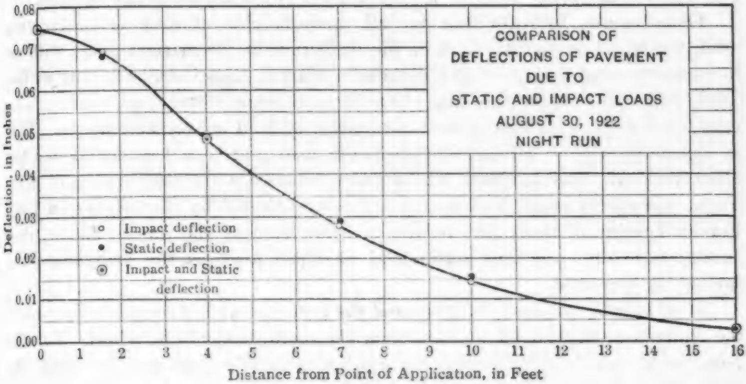


FIG. 1.

Procedure for Impact Tests.—As applied to actual impact of traffic, the method was as follows: A smooth runway consisting of steel plates was laid on the surface of the pavement near the edge (Fig. 2). A loaded truck was placed on the shoulder and arranged in such a manner that a hydraulic jack, re-acting against an I-beam, which could be quickly run out from under the truck body, might be used to impose a static load of any required amount at the point where one wheel of a moving truck would fall from the end of the runway. An Ames dial with a friction device, arranged to indicate maximum deflection, was placed at the edge of the pavement opposite the point where the wheel would strike (Fig. 3). An electric contact and light bulb was arranged so that a subsequent equal deflection would light the bulb. Electric contact points at fixed distances on the runway, and a stop-watch, afforded means for determining the speed of the truck. Immediately after the truck had passed, the hydraulic jack, together with a weighing device, was swung out, and a static load of increasing amount applied until contact was secured at the dial.

Assuming that the impact and static deflection curves are coincident in all directions and assuming also that if the radius of deflection curvature is the same, the fiber deformations and stresses are equal also, then the ratio of the static load to the moving wheel load should represent the correct impact factor for use under similar conditions.

Following a series of runs designed to determine this relationship for various speeds and height of drop, the truck was operated in the opposite direction so that the impact would be that caused by the wheel mounting the obstruction.

Results of Impact Tests.—Fig. 4 shows the results obtained for wheel loads of 4 000 lb., 6 000 lb., and 8 000 lb., for drops of ⅛ in., ¼ in., ⅜ in., and ½ in., and for truck speeds varying from about 1 mile per hour to about 20 miles per hour. The unsprung weight was constant. Fig. 5 shows the results obtained under similar conditions, except that the truck moved in the opposite direction so as to mount the obstruction. The increase in wheel loads was effected by placing weights in the body of the truck and, therefore, above the springs.

These results indicate that for all those heights of drop or obstruction used, the equivalent static load or the deflection at the critical point with an increase in speed decreased to a certain minimum, then increased more or less gradually. In amount this reduction in equivalent static load shows a distinct tendency to increase with the increase of load above the springs. This is especially true in all cases of dropping load and to a less degree for the ⅛-in. and ¼-in. vertical rises. The difference between the minimum and maximum equivalent static load was not greatly affected by the change in load. For all heights of drop, this results in a lowering of the impact factor, that is, the ratio of equivalent static load to wheel load, as the load above the springs is increased.

At all speeds, for the ⅛-in. drops and the ⅛-in. rise with the truck fully loaded, the equivalent static load was less than the static load of the wheel. For the ¼-in. drops, truck fully loaded, the equivalent static load was less than the truck-wheel load until the speed of the truck exceeded about 12 miles per hour, and did not increase materially for speeds in excess of 14 miles per hour; the maximum equivalent static load for the 8 000-lb. wheel load was only a little greater than the wheel load itself. In mounting the ¼-in. obstruction, the critical speed was about 10 miles per hour and the equivalent static load did not increase materially for speeds in excess of 14 miles per hour. For the drops and rises of greater magnitude, the critical point was passed at lower speeds and the maximum impact effect was much greater.

The value of Figs. 4 and 5 as an index of the relative magnitude of impact and static load stresses depends on the equality of the shortest radii of the impact and static load deflection curves. The close coincidence shown in Fig. 1 seems to indicate that these results are correct.

Practically all modern rigid pavement specifications permit a variation from the true surface up to ¼ in. As such variations are rarely abrupt, it would seem that the impact factor is not of sufficient importance to justify any great precautions in design. Accidental obstructions, as loose boards or a pavement slab that has heaved, are so unusual as to justify the neglect of such factors in design.

Warping of Rigid Pavement Slabs, Due to Temperature Changes

Observed structural failures of existing rigid pavements had previously indicated that corners formed by the intersection of transverse cracks and the edge of the slab were points of weakness; therefore, such corners, as well as unbroken edges, were subjected to loads of varying amounts and observations made. These proceedings soon disclosed the important fact that rigid pavement slabs warp seriously, due to daily changes in air temperature. Fig. 6

FIG. 2.—RUNWAY AND AUXILIARY TRUCK FOR APPLYING EQUIVALENT STATIC LOAD AT POINT OF IMPACT.

FIG. 3.—APPARATUS USED FOR RECORDING STATIC AND IMPACT DEFLECTIONS.

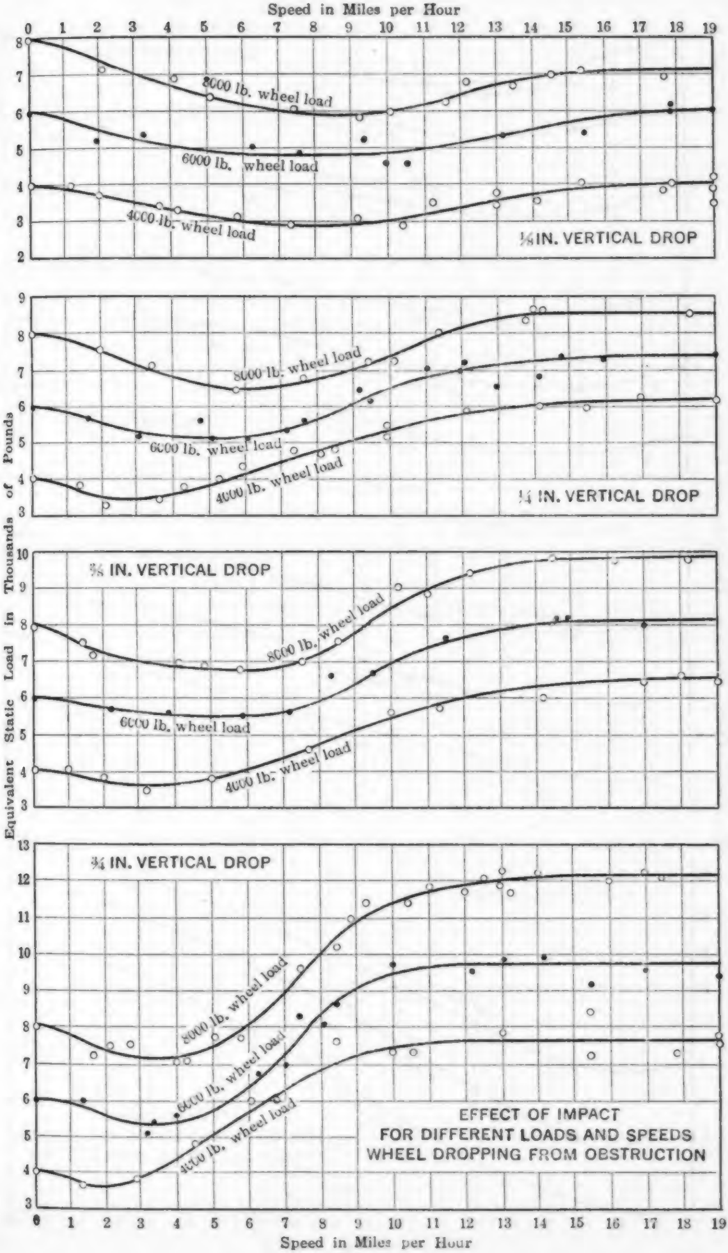

Speed in Miles per Hour
Equivalent Static Load in Thousands of Pounds
8000 lb. wheel load
6000 lb. wheel load
4000 lb. wheel load
⅛ IN. VERTICAL DROP
¼ IN. VERTICAL DROP
⅜ IN. VERTICAL DROP
¾ IN. VERTICAL DROP
EFFECT OF IMPACT
FOR DIFFERENT LOADS AND SPEEDS
WHEEL DROPPING FROM OBSTRUCTION
Speed in Miles per Hour

FIG. 4.

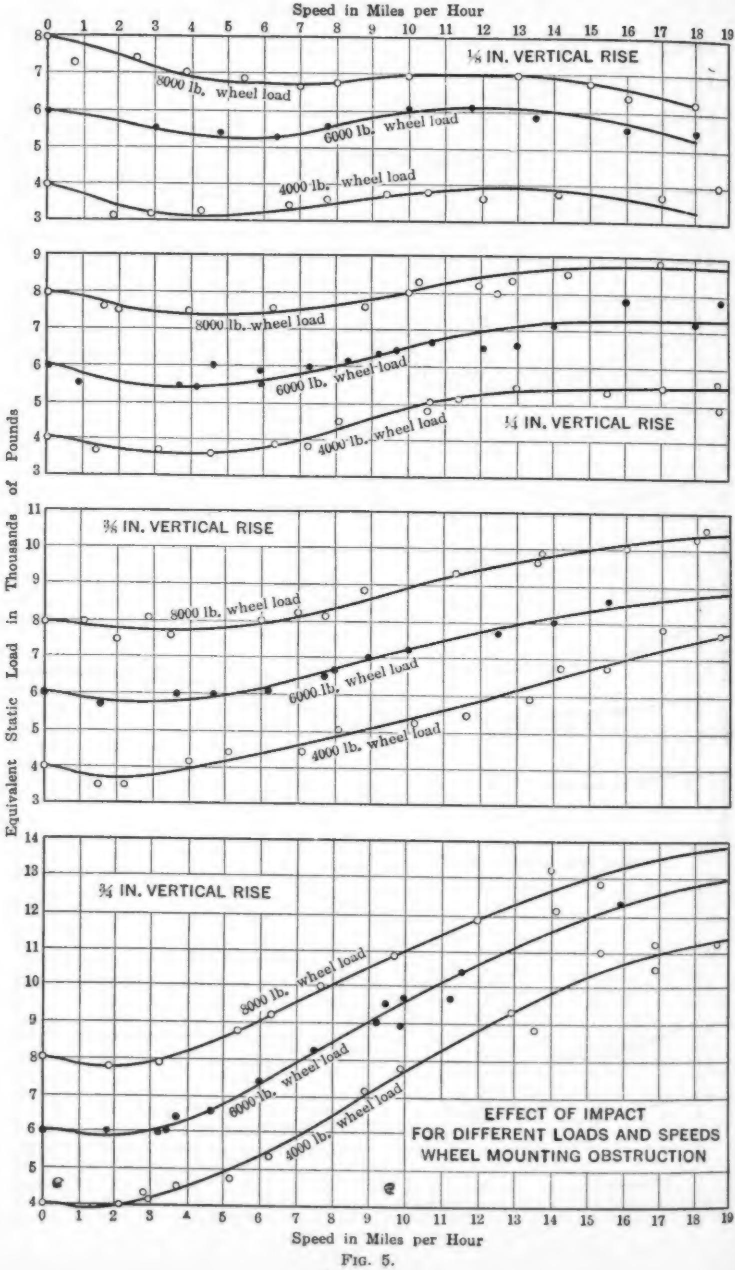

Speed in Miles per Hour
⅛ IN. VERTICAL RISE
8000 lb. wheel load
6000 lb. wheel load
4000 lb. wheel load
¼ IN. VERTICAL RISE
⅜ IN. VERTICAL RISE
¾ IN. VERTICAL RISE
Equivalent Static Load in Thousands of Pounds
EFFECT OF IMPACT
FOR DIFFERENT LOADS AND SPEEDS
WHEEL MOUNTING OBSTRUCTION
Speed in Miles per Hour

FIG. 5.

illustrates this for the corner of a 9-in. pavement slab during a 60-hour period, and shows also the deflection of the corner under a load of 6 000 lb. applied at hourly intervals throughout the period. Fig. 7 plotted from a number of simultaneous observations illustrates the warping effect of daily changes

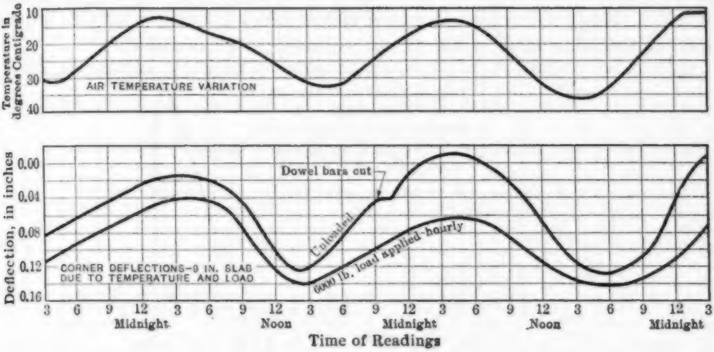


FIG. 6.

of temperature on various pavement slabs. Fig. 8 shows the air temperature, and that of the top, mid-depth, and bottom surface of a concrete slab for a 2-day period. It is to be noted that although the temperature of the top surface varied as widely as that of the air, the temperature of the under surface

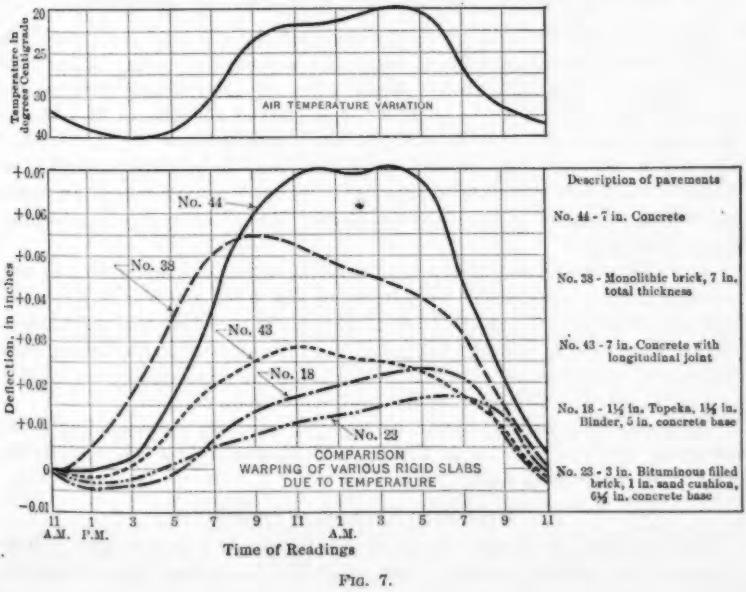


FIG. 7.

varied only a little. This condition being normal, the expansion and contraction of the top surface, due to temperature changes, must inevitably be followed by a corresponding warping of the slab. Corner warping of as much as ¼ in. often occurs in slabs 18 ft. wide. These observations, together with others relating to sub-grade support, including pressure-cell readings, confirmed the belief that rigid pavement slab corners frequently may be required to sustain passing loads while acting as unsupported cantilevers.

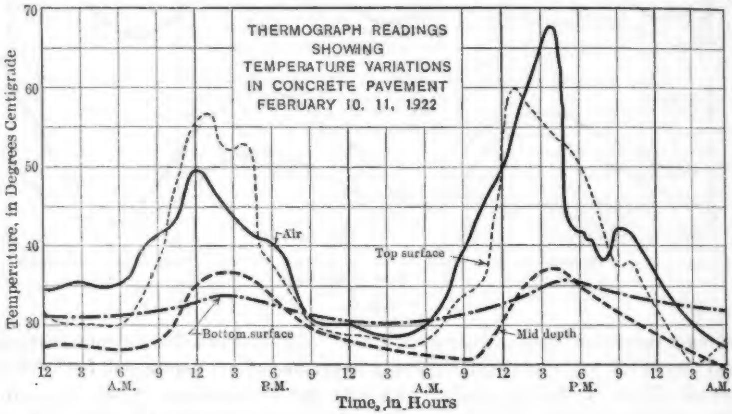


Fig. 8.

Influence of the Position of Wheel Loads on Deflections

To throw further light on the behavior of the edges of rigid pavement, loaded trucks were driven along completed sections and many observations of deflections were made, using Ames dials. Typical results from such a series of tests are shown on Fig. 9. The marked contrast of the observations represented by Fig. 9 (*b*) and Fig. 9 (*c*), with those of Fig. 9 (*d*), points strongly to the fact that stresses in corners may be greatly reduced if an effective method of doweling is provided. However, unless means are found to prevent transverse cracks, corners may be formed at any point along the edge of the slab.

A similar effectiveness of dowels in reducing deflections caused both by temperature and by loads, shown by comparing Fig. 9 (*c*) and Fig. 9 (*d*), is also indicated clearly by the observations of Fig. 6, during which the dowel bars in the corner were cut. On the night following the cutting of the dowels, when the range in temperature was the same as during the previous day, the warping increased and the deflection under load more than doubled.

Attempts were made to obtain deformation readings corresponding to the deflection readings recorded in Fig. 9, but no extensometer adaptable to the conditions could be devised.

First Step Forward in Design

The reduction of corner warping due to the use of a longitudinal joint as disclosed by comparing Curves 43 and 44 in Fig. 7, together with a consideration of the deflection behavior of doweled corners, led to the addition of Sections 63 and 63B to the original list. It was expected that this use of the longitudinal tongue and groove joint with dowel bars across it, would accomplish: First, the prevention of unsightly irregular longitudinal cracks; second, the closure of such joint and consequent mutual support of all interior corners; third, the reduction of warping at the outside edges and corners to the minimum which might be expected in a half width slab, thus insuring the maximum possible sub-grade support during periods following a drop in temperature.

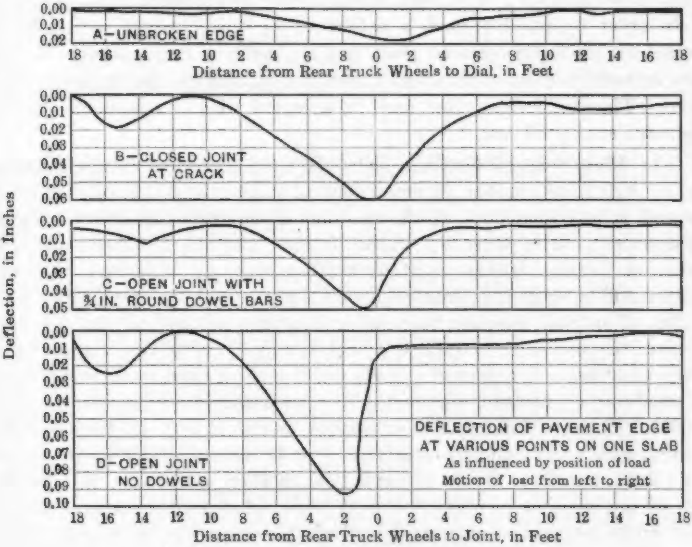


Fig. 9.

A continuous $\frac{3}{4}$-in., round, smooth bar embedded at half the depth of the slab and near each edge was included, in order that adjacent edge corners might be more or less mutually supported. This continuous dowel bar, as it might be called, was painted and oiled in order to avoid a concentration of tensile stress at cracks and joints during a general drop in temperature. The area of the bar was presumed to be sufficient to transfer by shear one-half (4 000 lb.) of the maximum wheel load permitted by the Illinois law. It was feared that under load the bearing of the bar on the concrete immediately adjacent to the joint might be great enough to pulverize the concrete gradually and thus eventually to destroy its usefulness. Subsequent observations indicate that 15 000 or 20 000 passages of maximum wheel loads along the pavement edge diminish the effectiveness of the bar as a shear member possibly 50 per cent.

Fatigue of Concrete

Concrete being so generally adaptable for paving purposes, it was considered important to determine its strength characteristics when subjected to practical conditions of traffic. It is obvious that concrete pavement slabs, or concrete bases carrying other types of wearing surface, are subject to bending stresses. Further, it is questionable whether reinforcing steel in sufficient quantity to relieve the concrete of tensile stresses may be used with economy. In fact, it was believed that if a safe working stress for concrete in tension could be developed, a pavement design in which the concrete itself would be called on to bear all tensile stresses might prove economical.

In order to establish such a safe working tensile stress, a machine was devised for applying repeated loads to plain concrete beams (Fig. 10).* The data accumulated since this report was issued, confirm the tentative results given. The conclusions that may be accepted with a reasonable degree of assurance are as follows:

(*a*).—Plain concrete beams or slabs will sustain without failure from bending an indefinite number of repetitions of a load if the tensile fiber stress induced is less than 50% of the modulus of rupture. At the present time (December 1, 1923) there are in the fatigue machine test beams that have withstood without failure about 5 000 000 repetitions of a load sufficient to produce a fiber stress of approximately 50% of the modulus of rupture.

(*b*).—For loads causing fiber stress in excess of 50% of the modulus of rupture, the tendency to failure increases rapidly with the increase of this excess of stress. For instance, loads causing fiber stresses of about 60% of the modulus of rupture, repeated a few thousand times (rarely more than 30 000) will cause failure; for stresses in excess of 70% of the modulus of rupture, only a few hundred repetitions (rarely more than 5 000) are required. The establishment of the fact that a tensile fiber stress somewhat less than 50% of the modulus of rupture may be assumed as safe for a road slab, will be of great value when analytical methods for computing fiber stresses in all parts of pavement slabs are found.

The phenomenon of accelerated failure is also of importance in interpreting the behavior of existing concrete slabs under traffic. For example, a corner break in a 4-in. concrete section of the Bates Road, under a 3 500-lb. wheel load, indicated that the concrete at corners was subjected to stresses nearing or exceeding the critical 50% endurance limit. In the succeeding increment, the wheel load was increased 1 000 lb., or 28 per cent. If, therefore, the 3 500-lb. load caused fiber stresses equal to approximately 50% of the modulus of rupture, the next increment was imposing stresses of about 78 per cent. The fatigue-test results indicate that at this percentage rapid failure should follow. This proved to be the fact inasmuch as many corners of 4-in. slabs were broken and the progressive destruction was quite rapid. Similar phenomena have been noticed in connection with Illinois pavements in service, some of which have withstood normal traffic for a number of years,

* A preliminary report of this test may be found in *Proceedings*, Am. Soc. for Testing Materials, Vol. 22. Pt. 2, p. 408.

Fig. 10.—Apparatus for Determining Fatigue or Endurance Limit of Plain Concrete Beams.

Fig. 11.—Typical Failure of Asphaltic Concrete Surfacing on Macadam Base.

and then have become seriously damaged by suddenly increased highway loadings.

SUB-GRADE SOIL INVESTIGATIONS

Before any rational method may be developed for determining stresses in all parts of pavement slabs, the character of the support afforded by the sub-grade must be thoroughly understood. Research on this subject by the Illinois Highway Department has been confined thus far to what might generally be classed as clay soils.

Moisture Content.—It has been fairly well established that the bearing value of a clay soil varies with its moisture content. Attempts made to control the moisture content of the sub-grade soil are, therefore, of interest.

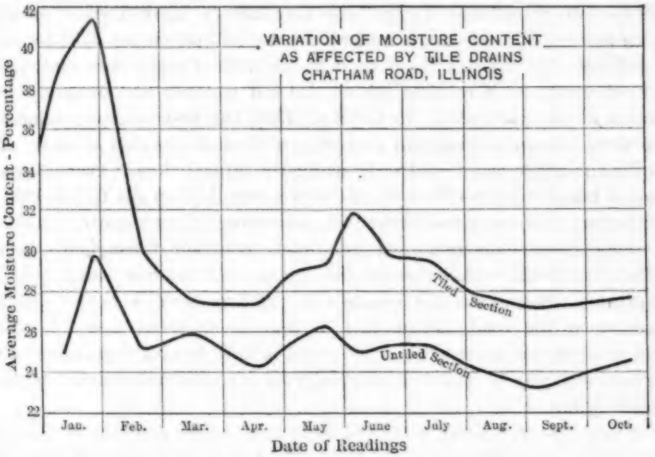


FIG. 12.

Under each edge of a 200-ft. section of the Bates Road was laid a tile drain 24 in. below the sub-grade, the trench back-filled with cinders, and a free outlet provided for the tile. Moisture samples were taken from the underlying soil at various points throughout this 200-ft. section, and likewise from the adjacent undrained slabs. During a period of three years, no measurable difference in the moisture content of the sub-grade at these points has been observed. At another place, on the "Chatham Road", where clay of a different character is found, tile drains were laid 42 in. under each edge of the pavement for a distance of 1 000 ft., the trenches back-filled with cinders, and similar extended observations were made, with results as shown on Fig. 12. No attempt is made to explain why the soil underneath the section provided with tile drains has throughout the entire period contained more moisture than that under the adjacent pavement. Judging from these two examples in which tile drains were of absolutely no apparent value, it is questionable whether such attempts to control moisture are of any merit whatever in clay soils.

It was found that both the brown silt loam of the Bates Road sub-grade and the yellow clay of the "Chatham Road", when they have a moisture content which may be considered normal for the summer months, resist further saturation to a marked degree. Attempts to saturate the soil underneath the Bates Road failed. Water standing at sub-grade elevation for six weeks during the summer months did not cause a perceptible rise in the moisture content of the sub-grade soil at a sampling station 30 in. distant. Tests now under way on thirty samples of clay soils, gathered from different points throughout the State, indicate that this phenomenon in slightly varying degrees probably is common to all.

Another series of experiments indicate that if the moisture content of any of these clay soils is reduced to a point where the soil is dry enough to crumble readily, absorption takes place rapidly, to the point of saturation.

These two properties of clay soils may have a marked effect on the supporting power of the sub-grade under a freshly laid pavement slab; for example, the sections of the Bates Road built in the fall of 1920 were laid on a sun-dried sub-grade, as a rainless period and hot weather had preceded the construction of the pavement. In October, 1920, the first moisture samples were taken from the underlying soil just after a three-day period of rain. At that time the sub-grade was found to be as nearly saturated as it ever became. On the other hand, Sections 64 to 68, inclusive, were laid in the fall of 1922, when the sub-grade soil contained about 25% moisture. The moisture content of the soil under these slabs remained practically constant throughout the winter months of 1922–23 and, although the spring and summer rains were heavy, it continued throughout the summer of 1923 materially below that of the remainder of the road. From this, it may be inferred that for perhaps a period of a year or more after a pavement is laid, the bearing power of a clay sub-grade soil may be affected materially by its moisture content at the time of construction.

Bearing Power.—Many attempts have been made to evaluate the bearing power of the sub-grade soil of the Bates Road, as well as that of other Illinois soils. As narrow rural pavements encourage the passage of highway loads along fairly definite paths, it was thought necessary to determine the relationship between the bearing power of sub-grade soils and repeated loads. An apparatus was devised, by which repeated loads on areas of a few square inches could be made with facility. The use of this apparatus immediately called attention to the excessive depression or permanent deformation caused by the first few applications of load. After several hundred applications, the soils in some cases seemed to become more or less stabilized, and to show decided elastic properties.

Believing that the initial excessive depression might be due to a poor contact between the metal shoe, used for imposing pressures, and the soil, and might also be affected by the small area under pressure, a number of concrete slabs, 3 ft. in diameter, were cast on the sub-grade adjacent to the edge of the Bates Road. It was thought that these slabs would have an initial bearing on the sub-grade soil at least as satisfactory as that of existing pavements. Repeated loads were applied to these slabs. Owing to the cumbersome arrangement of the apparatus used, it was not practicable to make large numbers of repetitions during periods while conditions affecting sub-grade support remained constant. Fig. 13 shows the results for Slab No. 3 of a series of tests which included ten applications of a load of 6 lb. per sq. in. repeated six times with intervening rest periods of 24 hours each. The loads were applied in each case at 15-min. intervals. The moisture content of the sub-grade (26.8%) may be considered normal for this soil during the early fall months. The principal points of interest are: The permanent depression due to the first load applied after each period of rest; the recovery of elevation during the rest periods; the resultant depression at the end of the third day; and the decreased permanent depressions on succeeding days.

Fig. 14 shows the effect of another series of load repetitions. The excessive permanent depression recorded on February 20, 1922, may be accounted for partly by the increased moisture content, but probably was due chiefly to freezing and thawing of the soil. This may be inferred from the fact that excessive depressions were also recorded on March 8, at which time the moisture content was practically the same as on December 1. However, the soil had been frozen and thawed once or twice between February 20 and March 8. All the other slabs used for similar observations behaved in the same manner, but in varying degree. Similar tests now are being made (1923) on thirty different types of Illinois sub-grade soils using an apparatus that will apply a large number of repeated loads at short intervals on areas of approximately 7 sq. ft. The results of these tests are not sufficiently complete to justify definite conclusions. Present indications, however, point to the probability that none of the clay soils exhibits sufficiently uniform elastic properties to justify an assumption of elastic sub-grade supporting power for use in a design formula. It is certain that, for purposes of pavement design, it is not safe to place reliance on a bearing-power test involving only a single application of load.

Effect of Truck Traffic Tests on the Bates Road

The entire Bates Road was laid out on a tangent. The artificial truck traffic consisted of Liberty B trucks driven west along the north side, and east along the south side. Inasmuch as the probability of edge weakness had been established, the east-bound traffic was made to follow a guide line painted on the pavement surface so as to bring the path of the center of the outer rear wheels 6 in. from the pavement edge. The edge of these wheels traveled practically flush with the edge of the pavement on all sections, except those having a macadam base. The west-bound traffic was likewise guided, the path being parallel to and 36 in. from the north edge of the pavement, except on the macadam base sections. On the sections having macadam bases, the wheels of both west-bound and east-bound traffic traveled about 18 in. from the edge of the pavement. The operation of the west-bound traffic was intended to approximate conditions that would normally apply on wide rural pavements and city streets.

In Table 2 will be found details of the wheel loads and the number of round trips for each increment of loading.

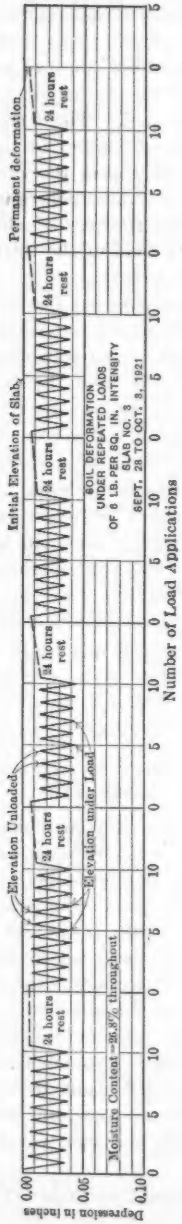

Initial Elevation of Slab
Permanent deformation
Elevation Unloaded
Elevation under Load
24 hours rest
Moisture Content = 26.8% throughout
SOIL DEFORMATION UNDER REPEATED LOADS OF 6 LB. PER SQ. IN. INTENSITY SLAB NO. 3 SEPT. 28 TO OCT. 8, 1921
Depression in inches
Number of Load Applications

FIG. 13.

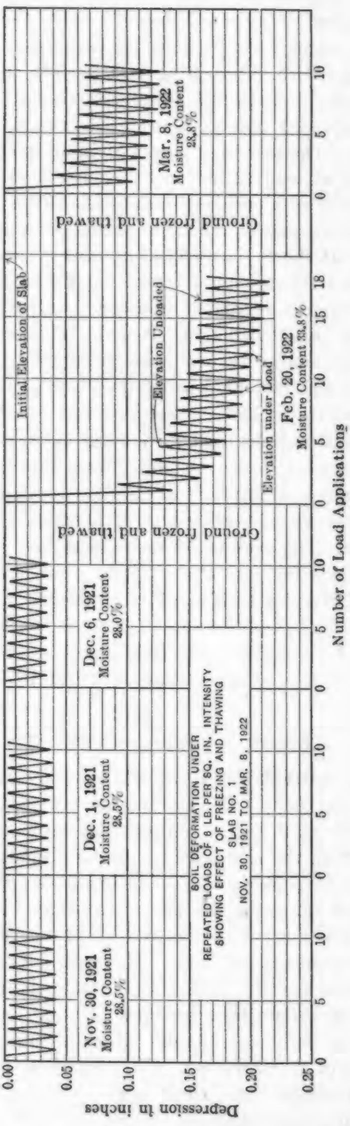

Initial Elevation of Slab
Elevation Unloaded
Elevation under Load
Ground frozen and thawed
Nov. 30, 1921 Moisture Content 28.5%
Dec. 1, 1921 Moisture Content 28.5%
Dec. 6, 1921 Moisture Content 28.0%
Feb. 20, 1922 Moisture Content 33.8%
Mar. 8, 1922 Moisture Content 28.8%
SOIL DEFORMATION UNDER REPEATED LOADS OF 6 LB. PER SQ. IN. INTENSITY SHOWING EFFECT OF FREEZING AND THAWING SLAB NO. 1 NOV. 30, 1921 TO MAR. 8, 1922
Depression in inches
Number of Load Applications

FIG. 14.

An attempt to give complete details of the behavior under truck traffic of each of the sections, or even of each of the groups of sections, would be impracticable. Only the characteristics believed to be of the greatest importance as affecting principles of design will be discussed.

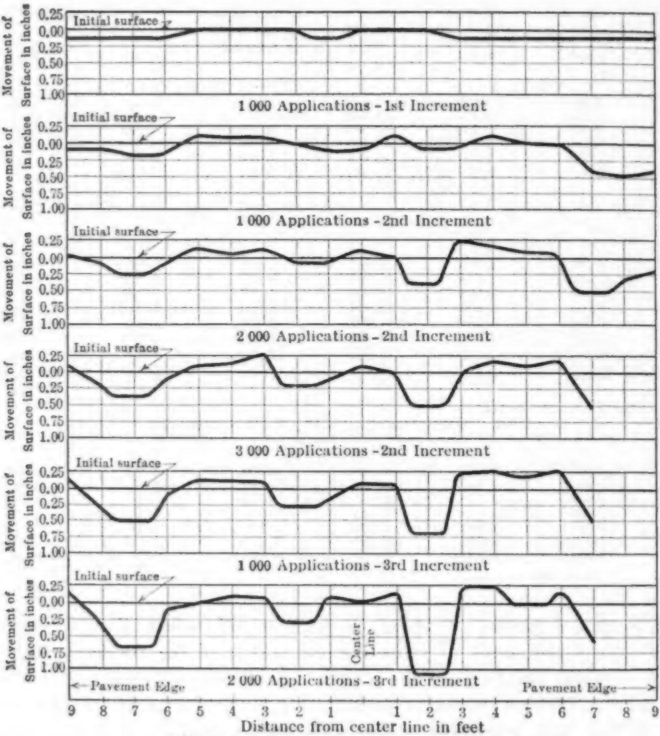
TABLE 2.—DETAILS OF WHEEL LOADS USED AND NUMBER OF ROUND TRIPS FOR EACH INCREMENT OF LOADING.

Increment number.	Load, in pounds, on each rear wheel.	Load, in pounds, on each front wheel.	Gross load.	Net carried or live load, in pounds.	NUMBER OF ROUND TRIPS.	
					Day.	Night.
1922.						
1	2 500	2 250	9 500	....	1 000	....
2	3 500	2 150	11 300	....	2 167	1 033
3	4 500	2 000	13 000	1 700	2 000	1 000
4	5 500	1 900	14 800	3 500	2 000	1 000
5	6 500	1 800	16 600	5 300	2 000	1 000
6	8 000	1 930	19 860	8 560	5 000	5 000
1923.—ORIGINAL SECTIONS (EXCLUDING SECTION 63):						
1	4 500	1 800	12 600	1 300	2 000	1 000
2	6 000	1 600	15 200	3 900	2 000	1 000
3	6 500	1 600	16 200	4 900	2 000	1 000
4	8 000	1 600	19 200	7 900	2 000	1 000
5	9 000	1 700	21 400	10 100	2 000	1 000
6	10 000	2 000	24 000	12 700	2 000	1 000
7	11 000	2 600	27 200	15 900	2 000	1 000
8	12 000	2 600	29 200	17 900	2 000	1 000
9	13 000	2 500	31 000	19 700	2 000	1 000
1923.—NEW SECTIONS (AND INCLUDING SECTION 63):						
1	6 500	1 800	16 600	5 300	2 000	1 000
2	8 750	1 700	20 900	9 600	2 000	1 000
3	8 000	1 600	19 200	7 900	7 000	3 000
4	10 000	2 000	24 000	12 700	2 000	1 000
5	11 000	2 600	27 200	15 900	2 000	1 000
6	12 000	2 600	29 200	17 900	2 000	1 000
7	13 000	2 500	31 000	19 700	2 000	1 000

Brick and Asphaltic Wearing Surfaces on Macadam Base.—Fig. 15 is typical of a large series of cross-sections taken, as the traffic loading progressed, at many points along the macadam base sections having a brick wearing surface. The last cross-section indicates the condition of the test section when failure had progressed to such an extent that the section could no longer be considered as representing a serviceable highway.

Fig. 16 is typical of a large series of macadam base, asphaltic concrete top, cross-sections, illustrating the particular section of this type which proved most satisfactory. Other tests illustrated the fact that an increase of total thickness is not necessarily a direct measure of serviceability under truck traffic.

General Results of Tests on Macadam Base Sections.—In general, the failure of all macadam base sections took the form of rutting along the wheel paths (Fig. 11). In the better sections having an asphaltic concrete top, the serious ruts were not always continuous, but sometimes took the form of elongated depressions. The full series of cross-sections indicates the probability that, during the test, the entire surface may have changed in elevation due to a general swelling or shrinking of the sub-grade. The fact that the subgrade soil in the wheel paths sometimes flowed horizontally, causing bulging between wheel paths, is evident. The entire series of cross-sections also shows that a progressive permanent depression of the sub-grade occurred along the wheel paths of all sections.



CROSS SECTION SHOWING PROGRESSIVE FAILURE

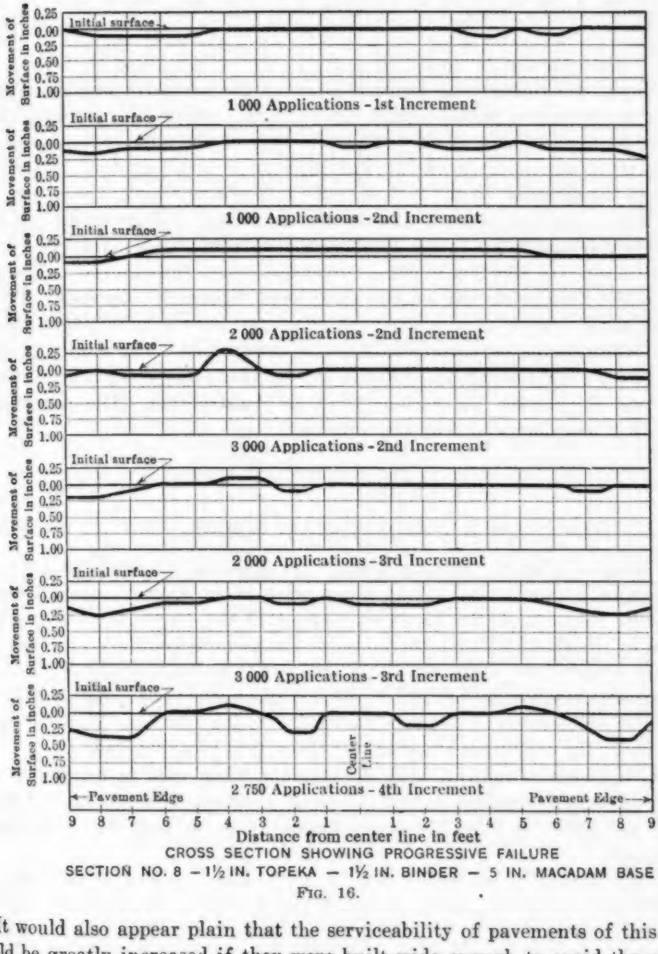
SECTION NO. 5 — 3 IN. LUGLESS BRICK — 2 IN. MASTIC CUSHION

8 IN. MACADAM BASE

FIG. 15.

It seems justifiable to conclude that none of the surfaces reduced the pressure transmitted to the sub-grade sufficiently to render harmless the progressive depression or flow of the sub-grade soil under the loads applied.

It is worthy of note that the traffic was purposely confined to well defined paths. Experience indicates that on rural pavements of the common width used for a double line of traffic and where the traffic is sufficiently continuous to cause vehicles to keep habitually to one side of the road, fairly definite lanes inevitably will be followed. Evidently, in pavements of this type, it is necessary to use thicknesses or other factors of design adapted to reduce the pressure on the sub-grade soil to that which it will bear without material permanent displacement.



CROSS SECTION SHOWING PROGRESSIVE FAILURE

SECTION NO. 8 — 1½ IN. TOPEKA — 1½ IN. BINDER — 5 IN. MACADAM BASE

FIG. 16.

It would also appear plain that the serviceability of pavements of this type would be greatly increased if they were built wide enough to avoid the necessity of vehicles following definite wheel paths. Under conditions favoring the spreading of traffic, a depression caused by one load would be filled sooner or later by the flow of soil from an adjacent wheel path.

Pressure-cell readings under the section having a 10-in. macadam base and 2-in. Topeka top are of decided interest. A 4-ton wheel load standing over a pressure cell of this section before the truck traffic was started resulted in a pressure of about 12 lb. per sq. in. After 1 000 round trips had been made by the trucks, the reading had increased to about 26 lb. per sq. in. Apparently. vibration caused by the traffic had loosened the mechanical bond originally secured by rolling the foundation courses. The suggestion is made that a bituminous binder would help to counteract this effect.

Asphaltic Concrete Top on Concrete Base.—Almost invariably failures of this type started by breaking a small corner involving an area of only 2 or 3 sq. ft. Subsequent loads, because of the excessive bearing pressure, caused a depression of the broken corner. This resulted in excessive impact on the depressed corner itself and on the edge of the adjacent unbroken slab as the truck wheels mounted it. The progressive breaking down of the pavement in the direction of the flow of traffic followed as a logical sequence. Disintegration often occurred in the reverse direction. All sections of this type were provided with an integral concrete curb equal to the thickness of the asphaltic top. In addition to corner breakage, cracks through the curb, extending to the bottom surface of the slab, were frequently observed. Whether or not these curb cracks represented transverse cracks extending across the entire width of the pavement could not be determined. The plotted points in Fig. 17 (*a*) show the relation between the loads causing critical corner breaks and base thicknesses for various types of construction. The curve passes through points determined by the formula:

$$d = \sqrt{\frac{3\ W}{S}},\ \text{or}\ W = \frac{1}{3}\ S\ d^2.$$

This formula is evolved from the well known equation, $S = \frac{M\,c}{I}$, the assumptions being as follows: That the load, W, is applied at the extreme point of a right-angled corner formed by the intersection of an open transverse crack or joint with the edge of the pavement slab; that the corner is entirely unsupported by the sub-grade and, therefore, acts as a simple cantilever; and that fiber stresses are uniform on any section normal to a line bi-secting the corner angle. The average modulus of rupture of the test specimens corresponding with that particular concrete slab being substituted for S, the value of W should represent, under the conditions assumed, the theoretical breaking load.

These diagrams indicate that the formula, when used in connection with the design of rigid pavement slabs of fairly constant cross-section and having no special provision for edge strengthening, may be used with considerable confidence.

It was distinctly noticeable that, in all paving sections of this type, the initial corner break was not immediately followed by rapid progressive destruction. No doubt, this may be attributed to the fact that the asphaltic concrete top by its cohesion and ability to diminish the abruptness of the depression helped materially to reduce excessive impact.

Brick Surfacing with Bituminous Joint Filler on Concrete Base.—The failure of sections of this type was of much the same character as in the group of sections having an asphaltic concrete top on a concrete base. Failure always started at a south side corner. Progressive failure after the initial corner break, however, was more rapid. These sections were provided with an integral curb having a depth equal to the combined thickness of the brick surfacing and the sand cushion. The thickness used in plotting Fig. 17 (*b*) does not take into account the presence of the curb.

Monolithic Brick.—The term monolithic brick is applied to all sections having a brick surface laid on a fresh concrete base, the cement grout joint filler being poured in as far as possible before the base concrete had attained initial set. In Fig. 17 (*c*), the plotted points show the wheel loads causing the initial serious corner failure of all sections of this type, the abscissas in this case being the total thickness of the pavement. In a true monolith, the total thickness should be a measure of strength. Inasmuch as failure was caused in all cases by loads much less than those which might be expected, a consideration of the actual behavior of these sections is of interest. At many points along the edges and adjacent to all corners, it was observed that, under load, the brick surfacing became distinctly separated from the concrete base. This seemed to indicate that the pavement was acting as two separate slabs rather than as a monolith. In Fig. 17 (*d*), abscissas were used which represent the thickness of a concrete slab computed as having transverse strength equal to the transverse strength of two superimposed independent slabs, each assumed to have a modulus of rupture equal to that of the test specimens cast at the time the base was poured and a thickness equal to that of the top and base courses. It is noticeable that by the use of this method for computing breaking loads, a reasonable agreement between the actual and theoretical failures obtains.

Concrete Sections.—In Fig. 17 (*e*), the plotted points show the loads causing critical corner failure in all plain concrete sections, and in sections considered as equivalent to plain concrete. These points include two sections of plain concrete, to which had been added 10% of hydrated lime; and two sections containing 42-lb. wire mesh placed at about the neutral axis. Considering the quantity and location of the steel in these sections, it would afford little, if any, relief of tensile stresses in the concrete.

In Fig. 17 (*f*) are shown the loads causing critical corner failure in all concrete sections which were provided with transverse joints spaced at 25-ft. intervals. These joints were formed by ordinary corrugated metal sheets placed on edge, the corrugations running horizontally. The concrete was poured against these metal sheets, no provision being made for expansion. This construction merely resulted in a transverse crack having a corrugated cross-section. The inclusion of these test sections was based on the assumption that possible intermediate transverse cracks would not be formed; that contraction would occur only at the joints; and that, because of the corrugations, more or less mutual support would be afforded by adjacent slabs, thus making corner failure less probable. All the plotted points in this diagram represent sections in which ¾-in. steel marginal bars were used. The position of the plotted points indicates that the presence of the transverse corrugated joints had little effect in increasing resistance to structural failure.

It is worthy of note that two plain concrete sections, divided also by transverse joints of the same type and spacing, but having no marginal reinforcing bars, withstood the entire traffic tests without failure although the thickness was 7 in. and 8 in., respectively. From this, it may be inferred that the use of marginal steel was also of doubtful value.

In Fig. 17 (g), the plotted points represent the loads causing critical corner failures in all sections of rigid type. These points were plotted in the same position relative to the curve determined by the formula, $D = \sqrt{\frac{3\,W}{S}}$ (using for S the average modulus of rupture of all test specimens), as they appear in Fig. 17 (a) to (e). In this diagram, attention is called to the grouping of the plotted points about the curve representing the theoretical breaking load as determined by the formula given. It will be noted that the lower curve, in which 50% of the modulus of rupture was used, gives safe values for all cases causing critical failure.

The grouping of the points about the theoretical breaking load curve indicates also that fatigue effect was not a predominant cause of failure in this test. To have operated the trucks a sufficient number of times and with sufficiently small increases in load to bring out the fatigue effect, would have been an endless task. The increments of load were no doubt great enough in most cases to increase the fiber stress from that which would be safe, as far as fatigue is concerned, to a figure which would result in breakage under comparatively few repetitions of load. (See Figs. 18, 19, and 20.)

Concrete Sections Having Strengthened Edges

As previously indicated, Sections 1 to 63, inclusive, were completed in the spring of 1921, and the traffic tests started in 1922. On the completion of the traffic runs of 1922, it was evident that a further modification of design would result in both increased service and economy of construction. The weakness along the edge, so apparent, suggested the necessity for a radical strengthening at that point in order that the pavement might offer a more uniform resistance to fracture. The 1922 traffic runs showed that Section 63, having the longitudinal edge-bar and doweled tongue-and-groove center joint, would be likely under further loading to show indications of edge weakness, inasmuch as after the passage of many loads along the south edge the deflection of adjacent corners was not equal when wheel loads approached and passed the joint. This was interpreted as an evidence of failure of the concrete above and below the side bar due to excessive bearing pressures. It also seemed clear that, even assuming a perfect transfer of shear across transverse cracks at corners, the corner or edge strength would still be less than that of the mid-portion of the slab.

New Designs and Tests.—Consequently, in the fall of 1922, an extension of about 350 ft. (called Section 64), was added to Section 63, and four additional sections were built, each about 350 ft. long. In each of these four sections, the edge thickness was increased to 9 in., tapering to the thickness of the mid-portion at a distance of 2 ft. from the edge; the same type of center

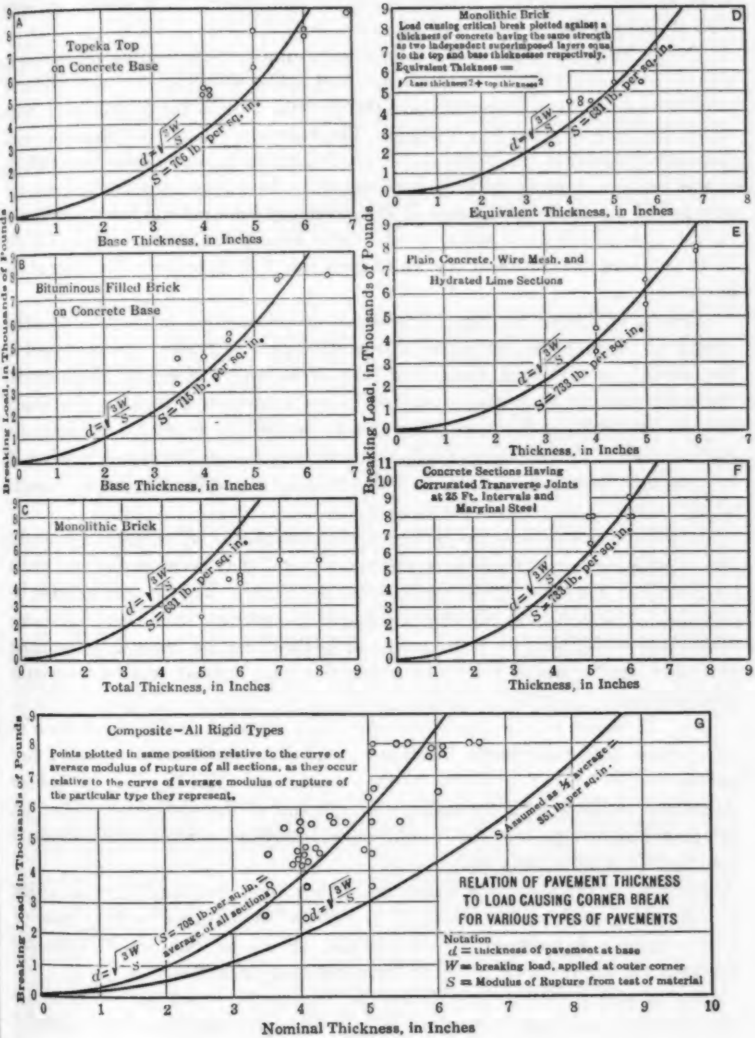

A
Topeka Top
on Concrete Base
S = 706 lb. per sq. in.
Base Thickness, in Inches
B
Bituminous Filled Brick
on Concrete Base
S = 715 lb. per sq. in.
Base Thickness, in Inches
C
Monolithic Brick
S = 631 lb. per sq. in.
Total Thickness, in Inches
D
Monolithic Brick
Load causing critical break plotted against a thickness of concrete having the same strength as two independent superimposed layers equal to the top and base thicknesses respectively.
Equivalent Thickness =
S = 631 lb. per sq. in.
Equivalent Thickness, in Inches
E
Plain Concrete, Wire Mesh, and
Hydrated Lime Sections
S = 733 lb. per sq. in.
Thickness, in Inches
F
Concrete Sections Having
Corrugated Transverse Joints
at 25 Ft. Intervals and
Marginal Steel
S = 733 lb. per sq. in.
Thickness, in Inches
Breaking Load, in Thousands of Pounds
G
Composite - All Rigid Types
Points plotted in same position relative to the curve of average modulus of rupture of all sections, as they occur relative to the curve of average modulus of rupture of the particular type they represent.
(S = 708 lb. per sq. in. = average of all sections)
S Assumed as ½ average = 351 lb. per sq. in.
RELATION OF PAVEMENT THICKNESS
TO LOAD CAUSING CORNER BREAK
FOR VARIOUS TYPES OF PAVEMENTS
Notation
d = thickness of pavement at base
W = breaking load, applied at outer corner
S = Modulus of Rupture from test of material
Breaking Load, in Thousands of Pounds
Nominal Thickness, in Inches

FIG. 17.

joint and the same arrangement of embedded steel was used as in Sections 63 and 64. In two of the slabs, the mid-thickness was made 6 in., one of these slabs being 20 ft. wide instead of the standard 18 ft. One 20-ft. slab was provided with a mid-portion thickness of 5 in.; and one of 18-ft. width was built with a mid-portion thickness of 4½ in.

In the spring of 1923, traffic tests were resumed. The loading on these sections started with 6 500 lb. on each rear wheel, under which condition 3 000 round trips were made, then increasing to 8 000 lb.—the Illinois legal load limit—with which 10 000 round trips were made. The rear wheel load was then increased successively to 8 750 lb., 10 000 lb., 11 000 lb., 12 000 lb., and 13 000 lb., and 3 000 round trips were made with each increment. As in previous traffic runs, the wheel path along the south side of the pavement imposed the loads practically on the edge of all these slabs, except those having the 20-ft. width. On the 20-ft. sections, the center of the wheel path was 1 ft. 6 in. from the edge of the pavement.

Results of Tests.—In Fig. 21 is shown a cross-section of Section 64 and a record of the damage caused to this section by the traffic. In this, and in the succeeding diagrams, the dotted lines show contraction and check cracks, the solid straight lines show longitudinal and transverse construction joints, and the irregular solid lines show cracks caused by traffic. Obviously, the corner break at *A* was due to faulty construction, the double corner break at *B*, to a normal structural failure, and the transverse cracks lettered *C* to traffic rather than to temperature contraction.

It will be noted that the broken corners at *A* and *B* withstood extensive heavy traffic before they became pulverized, and that even at the end of the test they had not suffered serious progressive failure. This is attributed to the fact that the continuous edge-bar prevented the corners from becoming immediately depressed, thus relieving temporarily the excessive impact, which, under prolonged traffic, would no doubt eventually have caused serious progressive destruction.

Fig. 22 shows in the same way the effect of truck traffic on Section 65. The letters, *AA,* indicate the location of very short cracks that appeared early but showed no extension as the loading continued. The letters, *BB,* indicate transverse cracks caused by traffic. At the end of the tests, this section was not damaged in any way that would cause interference with traffic service or increase the maintenance cost.

Section 65 withstood the traffic test better than Section 64, as no failure of the nature indicated at Point *B* in Section 64 occurred to jeopardize the service value. A pavement of the design shown by Section 65 represents 195.5 cu. yd. less concrete per mile than that of Section 64.

Fig. 23 shows similar information for Section 66, which has the same type of cross-section as Section 65, the width, however, being 20 ft. The number of cubic yards of concrete per mile is the same as for Section 64. A considerable number of shrinkage or check cracks appeared in this section immediately after the slab was laid and before traffic loading was started. Most of these cracks were only discernible on very careful inspection. A short longi-

FIG. 18.—TYPICAL CORNER BREAK IN A CONCRETE SECTION.

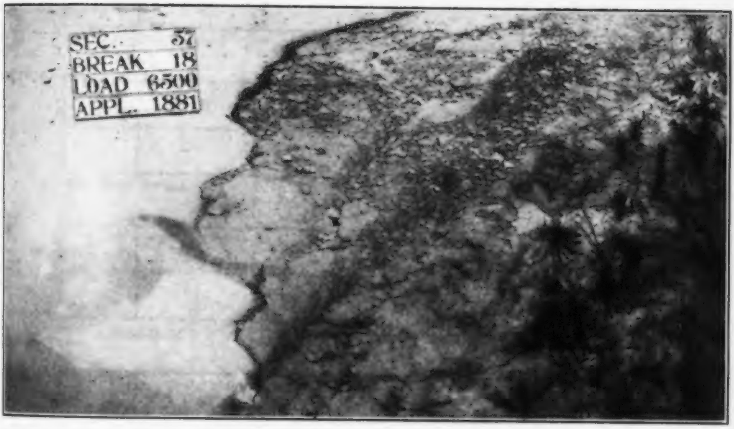


FIG. 19.—EARLY STAGES OF PROGRESSIVE DESTRUCTION FOLLOWING CORNER BREAK.

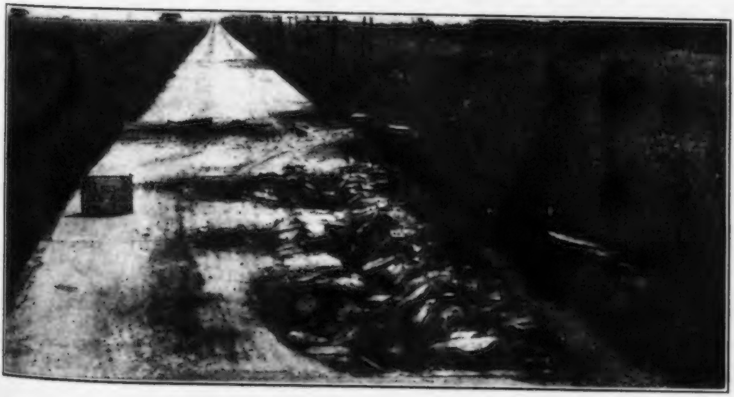
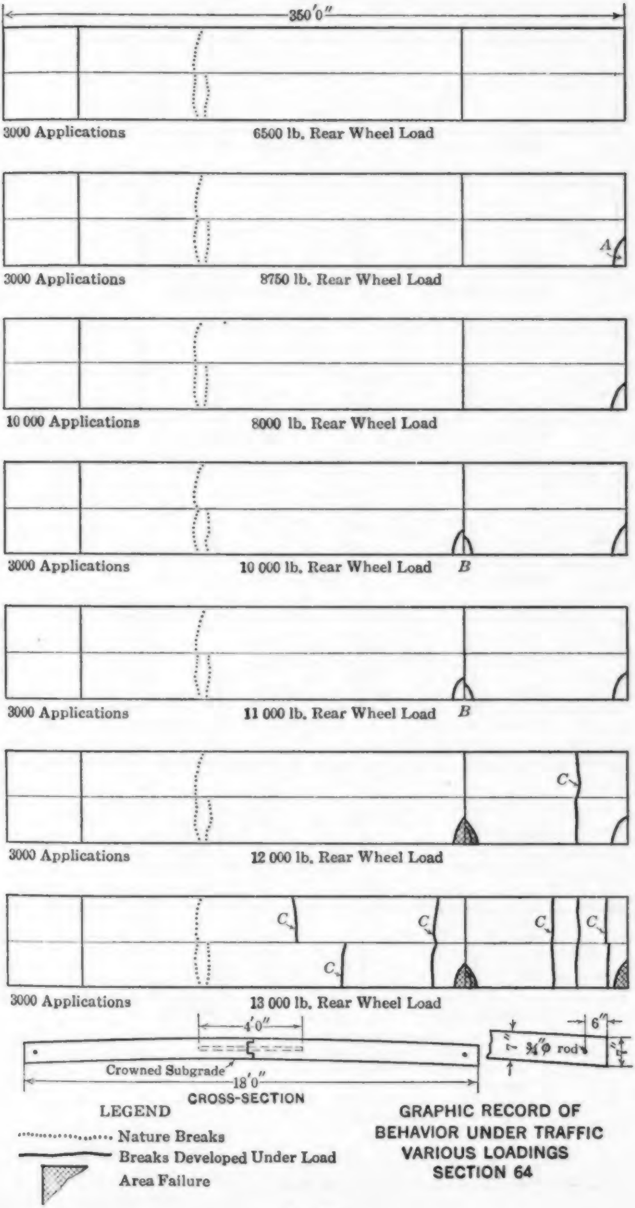


FIG. 20.—ADVANCE PROGRESSIVE DESTRUCTION.



350′0″
3000 Applications
6500 lb. Rear Wheel Load
A
3000 Applications
8750 lb. Rear Wheel Load
10 000 Applications
8000 lb. Rear Wheel Load
3000 Applications
10 000 lb. Rear Wheel Load
B
3000 Applications
11 000 lb. Rear Wheel Load
B
C
3000 Applications
12 000 lb. Rear Wheel Load
C
C
C
C
C
3000 Applications
13 000 lb. Rear Wheel Load
4′0″
Crowned Subgrade
18′0″
CROSS-SECTION
6″
3/4″ φ rod
LEGEND
Nature Breaks
Breaks Developed Under Load
Area Failure
GRAPHIC RECORD OF
BEHAVIOR UNDER TRAFFIC
VARIOUS LOADINGS
SECTION 64

FIG. 21.

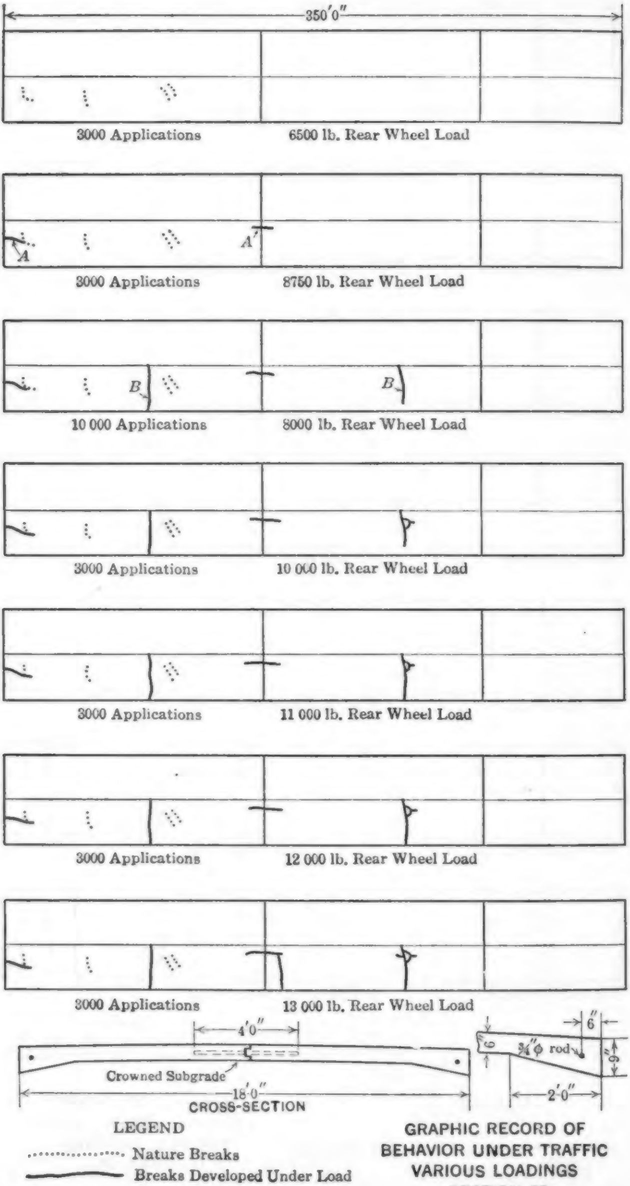
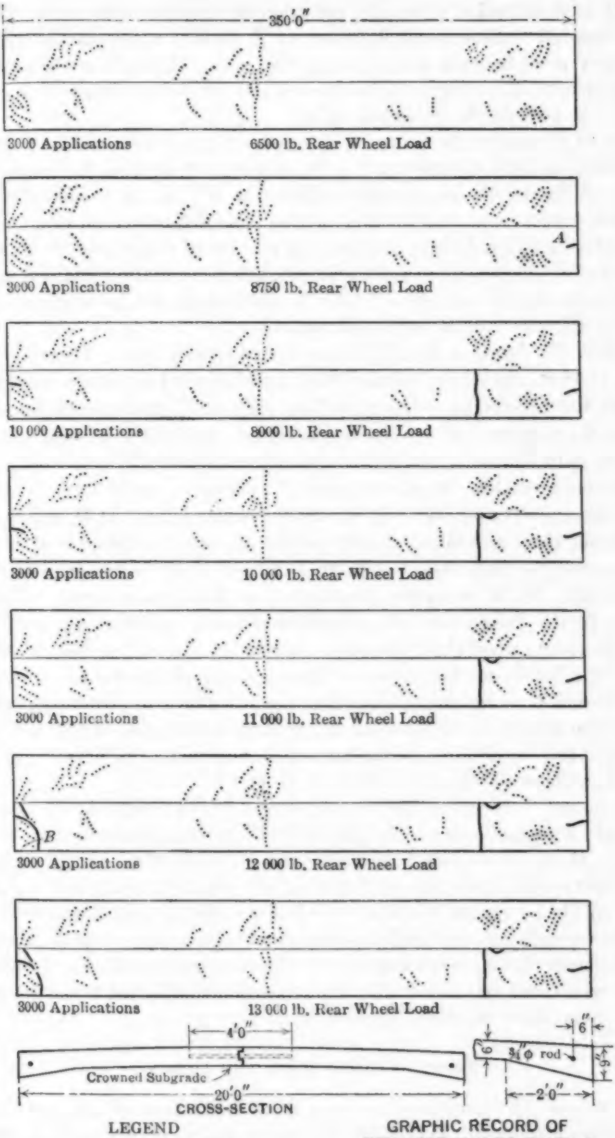

350'0"
A
A'
3000 Applications
6500 lb. Rear Wheel Load
3000 Applications
8750 lb. Rear Wheel Load
B
B
10 000 Applications
8000 lb. Rear Wheel Load
3000 Applications
10 000 lb. Rear Wheel Load
3000 Applications
11 000 lb. Rear Wheel Load
3000 Applications
12 000 lb. Rear Wheel Load
3000 Applications
13 000 lb. Rear Wheel Load
4'0"
Crowned Subgrade
18'0"
CROSS-SECTION
6"
¾" φ rod
9"
2'0"
LEGEND
Nature Breaks
Breaks Developed Under Load
GRAPHIC RECORD OF
BEHAVIOR UNDER TRAFFIC
VARIOUS LOADINGS
SECTION 65

FIG. 22.



LEGEND
.... Nature Breaks
———— Breaks Developed Under Load

GRAPHIC RECORD OF BEHAVIOR UNDER TRAFFIC VARIOUS LOADINGS SECTION 66

FIG. 23.

tudinal crack started at *A*, but did not progress throughout the test. The somewhat diagonal transverse crack shown at *B* did not result in the destruction of the pavement between the crack and the end of the section, the area of this part evidently not being sufficiently small to cause an abnormal increase of bearing pressure on the sub-grade soil.

Fig. 24 illustrates the behavior of Section 67, having a width of 20 ft. and edge thickness of 9 in. tapering to 5 in. at a point 2 ft. from the edge, the mid-portion of the slab having a uniform thickness of 5 in. A considerable number of check cracks appeared in this section also. A short longitudinal crack appeared at *A* which did not progress. A number of transverse cracks appeared under traffic. At the end of the traffic test, this section also remained in perfect condition as far as service to traffic is concerned; and no damage occurred which would cause additional maintenance cost.

Section 68, shown in Fig. 25, is worthy of special note. The width of this section is 18 ft., the edge thickness 9 in. tapering to 4½ in. at a point 2 ft. from the edge, the mid-thickness being uniformly 4½ in. Transverse cracks appeared early in the test run. Short transverse cracks appeared at *B* close to the construction joint, and soon also cracks approximately parallel to the edge, joining the transverse cracks. At *A*, a number of transverse cracks formed, beginning at the edge and running part way toward the center joint. At *D*, and at another point along the south edge, similar cracks appeared. Throughout the traffic test, however, the transverse cracks at *A* did not result in complete destruction of this area. At *B*, complete destruction of the edge occurred, which later resulted in the destruction of a considerable area of the mid-portion of the slab. At points marked, *C*, breakage started in the mid-portion of the slab, and developed to a marked extent. The character of the damage occurring at Points *B* and *C* seems to indicate that the resistance to structural failure of this section was about the same along the edge as throughout the mid-portion. No doubt the longitudinal edge-bar aided materially in preventing earlier destruction along the edges at Points *A*, *B*, and *D*.

It is unfortunate that a larger number of sections designed to develop more completely a proper balance of edge and mid-portion strength were not constructed. By way of contrast with the behavior of Sections 64 to 68, inclusive, that of Section 54 which was subjected only to the 1922 traffic run is shown in Fig. 26, this being typical of all sections lacking effective provisions for increasing edge strength. At the end of 3 000 round trips of the 5 500-lb. wheel load, distinct corner breaks appeared at *A*. These corners pulverized under the 6 500-lb. wheel load and progressive disintegration rapidly led to the destruction of the section under the 8 000-lb. wheel load.

Notes on Rigid Pavement Design

Dimensions.—No mention has been made heretofore of the fact that the wheel loads on the north half of the pavement, traveling at a uniform distance of 36 in. from the edge of the slab, caused practically no damage to any of the test sections, although the inner wheels traveled immediately adjacent to the center joint where such joint existed.

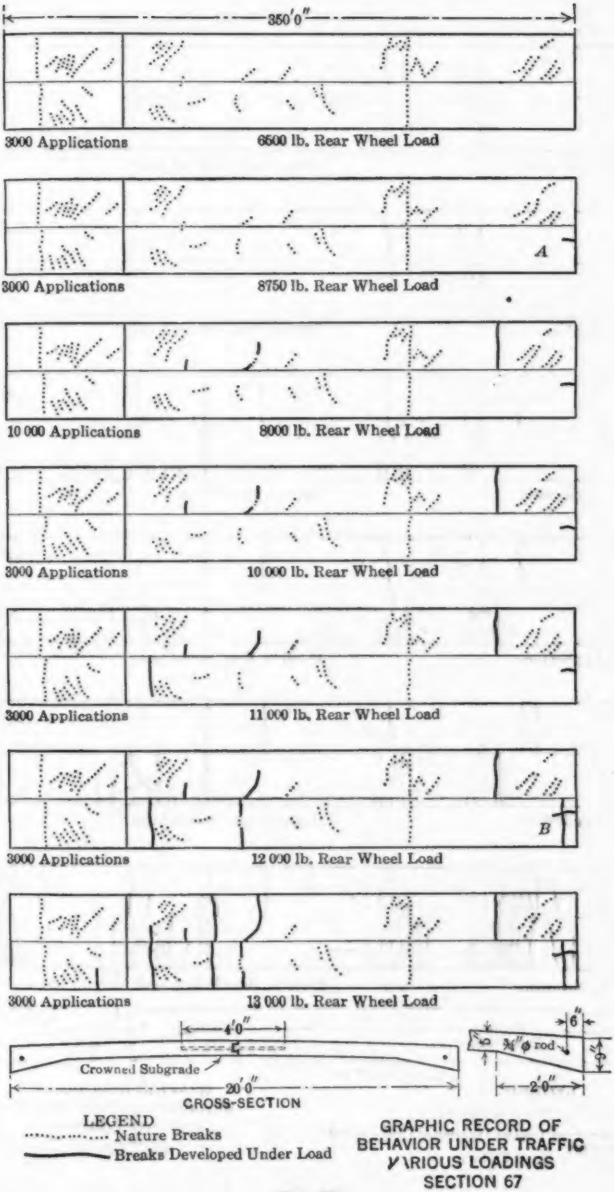

350' 0"
3000 Applications
6500 lb. Rear Wheel Load
A
3000 Applications
8750 lb. Rear Wheel Load
10 000 Applications
8000 lb. Rear Wheel Load
3000 Applications
10 000 lb. Rear Wheel Load
3000 Applications
11 000 lb. Rear Wheel Load
B
3000 Applications
12 000 lb. Rear Wheel Load
3000 Applications
13 000 lb. Rear Wheel Load
4' 0"
Crowned Subgrade
20' 0"
CROSS-SECTION
6"
¾" φ rod
2' 0"
LEGEND
Nature Breaks
Breaks Developed Under Load
GRAPHIC RECORD OF
BEHAVIOR UNDER TRAFFIC
VARIOUS LOADINGS
SECTION 67

Fig. 24.

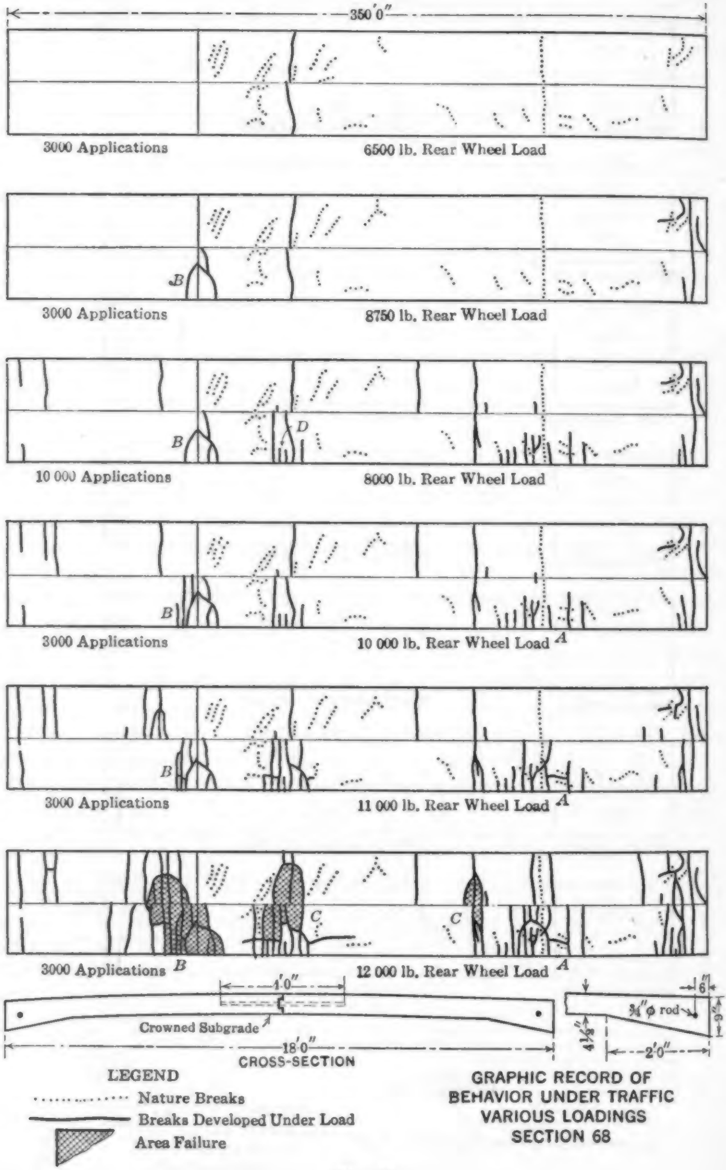

350' 0"
3000 Applications
6500 lb. Rear Wheel Load
B
3000 Applications
8750 lb. Rear Wheel Load
B
D
10 000 Applications
8000 lb. Rear Wheel Load
B
3000 Applications
10 000 lb. Rear Wheel Load A
B
3000 Applications
11 000 lb. Rear Wheel Load A
C
C
3000 Applications B
12 000 lb. Rear Wheel Load A
1' 0"
Crowned Subgrade
18' 0"
CROSS-SECTION
6"
¾" φ rod
9"
4½"
2' 0"
LEGEND
Nature Breaks
Breaks Developed Under Load
Area Failure
GRAPHIC RECORD OF
BEHAVIOR UNDER TRAFFIC
VARIOUS LOADINGS
SECTION 68

FIG. 25.

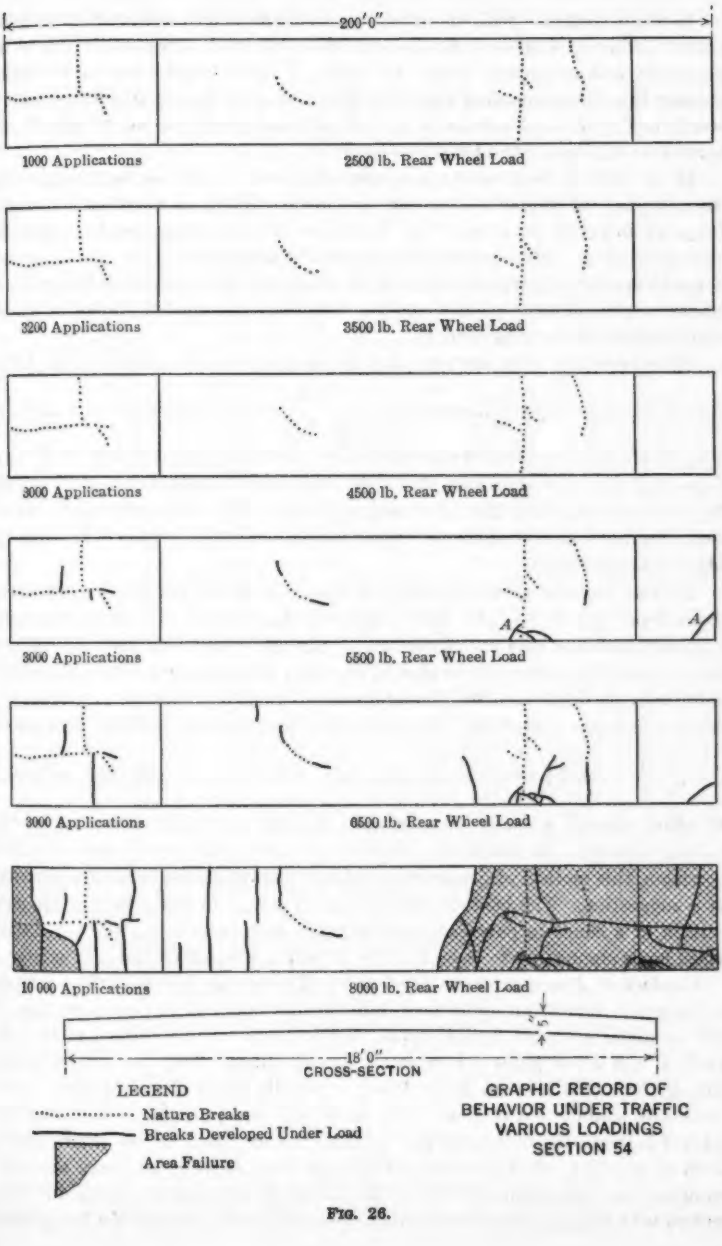

200′0″
1000 Applications
2500 lb. Rear Wheel Load
3200 Applications
3500 lb. Rear Wheel Load
3000 Applications
4500 lb. Rear Wheel Load
A
A
3000 Applications
5500 lb. Rear Wheel Load
3000 Applications
6500 lb. Rear Wheel Load
10 000 Applications
8000 lb. Rear Wheel Load
18′0″
CROSS-SECTION
LEGEND
Nature Breaks
Breaks Developed Under Load
Area Failure
GRAPHIC RECORD OF
BEHAVIOR UNDER TRAFFIC
VARIOUS LOADINGS
SECTION 54

FIG. 26.

In rigid sections (with the exception of Section 68), where eventually the entire width was destroyed, the damage always started at the south edge of the pavement and progressed across the slab. This fact indicates in a striking manner that if unsupported edges can be avoided, or if such edges are properly strengthened, the mid-portion of paving slabs may safely be built thinner than heretofore has been considered necessary.

It is believed that local sub-grade weaknesses, such as settlements and irregularities of supporting power, are always likely to exist at sufficiently frequent intervals to permit the formation of transverse cracks unless the joint spacing is made considerably less than in present practice. If this is true, it would appear that exposed edges of all pavement slabs should be thickened, or otherwise continuously strengthened, so that the occurrence of transverse cracks would not result in weak corners.

Self-supporting edge corners may be insured by proportioning the thickness of slab edges by the formula, $d = \sqrt{\frac{3W}{S}}$, in which the value of S should be not greater than one-half of the modulus of rupture of the concrete used. It is suggested that this thickness should be maintained for a distance of at least 2 ft. from the edge and then decreased in another 2 ft. to the mid-portion thickness, inasmuch as initial corner breaks rarely extend more than 2 ft. from the edge of the pavement.

No very definite conclusions may be drawn as to the necessary thickness of the mid-portion of the slab. It is suggested that inasmuch as deflection measurements indicate that the deflection of the mid-portion of slabs of uniform thickness is about one-third of that at the edge, the mid-portion thickness might tentatively be made such that the transverse strength calculated as a beam will be one-third that of the edge. A mid-portion thickness obtained by the formula, $d = \sqrt{\frac{W}{S}}$, would provide a mid-thickness corresponding with that of Section 68 which showed a fairly even balance of edge and mid-portion traffic supporting capacity. As the design of this one section only conformed with this provision, this method of determining mid-portion thickness is advanced merely as a suggestion. The behavior of Section 67 seems to indicate that the mid-portion of a concrete pavement may be made as thin as 5 in., and yet sustain wheel loads amounting to at least 8 000 lb. with a reasonable factor of safety.

Contact of Pavement and Sub-Grade.—The special investigations relating to sub-grade depression under load indicate that under rigid pavement slabs, as well as under so-called flexible types, distinct ruts may be formed in the sub-grade if the wheel paths follow fairly definite lines. This was shown clearly during the traffic tests on Bates Road, especially along the south edge, where numerous shallow excavations were made for the purpose of observing the contact between the bottom of the slab and the sub-grade as the trucks passed. Even at mid-day, when the edges of the slab were warped downward the maximum amount, the bottom surface of the slab at the edge never appeared to be in contact with the sub-grade except when deflected by the passing of a heavy wheel load. At night, this condition was pronounced. A similar state of affairs in all probability existed under the wheel path on the north side, although this could not be easily observed.

Moisture.—Many clay soils when dry, readily take up sufficient moisture to cause a high degree of saturation, but absorb water slowly when moist; hence, sub-grades of dry clay should be moistened to a considerable depth by sprinkling before a pavement is laid. If the construction is on a dry clay soil, excessive saturation and minimum bearing values may occur before the concrete has attained normal strength.

Edges and Joints.—A longitudinal tongue-and groove-doweled center joint in an 18-ft. pavement is apparently effective in preventing longitudinal cracks as well as in reducing temperature warping. During the past three years, about 1 500 miles of Illinois rural pavements have been built with this type of center joint, and no longitudinal cracks have appeared to date. The corners formed at the intersection of transverse joints or cracks with the center joint did not appear to be points of weakness in the Bates Road. This was no doubt due chiefly to the effectiveness of the tongue-and-groove joint in transmitting by shear one-half of the loads to the adjacent slab.

Longitudinal contraction in cold weather must always result in open transverse cracks or joints in rigid pavements, even when using a wearing surface other than concrete. Edge corners, therefore, must either be effectively doweled or be made self-supporting. Dowel bars, to be of value, should be continuous in order to provide for corners formed by unexpected transverse cracks and should have sufficient bearing area to minimize bearing pressures on the concrete immediately adjacent to cracks and joints.

Asphaltic concrete surfaces and bituminous filled brick surfaces apparently do not add materially to the strength of the base, but by lessening excessive impact at small broken corners, they give considerably increased resistance to progressive destruction.

Continuous longitudinal shear bars along the edges of concrete slabs aid materially in the mutual support of the adjacent edge corners for a more or less prolonged period, depending on the volume of traffic, and, in addition, are of marked advantage in preventing rapid progressive destruction in case corner breaks do occur.

Any design in which reinforcing steel is expected to relieve the concrete of all tensile stresses should take into account the possible formation of corners at any point along the edge of the slab.

Impact.—An examination of Fig. 17 indicates, by the relative position of the points representing initial structural failure and the breaking load curves based on static loads, that, in the test road, either impact was not an important factor in causing initial failure, or the increase of stress due to impact was very closely counterbalanced by some other factor. These diagrams also show that, in all probability, the strength of pavement slabs in service varies as the square of the thickness. Impact stresses are presumably directly in proportion to the thickness. If, therefore, impact was an important factor, the plotted points in the diagrams mentioned should fall at least approximately along a straight line passing through the zero point.

These considerations, strengthened by the impact deflection investigations previously described, lead to the belief that no allowance for impact need be made in the design of a pavement the nature of which makes practicable the construction and maintenance of a reasonably smooth surface.

Future Research.—The development of instruments suitable for determining fiber deformations in the surface of the pavement under traffic would aid greatly in a better understanding of stress distribution as well as magnitude. Progress in the design of such a device is being made by the U. S. Bureau of Public Roads. The development and use of this sort of instrument is exceptionally difficult, owing to the fact that the gauge length must be short, the observations taken under rapidly moving wheel loads, and deformations of less than 0.001 in. recorded with accuracy.

In view of the vast expenditures annually being made for paved roads, the lack of more complete scientific knowledge of pavement design is a challenge to engineers which should be answered as soon as possible by intense research activity.

DISCUSSION

H. F. CLEMMER,* Assoc. M. Am. Soc. C. E. (by letter).—The author is to be commended on the remarkably clear manner in which he has reviewed the mass of data that has been assembled in the several investigations conducted by the Illinois Division of Highways. The very practical interpretation of the results of the Bates Road tests has effected considerable saving in highway construction costs throughout the country.

The following is offered, not as a discussion of the material contained in Mr. Older's paper, but rather as additional information concerning a few of the investigations described.

Impact.—The author states that at the time of this investigation no suitable instrument could be found for determining the fiber deformation in the upper face of a concrete slab under moving load. Since then a strain gauge has been developed which may be able to measure the stress developed under static loads but which is not presumably reliable under moving loads, due to the overthrow, from inertia, of the recording arm.

It is an ascertained fact that when a concrete beam is in the form of a cantilever, its deflection varies directly as the load and therefore is a measure of the strength. This deflection under static load has been shown by Mr. Older to have a curve of the same radius as that under impact loading and is without doubt a true measure of the effect of impact loading.

Warping Due to Temperature Changes.—The use of the longitudinal center joint to relieve the warping action has unquestionably proven satisfactory, reducing it by one-half. It has not been considered that this warping action caused definite stress. However, recent investigation in the laboratory indicates rather conclusively that temperature differences in concrete do create stress. Considerable further scientific research will be required to determine the effect and magnitude of this stress, if such a stress is created. The Illinois Division of Highways is at present conducting laboratory investigations on the effect of temperature changes on concrete but sufficient data have not been assembled to give a conclusive statement.

Longitudinal Bar Along Edge of the Slab.—Recent tests made to determine the value of the ¾-in. longitudinal bar show that, in the case of temperature cracks, 33 to 46% of the load is carried from one corner to the adjacent corner while at construction joints only 6 to 8% is likewise transferred. During low temperature, natural cracks do not open to the same extent as construction joints. From this, it would seem advisable to increase the resistance to shearing action at construction joints.

Fatigue.—The term "fatigue" is accurate, as concrete beams, under repeated load and subsequent to failure, show an increase in deflection and a lack of complete recovery with each load application—a "tiring out". It is interesting to note in this study that the repeated application of a load less than 50% of the modulus of rupture increases the strength of the concrete at the stressed section. In other words, maximum traffic does not injure or wear out a pave-

* Engr. of Materials, Illinois Highway Div., Springfield, Ill.

ment provided the loads are within the so-called endurance limit of the concrete.

Sub-Grade Soil Investigation.—The author's statement that Illinois soils having a moisture content which may be considered normal for the summer months resist further saturation to a marked degree, has been definitely checked. It has been further established that the bearing value of a soil varies with its moisture content. Several experiments are now being carried on by the Illinois Division of Highways to determine the method and extent of treatment necessary to obtain the optimum moisture for a soil. It has been necessary to develop tests such as mechanical analysis, slaking value, and constancy of volume. Considerable data have been obtained on the bearing power of soils having various characteristics, and it is believed that means may be found for the treatment of a sub-grade so as properly to proportion the elements of the soil—sand, clay, and gravel—to control the moisture content and thereby to create a definite bearing power for that soil.

The prime development from "Highway Research in Illinois" that has been checked and proven practical for use is the formula, $d = \frac{\sqrt{3W}}{S}$. Concrete roads designed under this formula and on which traffic loads are properly controlled will last indefinitely.