Concrete Pavement Subbase Study in Ohio

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A 4-mi length of concrete surfaced arterial highway built in 1952 was designed as a test road with subbase treatment and slab length as variables. Subbases included dense-graded and open-textured crushed stone 3, 5, and 8 in. thick; cement-treated clay soil 6 in. thick, and clay soil-cement 3 and 5 in. thick. Slab lengths were 20 ft and 100 ft. Observations on performance of the road were made several times each year for five years. The periodic condition surveys were supplemented by moving load tests to observe differences in deflections and strains in the concrete slabs as related to the controlled variables.

After five years of heavy traffic, it appears that:

1. Test areas with subbases were better in over-all performance than the control areas with no subbase.
2. Open-textured limestone subbases with longitudinal edge drains prevented joint and edge pumping, and were effective in the reduction of edge blowing. Thickness of material made relatively little difference in the over-all performance of the open-textured subbases.
3. Dense-graded limestone subbases restricted joint and edge pumping and edge blowing. In this respect the 5-in. and 8-in. thicknesses were more effective than the 3-in. thickness. This was also true in the restriction of deflections under moving loads.
4. Soil-cement subbases made of clay soil and cement-modified clay soil subbases were not entirely successful because the top surface of these subbases was susceptible to erosion, which resulted in pumping at slab edges and to some extent at joints. Moving load tests, however, showed that the average record of the 5-in. soil-cement subbase, from the standpoint of restricting deflections and strains in the pavement, was equivalent to or better than that of all other subbases.
5. Little or no correlation was indicated between edge pumping and slab cracking.
6. Concrete gutters were an effective means of preventing edge pumping and blowing and greatly reduced joint pumping.

●DESIGN and construction features and preliminary results of visual observations and load tests on a 4-mi test road in Ohio have been presented previously by Allen and Childs (1). A brief review of the salient features included in the test area is given to facilitate the present discussion.

The test road is a portion of the east-bound lanes of US 20 in northern Ohio between Fremont and Clyde. This is a four-lane divided highway carrying heavy truck traffic between Toledo and Cleveland. The average week-day traffic is approximately 6,000 vehicles, of which about 2,000 are classified as heavy vehicles.

The road surface is 9-in. uniform mesh-reinforced concrete in 20-ft and 100-ft slab lengths with doweled contraction joints. The foundation consists of 12 subbase treatments built on a subgrade of clay soils of A-6(8), A-6(12) and A-7-6(13) Bureau of Public Roads classification. These materials, which are generally characterized as pumping soils, had an average of 79 percent passing a 200-mesh sieve, an average liquid limit of 35, and an average plasticity index of 16.

There were four types of subbase treatments as follows:

1. Open-textured crushed limestone having 38 percent passing a No. 4 sieve and 7 percent passing a 200-mesh sieve.

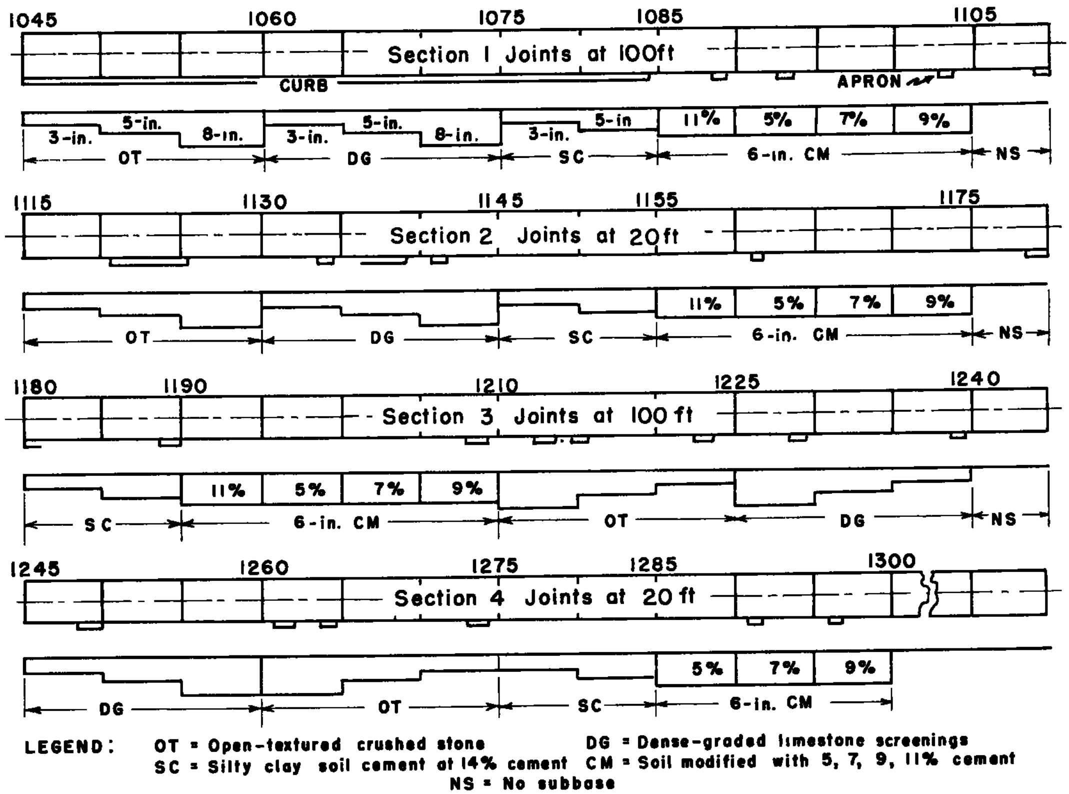


Figure 1. Location and identity of subbase treatments.

2. Dense-graded limestone screenings having 99 percent passing a No. 4 sieve and 22 percent passing a 200-mesh sieve.
3. Soil-cement made from the native clay soil with the addition of 14 percent cement.
4. Cement-modified clay soil containing lesser amounts of cement.

Figure 1 locates and identifies the subbases. Open-textured limestone was placed in 500-ft lengths at each of three thicknesses—3, 5, and 8 in. These were provided with longitudinal edge drains. They are identified hereafter as 3-OT, 5-OT and 8-OT. The dense-graded limestone screenings were also placed in three thicknesses and are identified as 3-DG, 5-DG and 8-DG. The silty clay soil with 14 percent cement met the durability and strength requirements for soil-cement, and subbases were placed in 3- and 5-in. layers. They are labeled 3-SC and 5-SC. The remaining cement-modified treatments were all 6 in. thick and contained 5, 7, 9, and 11 percent cement. They are hereafter noted as CM-5, CM-7, CM-9 and CM-11. Control sections with no subbase treatment were constructed directly on the A-6 soil and are designated NS. Figure 2 includes typical vertical sections of the road structure at a longitudinal edge of the concrete.

OBJECTIVES

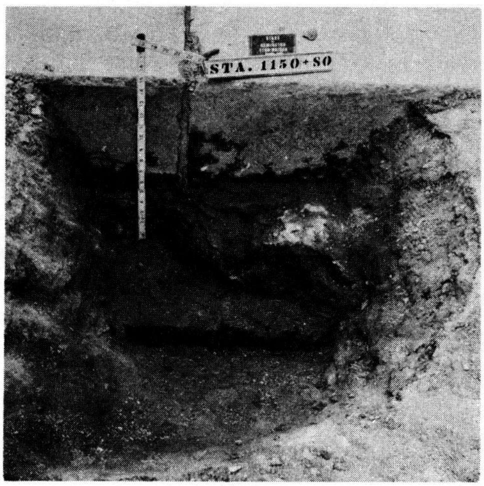
The test road is cooperative project by the State of Ohio and the Bureau of Public Roads to investigate the effect of subbases on pumping control. The Portland Cement Association assisted in the tests. This is one of a series of such studies recommended by the Highway Research Board Committee on Maintenance of Concrete Pavement as Related to the Pumping Action of Slabs (3). The road provided opportunity (a) to observe the effects of subbases materials and thicknesses on pumping; (b) to study the effects of subbases on pavement strength; and (c) to study relationships between pumping and structural durability of the pavement, that is, to correlate pumping with slab deflections and stresses, and ultimately with joint faulting and slab cracking.

TRAFFIC

Traffic counts and weight surveys of vehicles on the test pavement were made periodically. The average 24-hr weekday counts for the duration of the test are given in Table 1.

Heavy vehicles are defined as all commercial trucks and buses except panel and pickup trucks. The reduction of the vehicle counts for 1956 and 1957 was undoubtedly the result of the opening in October 1955 of the parallel Ohio Turnpike.

The weight surveys indicated that for the heavy trucks carrying payloads, 60 percent



5-in. soil-cement at Sta. 1150 + 80

8-in. open-textured stone at 1127 + 00

11 percent cement-modified soil at 1159 + 20

5-in. dense-graded stone at 1135 + 40

Figure 2. Typical subbases.

TABLE 1

TRAFFIC SUMMARY

Year	Vehicles per Day	
	Heavy	Total
1953	2292	5830
1954	1969	5668
1955	2336	6036
1956	1848	4559
1957	1799	4431

of the axles carried 14,000 lb or more. However, the number of empty trucks was such that of all truck axles counted only an average of 20 percent weighed 14,000 lb or more.

The traffic data revealed that an average of 94 percent of the heavy trucks traveled on the right (outside) lane. Legal load limits in Ohio are 19,000 lb for single axles and 31,500 lb for tandem axles spaced 4 to 8 ft. Tables showing the traffic counts and weight surveys obtained since 1954 are included in the Appendix.

MOISTURE AND TEMPERATURE RECORDS

An attempt was made to measure soil moisture content electrically when the condition surveys were made. The soil moisture units installed in the subbase and subgrade were of the Colman type, a fiberglass-monel electrode sandwich moisture cell combined with a type 7A thermistor for temperature readings. Readings were taken by measuring the electrical resistance of the cells and thermistors with a self-powered alternating-current ohm-meter operating at 90 cycles per second.

Moisture cell resistance readings were reduced to approximate moisture contents by means of laboratory calibration curves. However, the moisture contents so obtained were not considered to be sufficiently accurate for this study; the cells were found to be responsive to pressure or compaction as well as moisture content. The observed readings did not in any case indicate the seasonal variations in soil moisture content which were expected.

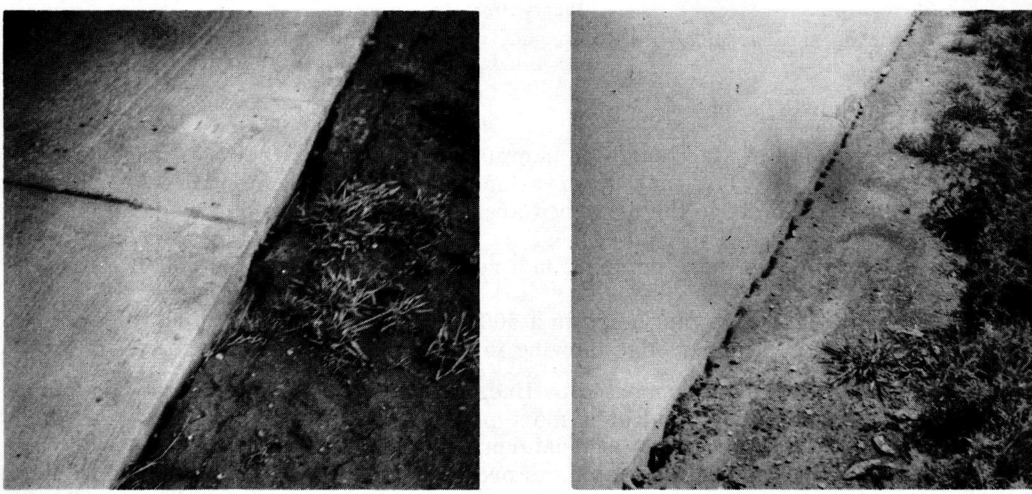
The temperature records, with the exception of a few scattered anomalous readings, did seem to follow a reasonable pattern of soil temperature distribution. On warm, sunny days the temperatures under the pavement slab were as much as 15 F higher than those at corresponding depths under sod. Isothermal lines plotted on the cross-section indicated that heat was flowing by conduction from the warm slab into the subbase and subgrade soil below. In cold weather under cloudy, overcast skies, temperatures at equal depths under pavement and under sod were similar. Isothermal lines indicated heat flow upward toward the surface.

CONDITION SURVEYS

Obsevations of pumping and blowing, begun in 1953 and described in Highway Research Board Bulletin 116 (1), were supplemented in 1954 by fault measurements at joints and by a log of the locations of cracks in the concrete slabs. All surveys and test data were obtained from observations and measurements on the righ-hand traffic lane. No edge action or joint faulting was observed in the passing lane, but a few cracks extended from the traffic lane through the center-line into the passing lane.

When the road was first opened to traffic, pumping developed on the no-subbase sections very quickly. After only two years of service, pumping joints in these sections were undersealed with bituminous material; they had already failed as controls on the subbase treatments. Observations were continued, however, and in the discussion which follows it should be noted that references to the condition of no-subbase sections since 1954 refer to pavement with undersealed joints.

Examples of pumping at joint and edge.



Blowing along edge--at joint and near mid-slab.

Figure 3. Evidence of action at slab edge.

PUMPING AND BLOWING

Visual examinations of the slab joints and edges were made in the early spring of each year and supplemented by fall and winter surveys in 1955 and 1956. It was apparent immediately that concrete gutters and aprons inhibited the edge and joint action. Although records were maintained on these areas, the analysis attempted here is based on uncurbed lengths of pavement where edge and joint action were readily observable. Summaries of the number of pumping joints, occurrences of edge pumping, occurrences of edge blows, and lineal feet of continuous blowing—all based on 100 ft of uncurbed slab length are given in the Appendix. Some of the conditions previously described are shown in Figure 3.

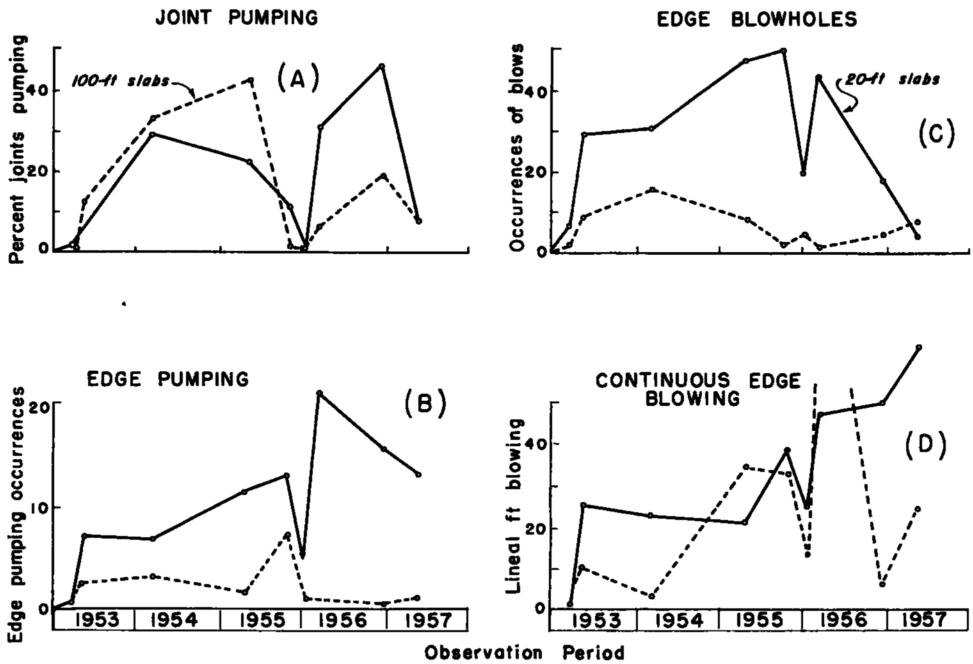


Figure 4. Pumping and blowing vs slab length, grand average of all treatments; 500-ft basic length.

Influence of Slab Length

To study the effects of slab length on pumping and blowing, the four graphs of Figure 4 were constructed. For each observation period the following data were plotted:

1. Percentage of joints in the uncurbed areas which were pumping regardless of severity.
2. The occurrences of edge pumping in a representative uncurbed 500-ft length of road.
3. The instances of edge blowholes in a 500-ft length.
4. The length of continuous edge blowing in lineal feet for an average 500-ft length.

In Figure 4 the points are connected by lines for the purpose of identity. Instances of pumping are greatly reduced after a short period of dry weather, so the behavior of the graph between plotted points is indeterminable.

Figure 4A suggests that joint pumping is probably independent of slab length. When observing the phenomenon on the road one is apt to conclude that joints between 20-ft slabs are more susceptible to pumping than joints between 100-ft slabs. However, there are five times as many joints in a length of 20-ft slabs as in a length of 100-ft slabs and the observer is influenced by quantity.

Edge pumping was more severe along edges of short slabs than on long ones. This is demonstrated by Figure 4B where the edge pumping occurrences for 20-ft slabs are several times greater than for 100-ft slabs. Also, there is an indication that edge pumping tends to become greater with time in areas with short slabs and to decrease at the edges of long slabs.

Edge blowholes were more frequent along 20-ft slabs than along 100-ft slabs. This is corroborated by Figure 4C with the exception of the 1957 observations.

Continuous edge blowing seemed to increase with time, especially in sections with 20-ft slabs. The severity of this phenomenon along 100-ft slabs was great in the spring of 1956; but aside from that and a small discrepancy in 1955, continuous edge blowing was worse along the edges of short slabs than along the 100-ft slabs.

Effect of Subbase Treatment

Joint Pumping. The percentage of pumping joints in each treatment based on the total number of pumping joints observed is given in Figure 5. These data are from the critical spring readings for each of the five years of observation. The following conclusions appear to be warranted:

1. Open-textured crushed stone was most effective in the prevention of joint pumping. In this respect the 3-in. thickness was as good as the 5-in. and 8-in. thicknesses.
2. Dense-graded, although not as good as open-textured stone, was still a good material for inhibiting pumping. Thickness of dense-graded material seemed to be a factor in its performance. In the early years some joint pumping was seen among 20-ft slabs on the 8-in. treatment, but this diminished and in 1956 and 1957 joint pumping in these areas was found on the 3-in. thicknesses. In 1955, 15 to 19 percent of the joints between 100-ft panels on 3-in. dense-graded stone pumped; in both 1955 and 1956 there was pumping at joints in the 5-in. thickness. Of the dense-graded treatments in this road, the 8-in. thickness appeared to be best; the 5-in. was slightly better than the 3-in. thickness.
3. The silty clay soil-cement of this project was not successful in preventing joint pumping. Erosion of the top surface of this material apparently developed due to a combination of water between the slab and the subbase and pavement deflections under moving truck loads. This slurry was ejected at joints and slab edges. In most cases there were more pumping joints on the 3-in. than on the 5-in. thickness. The percentage of pumping joints between 100-ft slabs was always greater than the percentage of pumping between 20-ft slabs when silty clay soil-cement was the subbase. In the 100-ft slab areas, joint pumping over the 3-in. soil-cement treatment was sometimes more and sometimes less than that in areas with no subbase, but with one exception—there was always less joint pumping over 5-in. soil-cement than over the control areas with no subbase.
4. The remaining cement-treated subbases were of some benefit in the reduction of joint pumping below that of the no-subbase area, but they did not prevent joint pump-

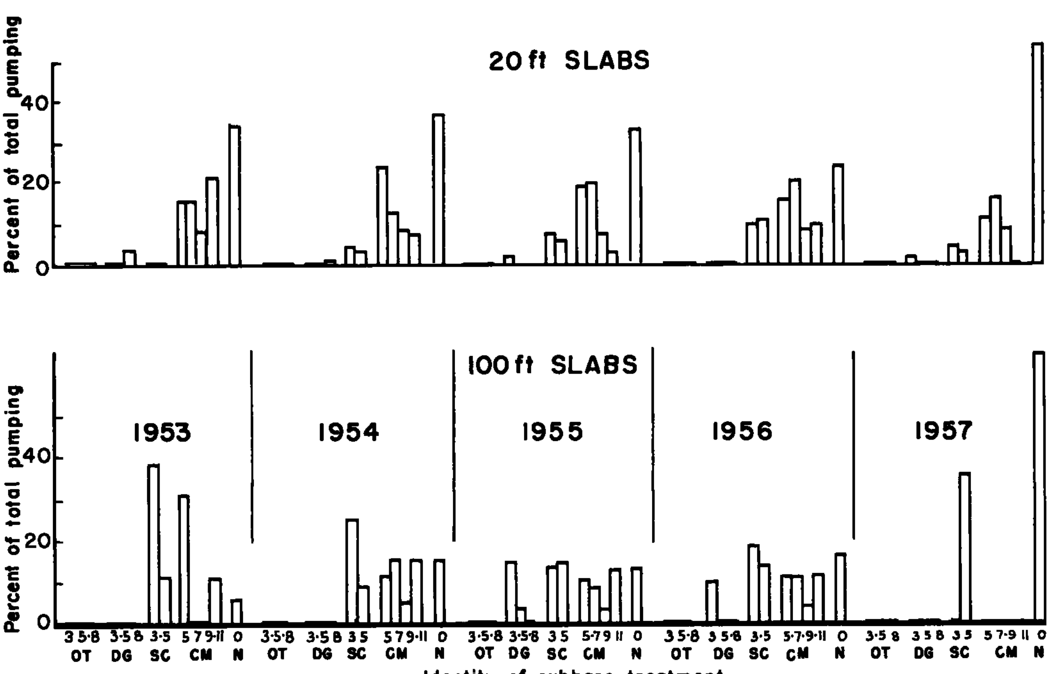


Figure 5. Joint pumping.

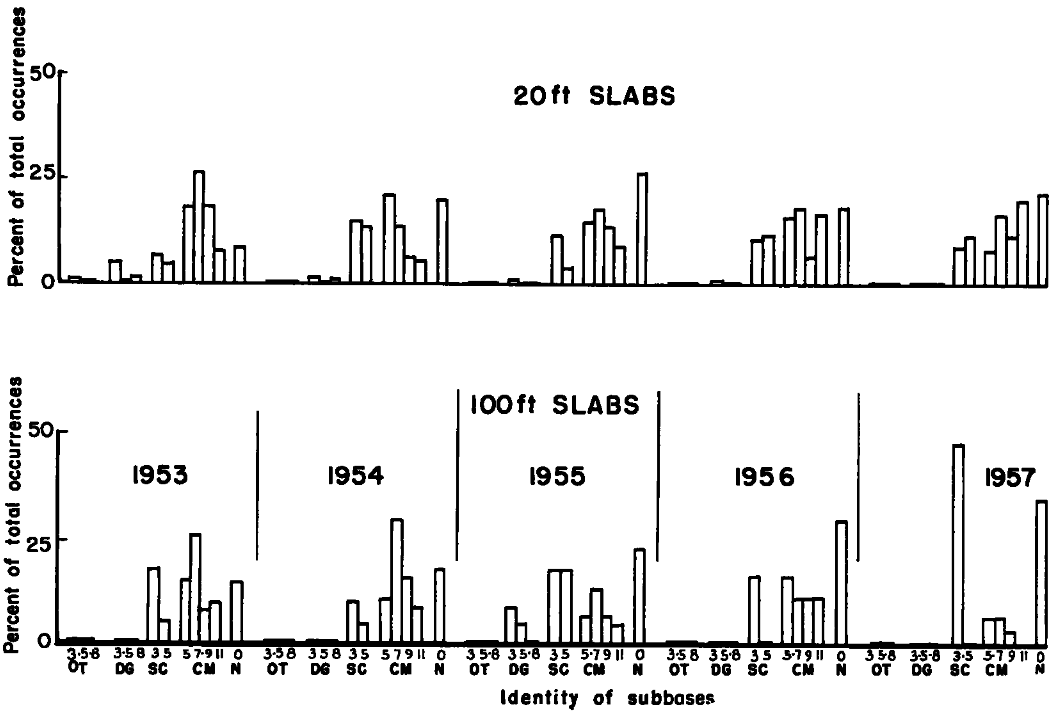


Figure 6. Edge pumping.

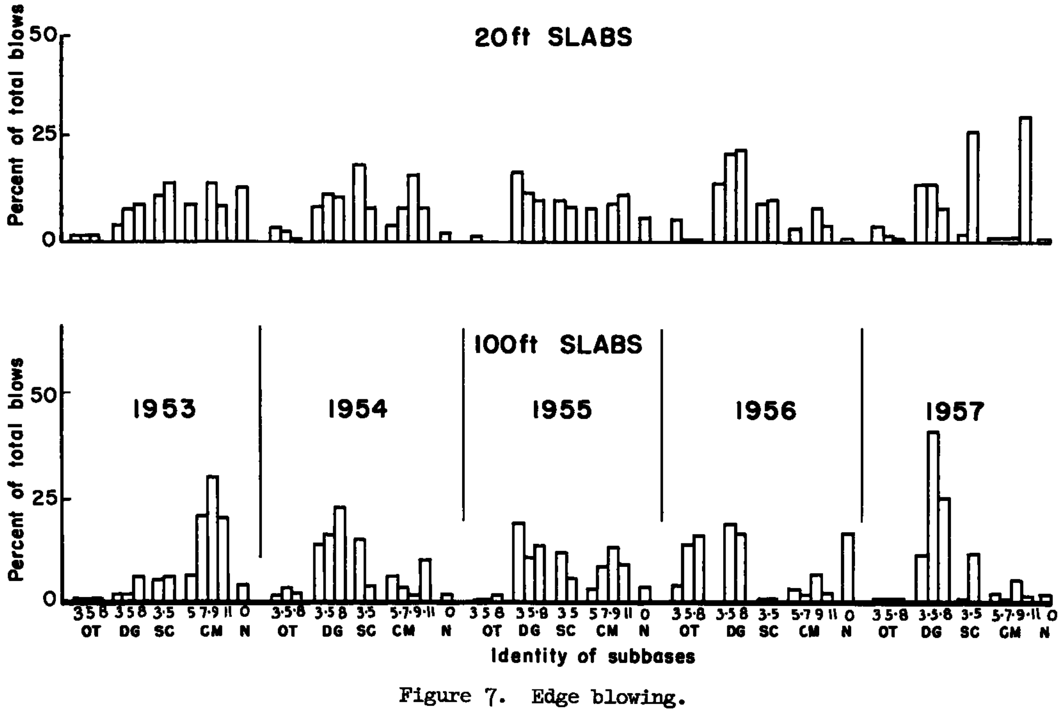


Figure 7. Edge blowing.

ing. Among 20-ft slabs there was less joint pumping over the cement-modified treatments than in the areas of no subbase. However, this was not always the case when the slab length was 100 ft. The 9 percent cement-treated subbase was generally the most effective of the cement-modified treatments in the reduction of joint pumping. In most cases, the number of pumping joints in this treatment was from ¼ to ⅓ of the number found in control areas without subbase.

5. It is difficult to classify CM-5, CM-7, and CM-11 as to their superiority in joint pumping reduction. CM-11 appears to be slightly better under 20-ft slabs, but loses its advantage under 100-ft slabs. CM-5 and CM-7 were for the most part about equally effective.

In summary, the observations indicate, with minor exceptions, that all treatments were of some benefit in the reduction of joint pumping below that in untreated areas. All open-textured treatments were successful in preventing joint pumping and there is no preferential thickness, the 3-in. thickness being equally as effective as the 5- and 8-in. thicknesses. Next in ability to reduce joint pumping are 8-DG, 5-DG, and 3-DG in that order. Of the cement treatments, 5-SC is next, followed by CM-9 and 3-SC. CM-11 showed slight advantage over CM-5 and CM-7.

Edge Pumping. Relationships between edge pumping and subbase treatment were similar to those between joint pumping and subbase treatment. Figure 6 gives the percentage of edge pumping in each treated area based on the total observed occurrences of edge pumping. The open-textured subbases with drains prevented edge pumping almost entirely; the dense-graded subbases were effective, but not as successful in edge pumping prevention as open-textured treatments. The effect of thickness on the performance of dense-graded subbases with respect to edge pumping was minor, with the 8-in. showing slight superiority over the 5-in. thickness, which in turn was a little better than the 3-in. thickness.

Of the cement-treated subbases, 5-SC appeared to permit less pumping than the remaining treatments. The CM-11 and CM-9 treatments permitted less edge pumping than the control except in one instance, and rated better than CM-5 and 3-SC. CM-7

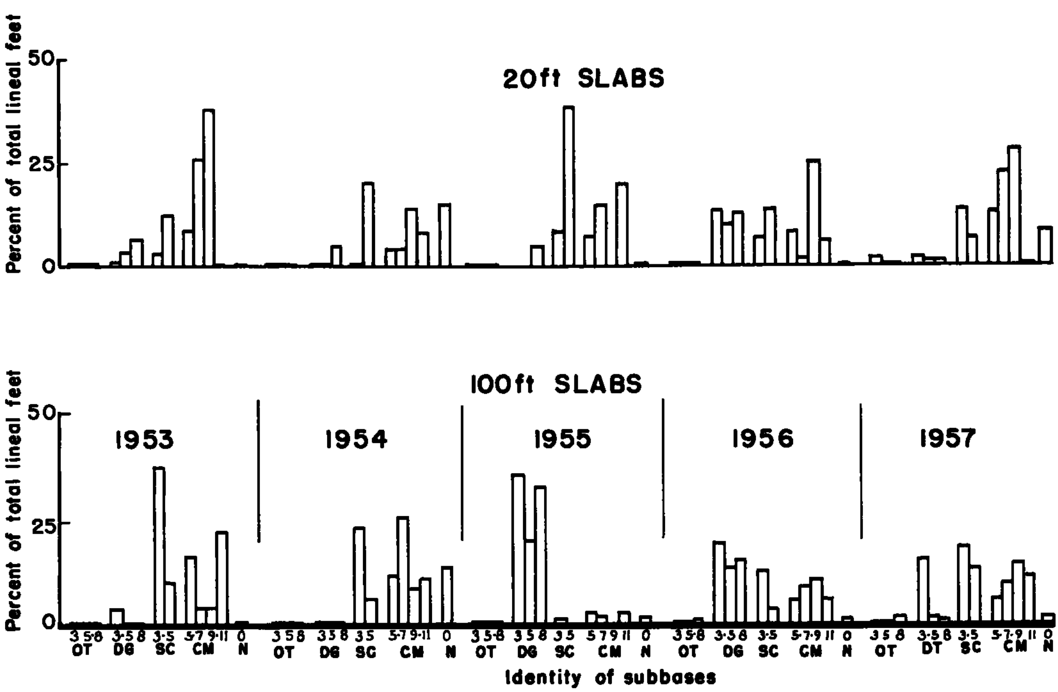


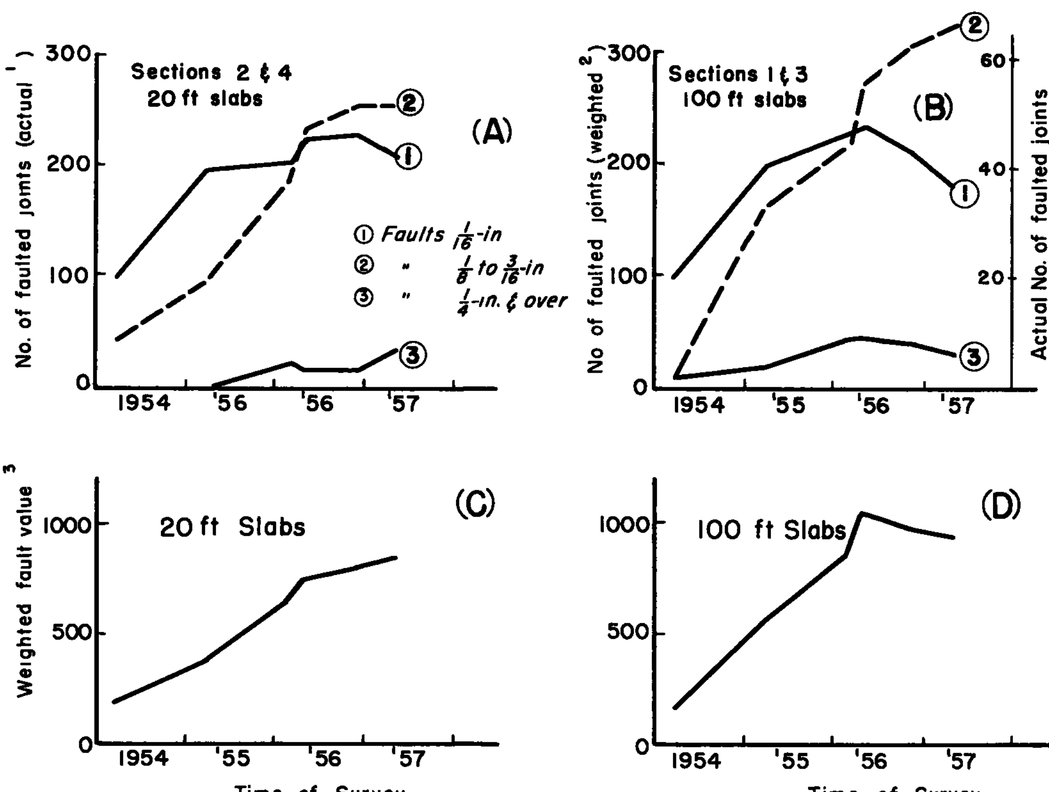
Figure 8. Continuous blowing.

was less effective in the inhibition of edge pumping than other treatments, but on the average was a small improvement over no subbase.

Edge Blowing. Figure 7 relates subbase treatment to the percentage of edge blows observed in that area. It is evident that edge blowing prevailed in all areas at some time. The open-textured material was effective in holding the occurrences of edge blows to a minimum, but it did not prevent blowing. The thickness of open-textured subbase did not appear to be significant.

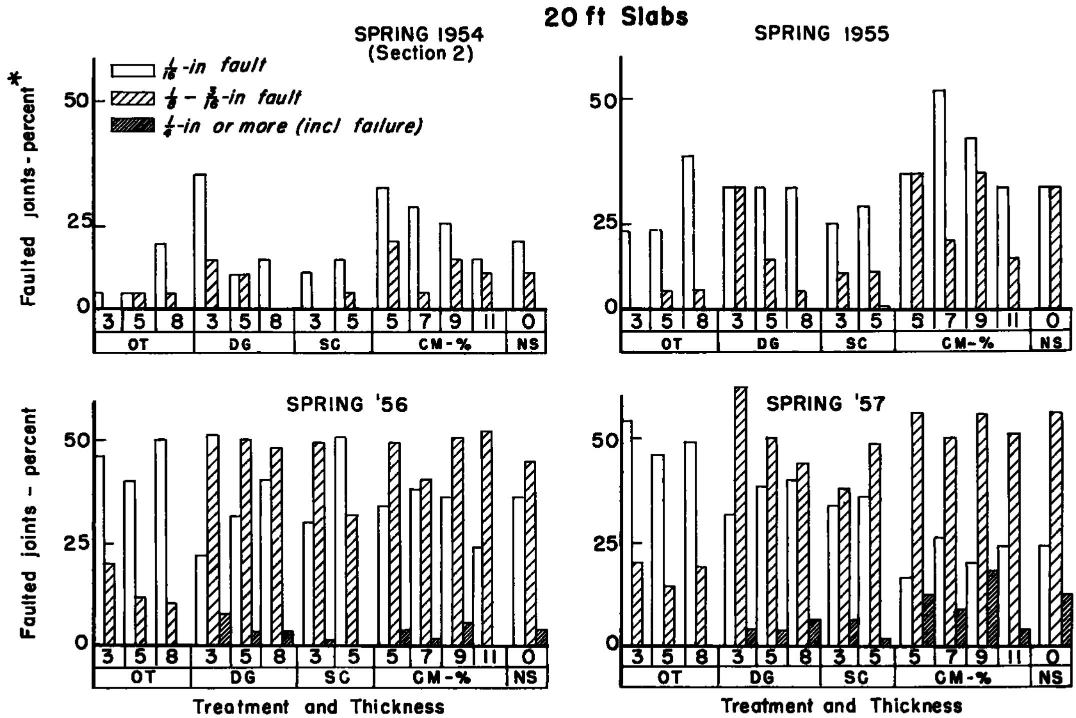
All remaining subbase treatments were ineffective in the reduction of edge blowing. In fact, in almost all cases there was less edge blowing along slabs built directly on the subgrade than along slabs with dense-graded or cement-treated subbase.

Continuous Blowing. Except for the case of open-textured subbases, Figure 8 presents a somewhat confused picture of the relations between continuous blowing and subbase treatment. Second to open-textured crushed stone in effectiveness in the prevention of continuous blowing is the control area with no subbase. Some blowing was seen in the control areas in 1954 and a little in 1957, but on the average it was less than that observed in the dense-graded and cement-modified treatments. Probably dense-graded treatments should be rated third in effectiveness in spite of the high percentage of continuous blowing along 100-ft slabs in 1955 and on the 3-in. thickness in 1956 and 1957. The soil-cement and cement-modified treatments ranged over great extremes and they are difficult to classify. In any case, they are less effective in the prevention of continuous blowing than no subbase.



[1] Actual values doubled for years '54 and '55 (see text)
[2] Weight factor 5 = ratio of No. of joints in Sections 2 & 4 to No. in Sections 1 & 3
[3] Class ① plus twice class ② plus four times class ③

Figure 9. Development of faulting.



* *Faulting expressed as percent based on No. of joints in each treatment*

Figure 10. Joint faulting.

JOINT FAULTING

In the spring of 1954, measurements of the faulting which developed at joints were begun. The change in elevations of the forward slab in the direction of traffic with respect to the adjacent slab immediately behind it was recorded in increments of $\frac{1}{16}$ in. and the direction of fault was noted. For the analysis the data were grouped into Class 1($\frac{1}{16}$ in.), Class 2 ($\frac{1}{8}$ to $\frac{3}{16}$ in.), and Class 3 ($\frac{1}{4}$ in. and greater) faults. This classification system does not include the case where the forward slab is higher than the reference slab.

A summary of classified fault data is given in the Appendix. In 1954 and 1955 the measurements were restricted to sections 2 and 3, which constitued one-half the project and consequently provided data on one-half the total number of joints. The data for subsequent years comprised all joints in the project, including those in the curbed sections. A graphical portrayal of faulting development is shown in Figure 9, where the 1954 and 1955 data are weighted by a factor of 2 to compensate for the shorter test section. Also, for comparison of slab length effect, the data for 100-ft slabs were weighted by 5 because there were only one-fifth as many joints in the sections with 100-ft slabs as in sections with 20-ft slabs. Curves (C) and (D) of Figure 9 are constructed on the premise that severity of faulting is proportional to the size of the fault. Thus the weighted fault value, plotted as the ordinate, is the sum of Class 1 faults plus twice the Class 2 faults plus four times the Class 3 faults.

Influence of Slab Length

There is reasonable similarity in trend in the development of Class 1 and Class 2 faulting in both 20-ft and 100-ft sections. The weighted number of Class 2 faults is larger for the long slabs. In 1956 and 1957 Class 1 faults on long slabs decreased more rapidly than Class 1 faults on short slabs. This suggests an upgrading in severity of faulting. The decrease in Class 3 faults in 100-ft slabs in 1956 and 1957

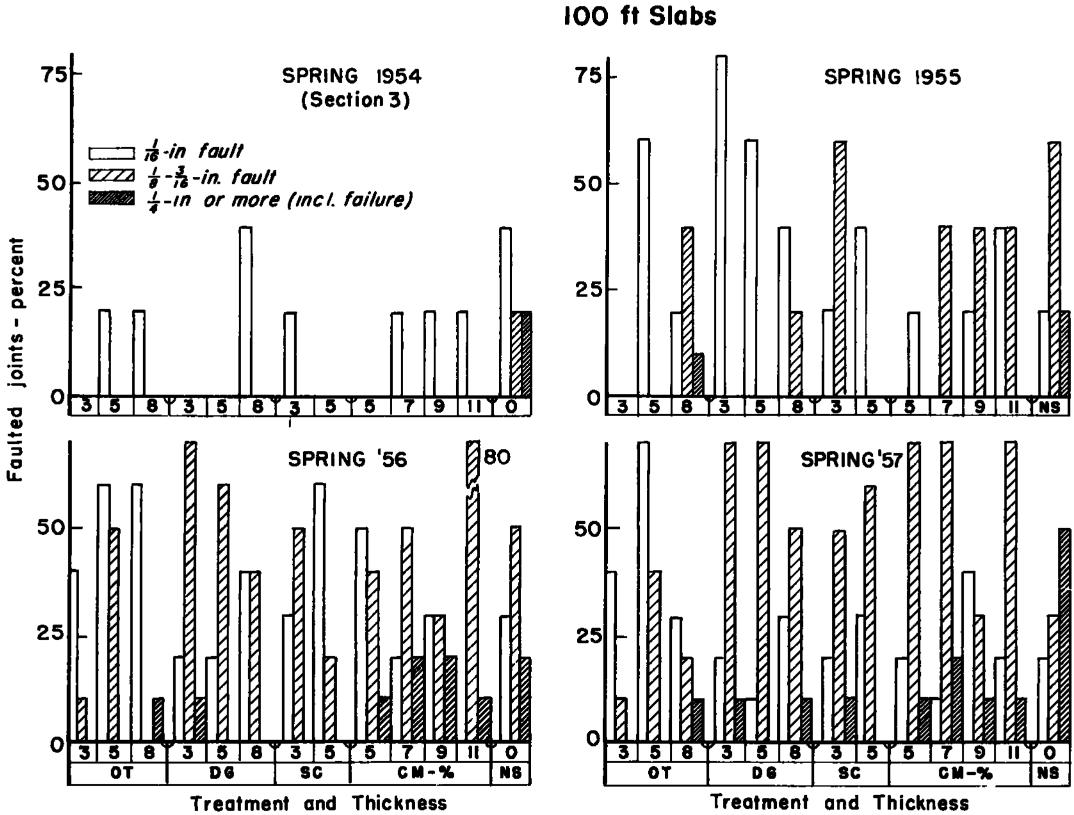


Figure 11. Joint faulting.

may have been due in part to the formation of transverse cracks within 10 to 12 ft of slab ends. The resulting stress relief permitted reorientation of the slab end with respect to subgrade and may have decreased the fault classification from Class 3 to Class 2.

The weighted fault value curves C and D of Figure 9 indicate greater fault severity between 100-ft slabs than between 20-ft slabs. In May 1956 the fault value for 100-ft slabs was one-third greater than that for 20-ft slabs, but it was only one-eighth greater in 1957.

Influence of Subbase

The joint faulting data for the critical spring surveys of 1954, 1955, 1956 and 1957 were classified by severity and separated by slab length and subbase treatment to obtain Figures 10 and 11. The ordinates for these charts are the percent of faulted joints based upon the number of joints in each category. There were 50 joints over each subbase treatment with 20-ft slabs and 10 joints for 100-ft slabs, with the exception that Section 4 omitted the CM-11 and NS areas leaving 25 joints for each of these treatments with 20-ft slabs. In 1954 only one-half the project was surveyed.

Faulting began to appear to a degree which complicated the analysis of subbase influence in the spring of 1956. The general distribution of faulting throughout the test road suggested a weakness in joint construction. This was corroborated by observations of general joint spalling.

In 1957 cores were taken from the pavement at a few joints. They were drilled at locations 30 in. inward from the free edge to include one of the dowels. Elongation of the dowel socket in the approach slab was noted in some instances and honeycombing was found under some of the dowels. This lack of dowel support may have contributed in some degree to the magnitude of faulting. The degree to which these conditions

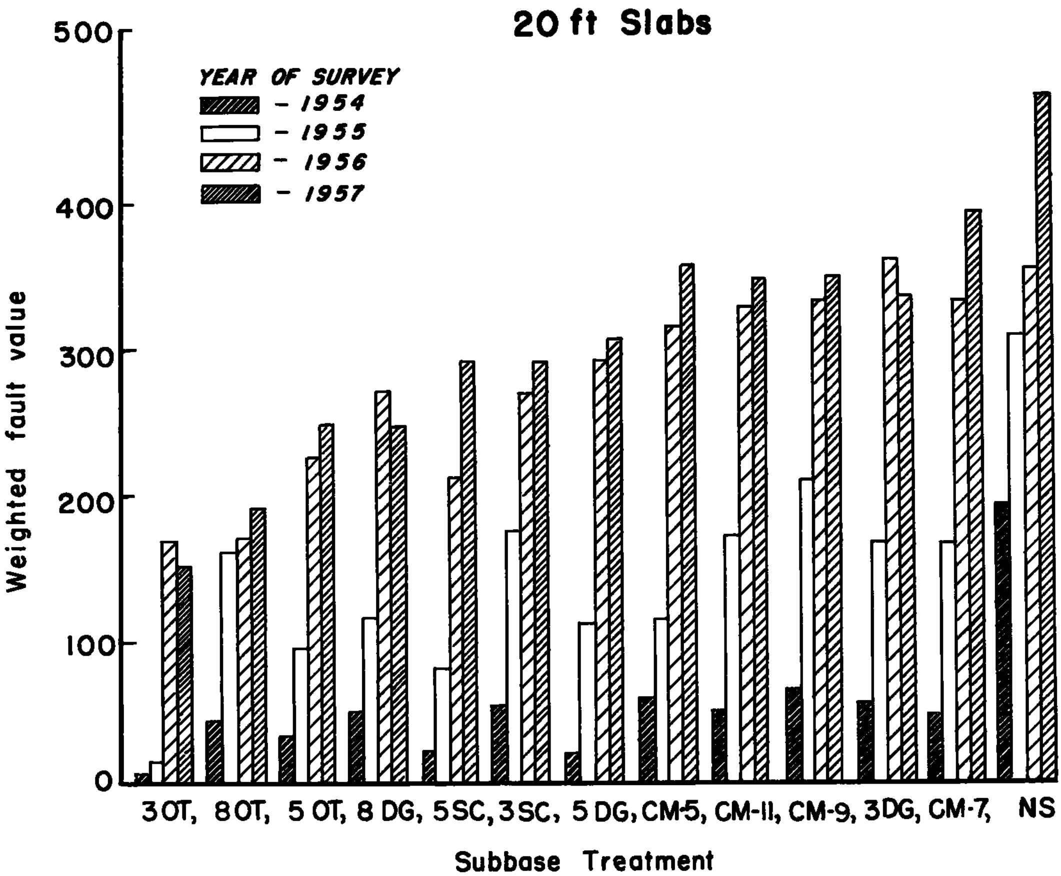


Figure 12. Effect of subbase on faulting.

increased the fault cannot be determined and for this analysis it is assumed that all joints are affected equally.

Figures 10 and 11 are too complicated to permit satisfactory analysis by inspection, but a few general remarks may be in order. Slabs on open-textured subbases developed less Class 2 faults than on other subbases in the 20-ft slab sections and there were no Class 3 faults. In sections with 100-ft slabs the faulting in areas with open-textured subbases was more severe than in similar areas with 20-ft slabs, but open-textured subbases were still among the treatments with least faulting. Soil-cement appeared to be slightly better in fault resistance than dense-graded material.

On the basis of weighted fault value, it is possible to rank the subbases in order of their resistance to faulting. Figure 12 is drawn with emphasis on the weighted fault values for the last two years. Comparisons are made with the reservation that the faulting on the project is not representative of standard pavement construction.

It is seen that the faulting was least in areas with 3-in. and 8-in. open-textured subbases. The 5-OT was slightly better than 8-DG. The 5-SC, 3-SC and 5-DG were the next group, followed by all of the cement-modified treatments and 3-DG. Most susceptible to faulting was the control area without subbase.

DEVELOPMENT OF TRANSVERSE CRACKS

To complete the condition survey of the road, a map was drawn showing the locations of all of the full-depth transverse cracks which developed during the five years of observation. From these maps the number of cracks were tallied and the data for the spring observations of 1954, 1955, 1956 and 1957 are shown graphically in Figure 13.

Transverse cracks were infrequent during the early years, but between March 1956 and May 1957 a large number of cracks developed. The survey of December 1956 showed that many of these had formed prior to the December survey, but at least as many more developed between December and the following May.

The record exhibited in Figure 13 is for the right-hand traffic lane. No data are shown for the passing lane, but the cracking in that lane was very limited and almost entirely confined to extension of cracks in the right-hand lane in long slabs at distances well away from the joints.

Effect of Slab Length

Some transverse cracking in 100-ft slabs is expected and the design of the pavement takes this into consideration. Cracking, however, is not expected in 20-ft slabs. Accordingly, cracks that occur in 20-ft slabs are generally considered more serious than those that occur in 100-ft slabs.

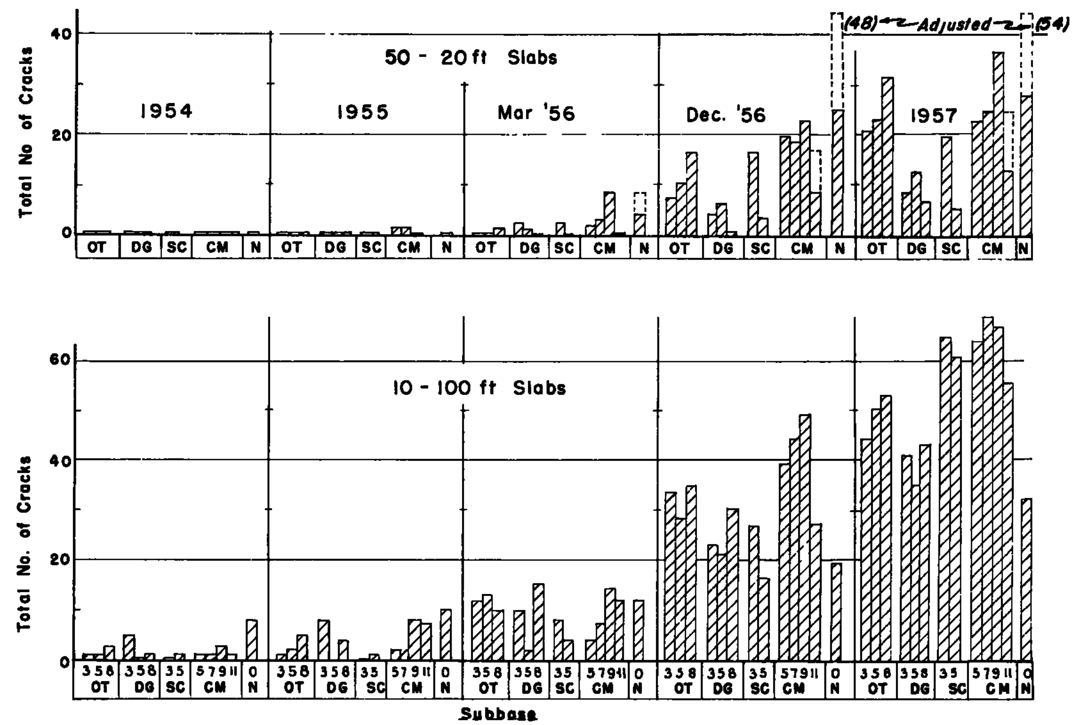


Figure 13. Transverse cracks.

Figure 13 shows more cracks in 100-ft slabs than in 20-ft slabs. However, for one type of analysis, a contraction joint in a pavement may be considered a controlled crack, and if the cracks through the joints are added to the cracks observed, and the long-slab and short-slab sections are compared on a basis of total cracks per 100 ft, it is seen that there are more cracks in sections with 20-ft slabs than in sections with 100-ft slabs. This observation is substantiated in Table 2, which is a summary of the crack survey data of May 1957.

Influence of Subbase

From Table 2 it is apparent that areas of least cracking under 20-ft slabs do not necessarily have the same subbase as areas of least cracking under 100-ft slabs. For example, in the 20-ft slab sections, where complete elimination of all cracking is desirable, 5-SC, 8-DG and 3-DG had less than 1 crack per 100 ft, and 5-DG followed closely with 1.2 cracks per 100 ft. In the next group were 3-SC, 3-OT, 5-OT, CM-5,

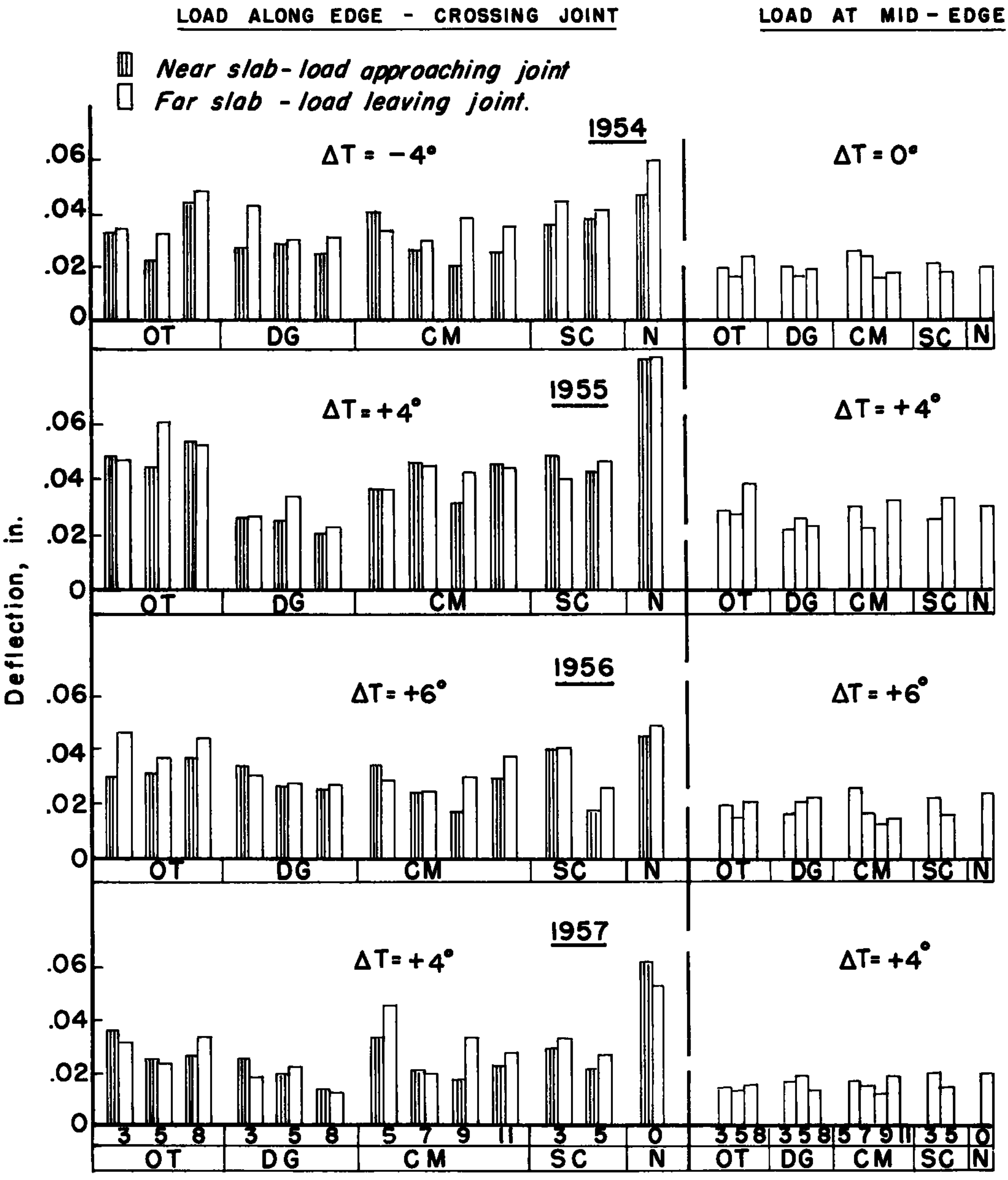


Figure 14. Early morning deflections; 31,500 lb on tandem axles, 20-ft slabs.

TABLE 2

TRANSVERSE CRACKS IN RIGHT-HAND TEST LANE

Slab Length (ft)	Cracks per 100 Ft in Designated Treatment												
	3OT	5OT	8OT	3DG	5DG	8DG	3SC	5SC	CM5	CM7	CM9	CM11	NS
20	2.0	2.2	3.3	0.8	1.2	0.6	1.9	0.5	2.2	2.4	3.6	2.4	5.4
100	4.4	5.0	5.3	4.1	3.5	4.3	6.4	6.0	6.3	6.8	6.6	5.5	3.2
20[1]	6.0	6.2	7.3	4.8	5.2	4.6	5.9	4.5	6.2	6.4	7.6	6.4	9.4
Excess[2]	1.6	1.0	2.0	0.7	1.7	0.3	-0.5	-1.5	-0.1	-0.4	1.0	0.9	5.8

[1] Adjusted value = 20-ft count plus 4 contraction joints.
[2] 20-ft adjusted less 100-ft observed.

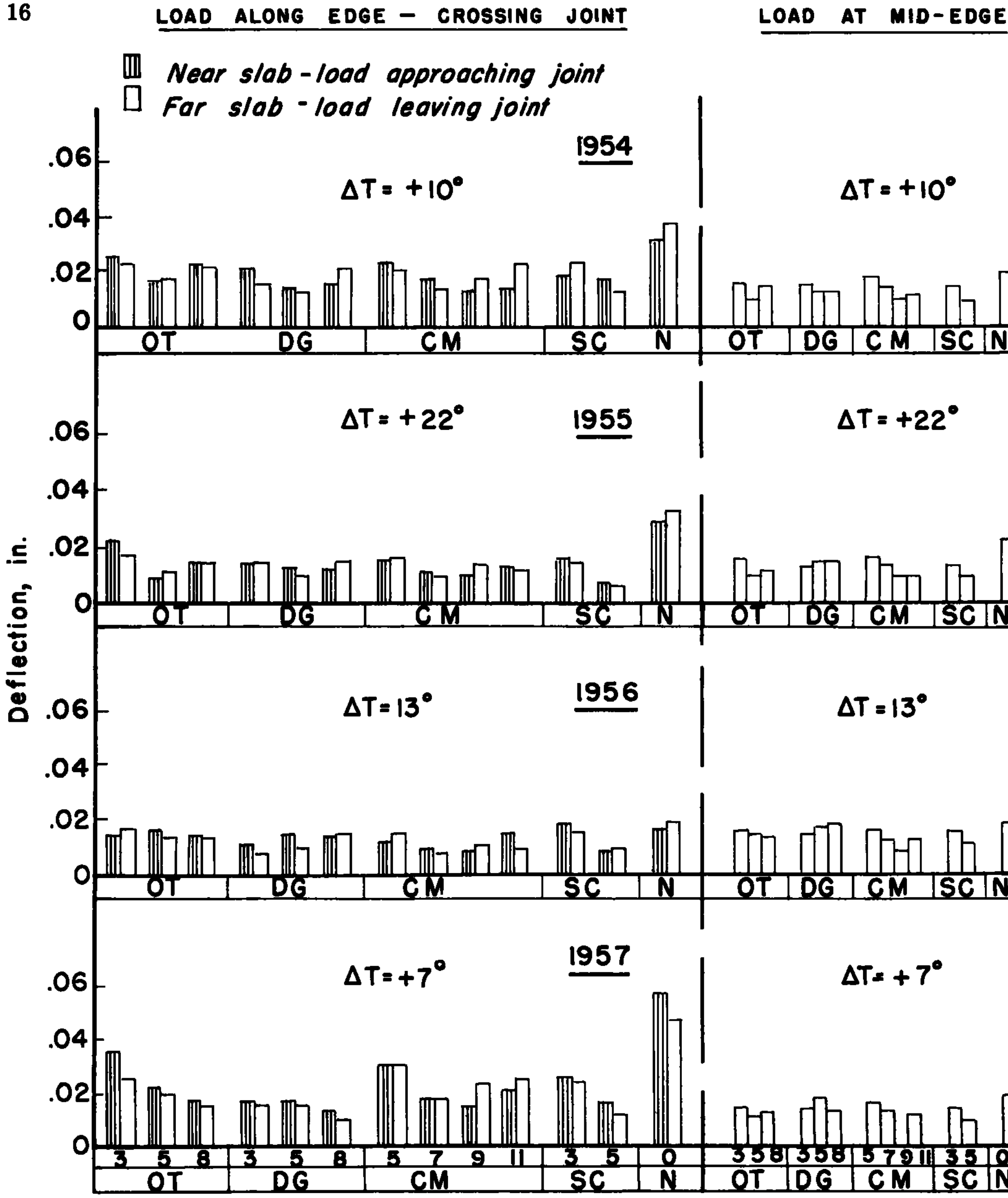


Figure 15. Afternoon deflections; 31,500 lb on tandem axles, 20-ft slabs.

CM-7 and CM-11 with 1.9 to 2.4 cracks per 100 ft; 8-OT and CM-9 had more than three cracks per 100 ft, and there were 5.4 cracks in 100 ft of slabs without subbase treatment.

In 100-ft slab sections the control length without subbase had least cracks and 5-DG was next with 3.5 cracks per 100 ft. Treatments 3-DG, 8-DG and 3-OT had 4.0 to 4.4 cracks per 100 ft. Next were 5-OT, 8-OT and CM-11 with 5.0 to 5.5 cracks per 100 ft, followed by 5-SC, CM-5, 3-SC, CM-9, and CM-11, which had 6.0 or more cracks per 100 ft.

The only subbases which rate well under both slab lengths are the three dense-graded thicknesses; 3-OT and 5-OT were fair in crack resistance, but 8-OT was poor under 20-ft slabs. 5-SC was best under 20-ft slabs, but was well down the line under 100-ft slabs. Likewise the 100-ft slabs with no subbase had the least cracking, but 20-ft

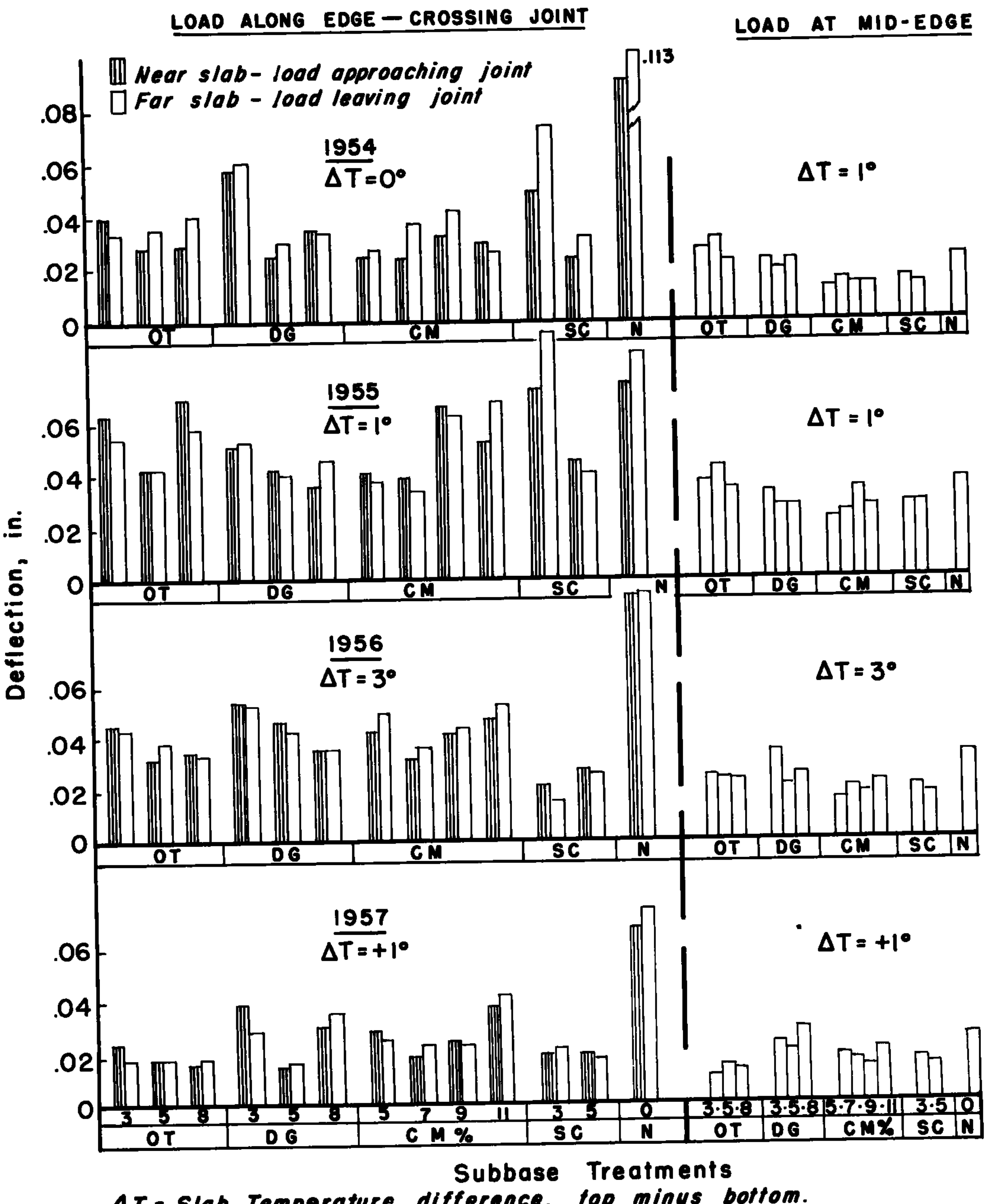


Figure 16. Early morning deflections; 31,500 lb on tandem axles, 100-ft slabs.

slabs without subbase had the most. The CM-9 modification was poor under both slab lengths.

DEFLECTIONS AND STRAINS

The two types of deflection measurement described in HRB Bulletin 116 (1) were repeated throughout the five-year period. The first was a measurement of maximum slab deflections at edges and corners under moving controlled loads in representative areas of each subbase for a full section; the second was a record of the complete deflection curves at edges and corners for selected areas in several treatments. Measurements

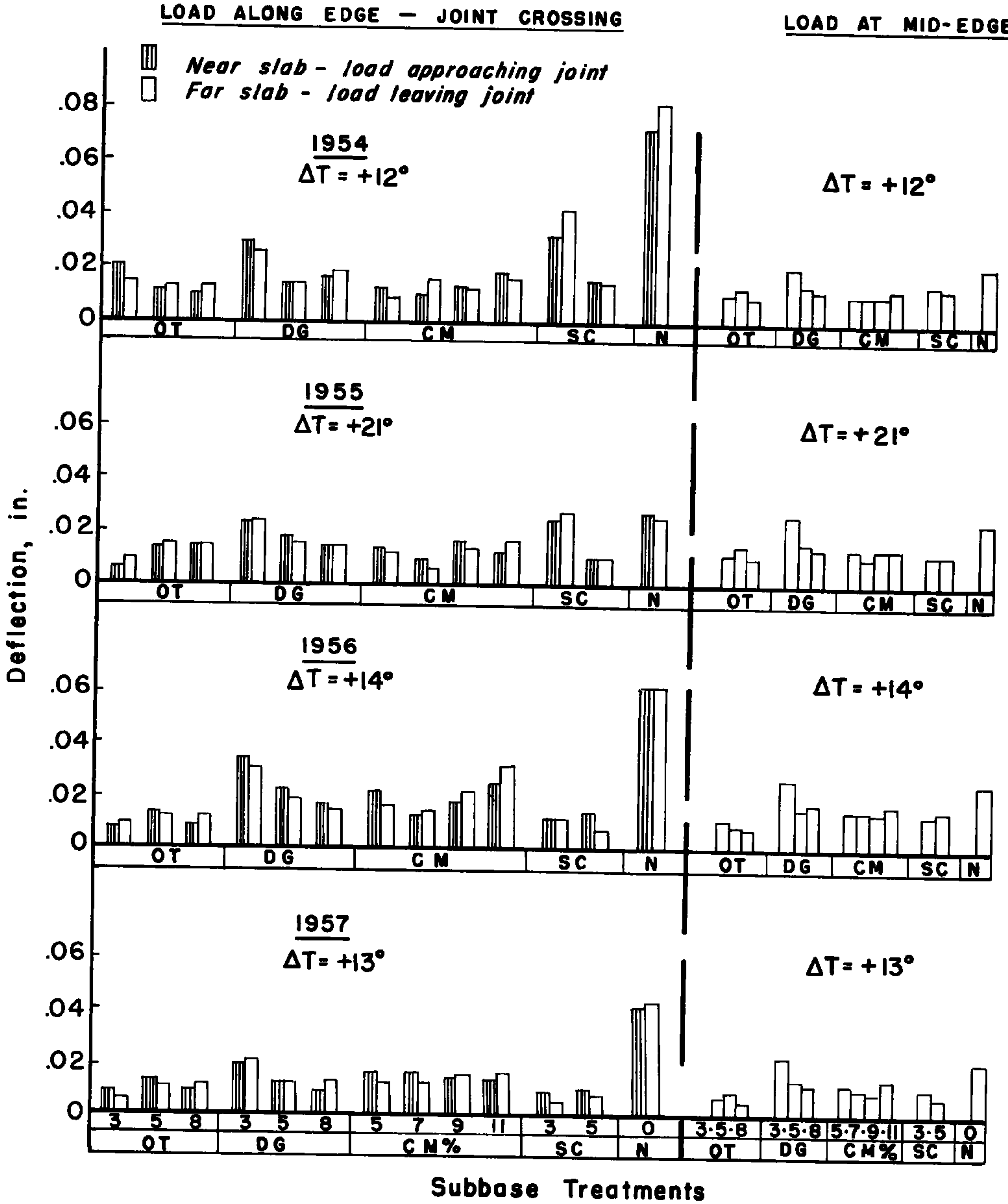


Figure 17. Afternoon deflections; 31,500 lb on tandem axles, 100-ft slabs.

of critical surface strains at slab edges were made simultaneously with the dynamic deflection records.

MAXIMUM DEFLECTION STUDY

The deflectometer for the measurement of maximum deflections utilized a steel pin held in a machined brass housing by a leather friction pad; the housing was attached to the vertical face of the concrete slab by a bracket and the steel pin rested upon a rod driven through a casing deep into the subgrade. The length of pin extending above the housing was read with a 0.001-in. dial indicator equipped with an adapter. The change in this length occurring as the housing was forced to slide down over the pin by passage of the test vehicle wheels along the slab edge was recorded as the maximum deflection.

The test vehicle for this operation was a 3-axle dump truck with a 31,500-lb load on the rear tandem axles. The driver became proficient at steering his truck with the outside walls of the rear tires within 2 or 3 in. of the slab edge. The test speed was about 5 mph.

To minimize the effect of temperature variations during the test run, the time was made very short. Five engineers were each assigned 15 deflectometers and each man was able to read deflections in his assigned section, reset the pins and read new zeros in the 20 min required for the truck to return on the next run. Three runs were made for each test. The same area was tested in early morning and mid-afternoon to observe the effects of temperature differential and resulting slab curl on the maximum deflections. Figures 14 through 17 have been prepared from the tabulated data given in the Appendix. Because the tests in 1953 were made in summer instead of spring, the deflections and strains were affected by lower subbase moisture and higher slab temperatures, and these data are not included in the figures.

TABLE 3

EFFECT OF TEMPERATURE ON DEFLECTION;
Mean Deflection, d (0.001 in), at Indicated Temperature Differential, T (F)

Time	1954				1955				1956				1957			
	Corner		Edge		Corner		Edge		Corner		Edge		Corner		Edge	
	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
(a) 20-ft slabs																
A. M.	-4	36	0	20	4	44	4	27	6	32	6	18	4	29	4	16
P. M.	10	21	22	13	13	13	7	23	10	14	22	12	13	14	7	14
Diff.	14	15	22	7	9	31	3	4	4	18	18	6	9	15	3	2
d/T[1]	1.1		0.3		3.4		1.3		4.5		0.4		1.7		0.7	
(b) 100-ft slabs																
A. M.	0	43	1	21	-1	56	-1	32	3	43	3	23	1	28	1	19
P. M.	12	23	12	14	21	15	21	15	14	20	14	16	13	16	13	17
Diff.	12	20	11	7	22	41	22	17	11	23	11	7	12	12	12	2
d/T	1.7		0.6		1.9		0.8		2.1		0.6		1.0		0.2	

[1] d/T=Change in deflection per degree temperature difference between top and bottom of slab.

Influence of Temperature and Slab Length

Figure 14 may be compared with Figure 15 and Figure 16 with Figure 17 to observe the increase in deflection resulting from low-temperature differential between top and bottom of the concrete. The magnitudes of these differences are more clearly shown by the comparison of means of deflection in Table 3.

The doweled corners of the pavement slabs were three to four times as sensitive to changes in temperature differential as were the edges. For 20-ft slabs the grand average of the d/T values for corners is 0.0027 and for edges it is 0.0007 in. For corners of 100-ft slabs d/T averages 0.0017 as compared to 0.0006 in. for edges. These values indicate that the 20-ft slabs were more responsive to temperature differential than were the 100-ft slabs.

Influence of Subbase Type

A brief inspection of Figures 14 to 17 is sufficient to warrant the statement that subbases in general were of benefit in the reduction of slab deflections. The advantage of subbases was not as great at the pavement edges as at the corners, but the figures show that with very few exceptions the roadway structure benefited greatly under corner loading; that is, when the truck, with outer wheels on the slab edge, traveled across the joint.

Morning tests on 20-ft slabs indicated that 8-DG consistently reduced corner deflections to 50 percent or less of control area deflections. All dense-graded subbases were generally more effective than open-textured subbases. Cement-treated subbases

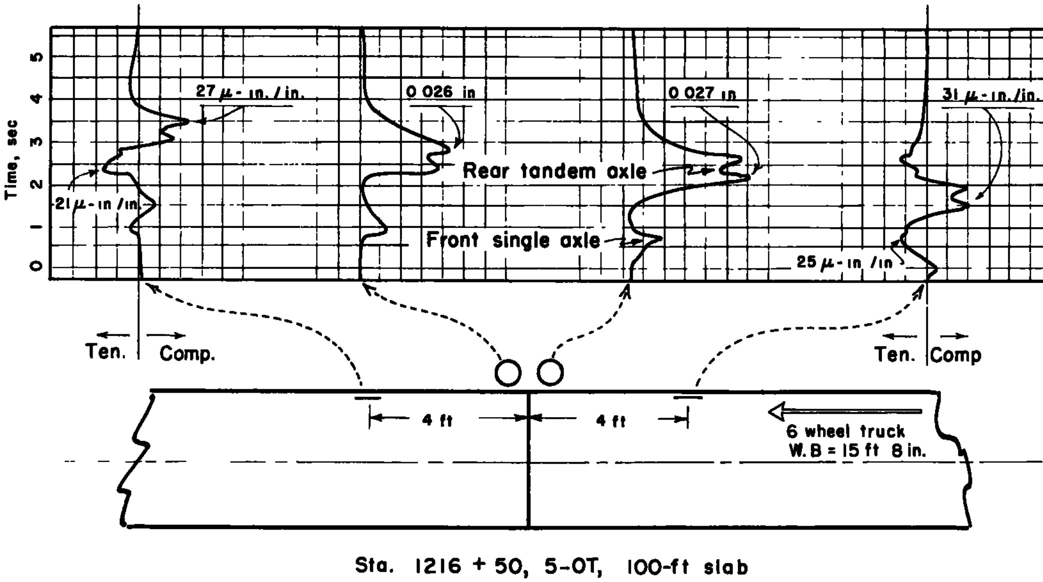


Figure 18. Deflections and strains at joint; 31,500-lb tandems moving along slab edge.

were slightly better than open-textured subbases, but not as good in deflection reduction as the dense-graded areas. At slab edges, CM-9 reduced deflections more consistently than other cement treatment.

Afternoon tests on 20-ft slabs showed corner deflections to be least on subbases 5-SC, 5-DG and CM-9. The other two dense-graded treatments and CM-7 were next in effectiveness, followed by 5-OT and 8-OT. At edges, CM-9 was most effective.

Morning tests on 100-ft slabs showed that corner deflections were least on subbases of 5-DG, 5-SC, 5-OT and CM-7. In 1957 all subbases reduced deflections 50 percent or more below those in the control area. At this time CM-11, 3-DG and 8-DG were not as effective as the others. At slab edges, deflections were lower over cement-treated subbases than over the granular treatment, except in 1957 when the open-textured treatments were most effective.

Afternoon records of tests on 100-ft slabs showed that all treatments except 3-DG and 3-SC were very effective in reducing corner deflections. In 1957 all treatments were good in this respect. At edges, 3-DG allowed deflections as large as those on the control area, but all other treatments reduced deflections by at least 30 percent. In 1957 the most effective were the three open-textured subbases and CM-9 and 5-SC.

In summary, with few exceptions all subbase treatments reduced slab deflections appreciably below those measured in the control areas. Although no single treatment or group was consistently best in all tests, it appears that deflections were reduced most consistently by treatments 5-SC, 5-DG, 8-DG, and CM-9. Of the open-textured treatments the 3-in. and 5-in. thicknesses were more effective than the 8-in. thickness. This trend was not substantiated in the dense-graded series, where 3-DG was the least effective. CM-5, CM-7, CM-11, and SC-3 were among the poorer subbases with respect to deflection reductions, although they were considerably superior to control.

MOVING LOAD STUDY

The scope of the study of strains in the concrete slabs due to applied loads was limited because strain measurements required electronic instrumentation. Strains on the slab upper surface at the outside edge at mid-slab and near corners were measured at treatments 5-OT, 5-DG, 5-SC, CM-7, and NS. This was accomplished by the use of SR-4 type A-9 gages and a four-channel automatic recorder.

Exploratory tests were made to find the distances from the joint at which maximum strain was developed when the load crossed the joint. These distances were used as the spacing for the SR-4 gages throughout the section tested. Other gages were cemented

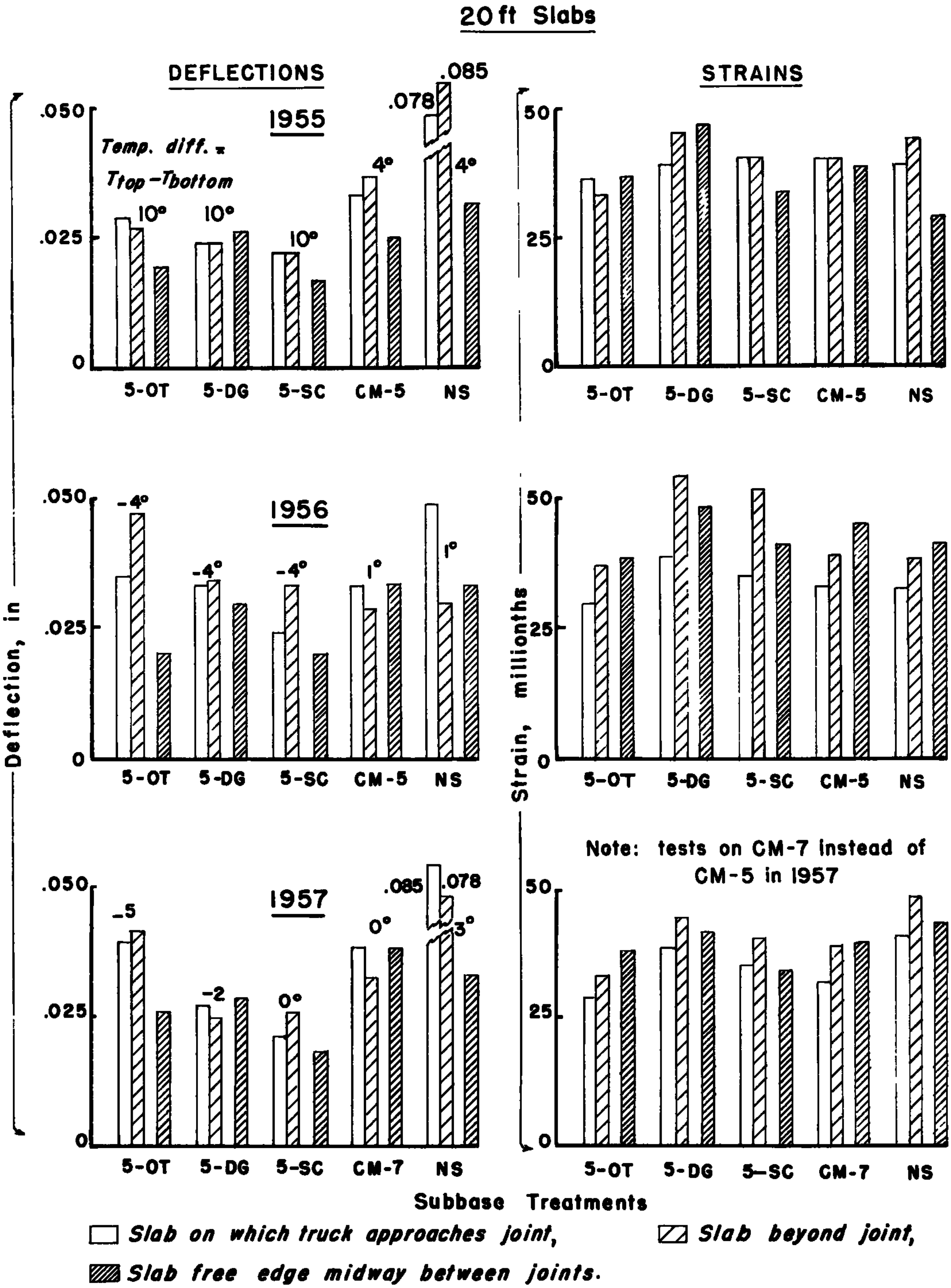


Figure 19. Maximum deflections and strains; 31,500-lb tandems moving along slab edge.

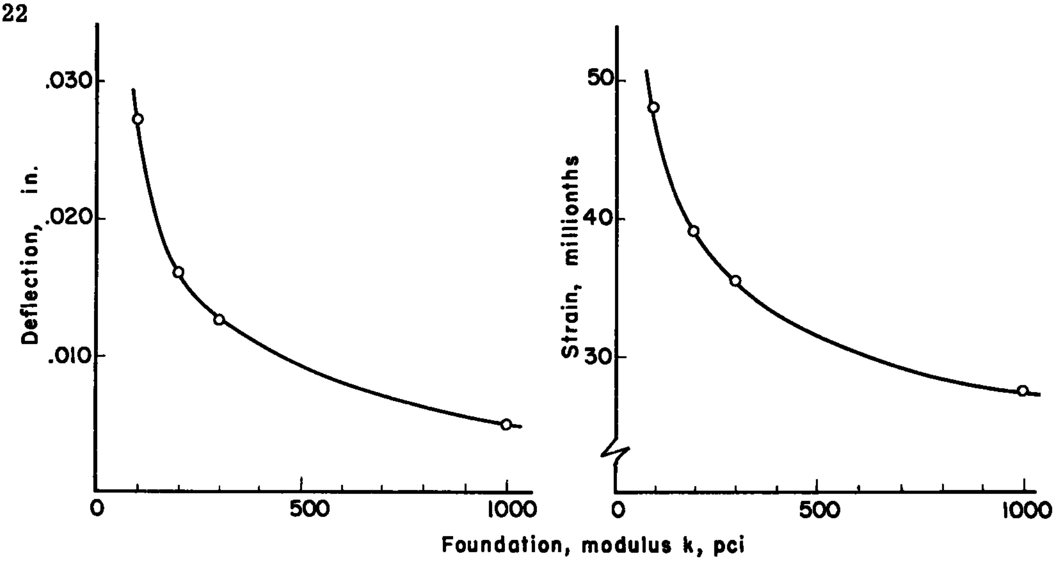


Figure 20. Theoretical deflections and strains; 31,500-lb tandems moving along free edge of 9-in. slab.

on the slab surface at mid-edge, where maximum deflections had been read in the deflection study. Compression readings in these gages were assumed to be approximately equal to the tensile strain developed directly beneath them in the bottom surface of the slab.

Linear variable differential transformers were attached to the brackets formerly used for maximum deflection measurement in order that deflections under moving loads could be correlated with measured strains.

One joint and two mid-slabs were instrumented in each specified treatment. Two deflections and two strains were read for each pass of the loading vehicle. A sample record is shown in Figure 18. The truck moved along the extreme edge at approximately 5 mph, and three passes constituted a test.

Strain and Deflection Magnitudes

A summary of maximum deflections and strains is given in the Appendix. Figure 19 is a graphic excerpt of the data from the 20-ft slab section for the last three years. It is impractical to try to compare deflection and strain magnitudes from year to year because tests were not made under the same conditions of temperature and foundation moisture content. Tests made during the same year were usually made with stable moisture content in the subbase, but often at different temperature differentials in the slabs. Thus, the moving load studies serve primarily to show the relations between deflections and strains at the time the test was made.

There is no well defined relationship between corner deflections and strains. This is explained in part by the fact that the bending radii are inversely proportional to the subgrade modulus, k. Although corner deflections on 5-OT are greater than those on 5-DG, corner strains are greater on the dense-graded material. Also, corner deflections on 5-SC are generally less than those on CM-5 or CM-7. However, the corner strains on SC-5 are as great or greater than those on CM-5 or CM-7. The slabs on the NS control areas deflected much more than the others when loads were at corners, but strains were about the same as those in slabs over subbases.

At slab edges midway between joints, strains were more nearly proportional to deflections than at corners. Ranked in order of their resistance to edge deflections the subbases were 5-SC, 5-OT, 5-DG, and CM-5. Slabs on the NS control area had highest deflections. Strains were smallest over 5-SC and largest over NS, but the differences among edge strains in slabs over the other three treatments did not appear to be significant.

COMPUTATIONS

Foundation Modulus

Influence charts (4) were used to compute theoretical deflections and strains at the edge of a 9-in. concrete slab loaded by 31,500-lb tandem axles. Young's modulus for the concrete was assumed to be 4,500,000 psi, Poisson's ratio 0.15, and subgrade modulus values were arbitrarily chosen at 100, 200, 300, and 1,000 pci. These points were used to plot the curves of Figure 20, which express relations between deflection and subgrade modulus and between strain and subgrade modulus for the assumed conditions.

Estimates of foundation modulus k for each subbase were found by comparing theoretical deflections and strains with average values of those measured at the slab edges during the five years of testing. The graphs were entered with the average deflection or strain as the ordinate to find the corresponding k on the abscissa (Table 4).

Deflection data show best support from 8-OT, 5-SC and CM-9 with k=360 pci. The

TABLE 4

AVERAGE DEFLECTIONS, STRAINS, AND COMPUTED K-VALUES

Subbase		Deflection[1] (0.001 in.)				Strain[2] (millionths)			
Type	Thickness (in.)	100-ft slab	20-ft slab	Average	k[3] (pci)	100-ft slab	20-ft slab	Average	k[3] (pci)
Open-textured	3	13	15	14	250				
	5	13	11	12	320	36	36	36	275
	8	9	13	11	360				
Dense-graded	3	24	15	20	150				
	5	15	15	15	220	36	42	39	200
	8	12	13	13	280				
Soil-cement	3	13	14	14	250	35	34	34	350
	5	12	9	11	360				
Cement-modified	5	13	17	15	220				
	7	11	13	12	320	37	40	38	225
	9	12	9	11	360				
	11	14	10	12	320				
Control	0	22	20	21	130	47	43	45	120

[1] Average slab deflection under edge load; afternoon tests.
[2] Average strain at edge; moving load tests.
[3] Figure 20

lowest modulus for a subbase was k=150 pci, found in the 3-DG area. This was only a small improvement over the 130-pci value computed for the NS control.

A check on foundation modulus found by the deflection method was made using average experimental strain values and the strain-vs-k curve. The k-values by this method were in agreement for 5-DG, 5-SC, and NS, but were low for 5-OT and CM-7.

Maximum Stresses

Using a value of 4,500,000 psi for the elastic modulus of the concrete, slab stresses were computed from strain measurements. Inasmuch as all strains were measured at the edges of slabs, Poisson's ratio is not a factor in the computation and stress is the product of strain by elastic modulus. Maximum strains noted in Figure 19 for each of the subbase areas tested were 39, 54, 52, 44, and 54 millionths, respectively, for 5-OT, 5-DG, 5-SC, CM-7, and NS areas. Stresses which would produce these strains would be approximately 175, 245, 235, 200, and 245 psi. These stresses are well below 50 percent of the 600- to 630-psi modulus of rupture values noted in HRB Bulletin 116 (1).

SUMMARY AND CONCLUSIONS

Observations and tests were made for five years on a typical concrete pavement built on 12 subbase treatments including open-textured crushed stone, dense-graded crushed stone, clay soil-cement and cement-modified clay soil. Items studied were joint pumping, edge pumping, edge blowing, continuous blowing, joint faulting, transverse cracking, and slab deflections and strains under legal loads. Attempts were made to rate the subbases on their ability to prevent joint and edge pumping and blowing and on their contributions to the load carrying capacity of the pavement. Although an absolute rating of each subbase was not achieved by this experiment, the data distinguish the best and the poorest subbases, and the following conclusions are drawn:

1. Joint Pumping: The ratio of pumping contraction joints to total number of joints observed was about the same in sections with 20-ft slabs as in sections with 100-ft slabs. All thicknesses (3 in., 5 in. and 8 in.) of open-textured subbases prevented joint pumping. The dense-graded subbases resisted joint pumping, the 8-in. thickness being better than the 5-in. thickness, which in turn was better than the 3-in. thickness. The silty clay soil-cement and cement-modified subbases tended to erode under the influence of water and heavy traffic, and pumping of this slurry at joints frequently developed. The 5-in. soil-cement subbase was the best of the cement-treated subbases.

2. Edge Pumping: The severity of edge pumping was greater in sections with short slabs than in the 100-ft slab sections. Open-textured subbases prevented edge pumping almost entirely. The dense-graded treatment was effective and the thicker subbase showed a slight advantage. The cement-treated subbases showed considerable edge pumping and the 5-in. soil-cement was the best of these treatments.

3. Edge Blowing: This phenomenon was more severe along edges of short slabs than in areas with long slabs. Again the open-textured materials were most effective, but they did not prevent edge blowing. No other treatments were significantly successful in the reduction of edge blows.

4. Continuous Blowing: The severity of continuous blowing increased with time, and there were more lineal feet of blowing at the edges of short slabs than at edges of long slabs. Only the open-textured treatments were effective in restricting continuous blowing.

5. Joint Faulting: The number of faulted joints and severity of fault increased with time. Severity of fault was slightly greater between 100-ft slabs than between 20-ft slabs. Joint faulting was least on open-textured subbases, and in this group the 3-in. and 8-in. thicknesses were better than the 5-in. thickness. Next in ability to resist joint faulting were sections of 8-in. dense-graded, 5-in. and 3-in. soil-cement, and 5-in. dense-graded material. Faulting on all treatments was less than on the control area.

6. Transverse Cracks: Full depth transverse cracks were infrequent until the pavement was almost four years old. After March 1956 cracking in the right-hand lane developed rapidly. The relations among crack occurrences and subbases were not the same in sections with 20-ft slabs as in sections with 100-ft slabs: in the 20-ft slabs, fewest cracks occurred on the 5-in. soil cement and on the dense-graded subbases; in the 100-ft slabs, the dense-graded subbases were generally better than average with respect to crack resistance. There is little correlation between cracking resistance and subbase among the remaining treatments.

7. Slab Deflections: Maximum slab deflections under the loading vehicle were considerably higher during the morning tests when the slab temperature differential was low than in the afternoon when the top of the concrete was 10 to 20 degrees warmer than the bottom. This influence of slab curling and edge and corner deflections was greater on 20-ft slabs than on 100-ft slabs.

No single subbase treatment was consistently best in restricting slab deflections under all conditions of loading. In the morning tests, however, 5-in. and 8-in. dense-graded, 5-in. soil-cement, and 5-in. open-textured subbases, were best; and 8-in. open-textured, 3-in. soil-cement, and 3-in. dense-graded, were the poorest. In the afternoon tests, 5-in. soil-cement and the three open-textured subbases were among the best, and 3-in. soil-cement and 3-in. dense-graded were the poorest. Although deflections of the slab on subbases were generally less than the deflections of the slab on the control areas, under some loading conditions 3-in. soil-cement and 3-in. dense-graded subbases were less effective than the untreated subgrade soil.

8. Slab Strains: On the four areas tested, strains were smallest on slabs over 5-in. soil-cement, and were only slightly larger in 5-in. open-textured areas. Next in order were the 7 percent cement-modified and 5-in. dense-graded. Average strains in slabs on subbases were less than those in control areas.

Finally, it appears that the open-textured subbases with edge drains were the most satisfactory over-all treatments, although they were inferior to dense-graded subbases and soil-cement subbases in preventing cracking in 20-ft panels, and in restricting delections. Thickness of the open-textured subbase was not a major factor in its effectiveness and the 3-in. thickness was about as good as the 5-in. and 8-in. thicknesses. Dense-graded subbases restricted pumping and contributed to the strength of the foundation, but the 3-in. thickness was inferior to the 5-in. and 8-in. thicknesses. Subbases of soil-cement made of clay soil and subbases of cement-modified clay soil were not entirely successful because of pumping. However, 5-in. soil-cement provided a strong subbase and averaged slightly better than the other subbases from the standpoint of restricting deflections and strains and in restricting cracking in 20-ft slabs. The fact that the 5-in. clay soil-cement subbase pumped but still contributed greatly to the support of the pavement indicates that the pumping had not reached serious proportions. Nevertheless, pumping cannot be condoned and this experience suggests that clay soil-cement subbases under concrete pavements cannot be expected to control pumping until a means of preventing surface erosion is developed.

Concrete aprons and gutters adjoining the paving slabs prevented edge blowing and pumping and were very effective in the restriction of joint pumping. Subbases in areas which were built with gutters and aprongs could not be classified as to performance because of the universal effectiveness of these adjuncts over all treatments.

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Appendix

TABLE 5

TRAFFIC SUMMARIES

(a) 24-HOUR WEEKDAY TRAFFIC COUNT

Month		Light Vehicles: Pass. Cars	Light Vehicles: Panels and Pickups	Heavy Vehicles: Single Unit Trucks	Heavy Vehicles: Combination Trucks	Heavy Vehicles: Total	Total Vehicles
February	1955	2555	197	265	2407	2672	5424
May	1955	3783	345	322	2251	2573	6701
August	1955	5595	223	334	2076	2410	8228
September	1955	5341	302	280	2042	2322	7965
October	1955	2288	190	315	1802	2117	4595
November	1955	2174	172	192	1836	2028	4374
December	1955	2584	154	222	2002	2224	4962
Avg.	1955	3474	226	276	2060	2336	6036
February	1956	2062	167	197	1841	2038	4267
June	1956	2684	209	214	1704	1918	4811
August	1956	2886	205	192	1404	1596	4687
December	1946	2455	177	219	1619	1838	4470
Avg.	1956	2522	189	205	1642	1848	4559
February	1957	2223	163	189	1649	1838	4224
September	1957	2665	214	331	1428	1759	4638
Avg.	1957	2444	188	260	1539	1799	4431

(b) TOTAL TRUCK AXLE FREQUENCY BY VARIOUS WEIGHT GROUPS FOR A 24-HOUR WEEKDAY

Weight Groups 1,000 lb	Total Number of Axles: 1954		1955						1956				1957	
	Nov.	Dec.	Feb.	May	Aug.	Sept.	Oct.	Nov.	Feb	June	Aug.	Dec.	Feb.	Sept.
No Pay Load	2391	3570	3954	3750	3474	3536	3117	3036	2810	2557	2069	2821	2703	2136
Under 14	3015	3314	3730	3627	3579	3323	3056	2997	3278	3102	2588	2623	2774	2996
14 - 15	444	550	547	520	454	455	446	515	380	394	308	349	368	266
15 - 16	365	433	427	570	473	434	361	365	353	285	230	244	288	242
16 - 17	356	288	259	317	270	278	262	228	274	207	208	202	231	231
17 - 18	257	188	250	238	200	240	181	170	179	229	157	200	214	183
18 - 19	168	145	238	204	169	158	120	104	122	154	124	154	104	142
19 - 20	102	81	127	81	65	104	56	69	45	68	85	104	95	61
20 - 21	16	26	33	15	18	34	9	8	12	23	10	20	24	20
21 - 22	-	9	20	7	3	10	3	5	-	3	9	2	3	7
22 - 23	-	2	6	-	-	-	-	-	3	5	2	-	-	2
23 - 24	-	-	2	-	-	2	-	3	-	-	-	-	-	-
24 and over	-	-	-	-	-	-	-	-	-	-	-	-	-	2
Total Axles	7114	8606	9593	9329	8705	8574	7611	7500	7456	7027	5788	6719	6804	6288

(c) SINGLE TRUCK AXLE FREQUENCY BY WEIGHT GROUPS FOR A 24-HOUR WEEKDAY

Axle Weight Groups 1,000 lb	Number of Single Axles: 1954		1955						1956				1957	
	Nov.	Dec.	Feb.	May	Aug.	Sept	Oct.	Nov.	Feb.	June	Aug.	Dec.	Feb.	Sept.
No Pay Load	1699	2718	3176	2874	2690	2754	2403	2310	2144	1917	1457	2069	2015	1510
Under 14	1708	2320	2592	2207	2316	1960	1871	1799	1996	1893	1459	1720	1619	1642
14 - 15	235	390	412	352	309	296	318	412	281	248	186	231	234	154
15 - 16	250	341	329	472	387	335	307	279	283	227	183	172	227	188
16 - 17	309	265	233	271	236	249	244	205	254	189	172	173	186	194
17 - 18	235	173	236	236	188	236	165	159	169	217	147	172	206	157
18 - 19	168	139	226	204	159	144	109	93	102	139	116	129	96	127
19 - 20	98	73	117	79	53	92	53	69	42	65	77	93	81	58
20 - 21	16	26	31	13	15	30	6	8	12	20	10	20	16	17
21 - 22	-	1	17	7	-	10	3	5	-	3	7	2	-	7
22 - 23	-	-	6	-	-	-	-	-	3	5	2	-	-	2
23 - 24	-	-	2	-	-	2	-	3	-	-	-	-	-	-
24 and over	-	-	-	-	-	-	-	-	-	-	-	-	-	2
Total	4718	6446	7377	6715	6353	6108	5479	5342	5286	4923	3816	4781	4680	4058

(d) TANDEM TRUCK AXLE FREQUENCY BY WEIGHT GROUPS FOR A 24-HOUR WEEKDAY

Axle Weight Groups 1,000 lb	Number of Tandem Axles, Listed Individually: 1954		1955						1956				1957	
	Nov.	Dec.	Feb.	May	Aug.	Sept.	Oct.	Nov.	Feb.	June	Aug.	Dec.	Feb.	Sept.
No Pay Load	692	852	778	876	784	782	714	726	666	640	612	752	688	626
Under 14	1307	994	1138	1420	1263	1363	1185	1198	1282	1209	1129	905	1155	1354
14 - 15	209	160	135	168	145	159	128	103	99	146	122	118	134	112
15 - 16	115	92	98	98	86	99	54	86	70	58	47	71	61	54
16 - 17	47	23	26	46	34	29	18	23	20	18	36	28	45	37
17 - 18	22	15	14	2	12	4	16	11	10	12	10	28	8	26
18 - 19	-	6	12	-	10	14	11	11	20	15	8	25	8	15
19 - 20	4	8	10	2	12	12	3	-	3	3	8	11	14	3
20 - 21	-	-	2	2	3	-	3	-	-	3	-	-	8	3
21 - 22	-	8	3	-	3	-	-	-	-	-	-	-	3	-
22 - 23	-	2	-	-	-	-	-	-	-	-	-	-	-	-
23 - 24	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24 and over	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	2396	2160	2216	2614	2352	2466	2132	2158	2170	2104	1972	1938	2124	2230

TABLE 6

NUMBER OF PUMPING JOINTS PER 100 FEET OF UNCURBED LENGTH

Sub-base	1953		1954	1955		1956			1957
	Mar.	May.	Mar.	Apr.	Oct.	Jan.	Mar.	Dec.	May
(a) 20-Ft Slabs									
3-OT	-	-	-	-	-	-	-	-	-
5-OT	-	-	-	-	-	-	-	-	-
8-OT	-	-	-	-	-	-	-	-	-
3-DG	-	-	-	0.3	-	-	-	0.5	0.1
5-DG		-	-	0.1	-	-	-	-	-
8-DG	-	0.1	0.2	-	-	-	-	-	-
3-SC	-	-	0.9	1.2	0.2	-	1.9	3.9	0.3
5-SC	-	-	0.7	0.9	0.3	-	2.2	3.3	0.2
CM-5	-	0.6	4.2	2.8	0.9	-	3.4	4.7	0.7
CM-7	-	0.6	2.5	2.9	1.2	0.1	4.0	4.1	0.9
CM-9	0.1	0.3	1.7	1.2	1.3	-	1.5	4.7	0.5
CM-11	-	0.8	1.6	0.4	0.2	-	2.0	3.4	-
NS	0.7	1.3	7.0	4.6	3.0	0.7	4.7	5.0	3.0
(b) 100-Ft Slabs									
3-OT	-	-	-	-	-	-	-	-	-
5-OT	-	-	-	-	-	-	-	-	-
8-OT	-	-	-	-	-	-	-	-	-
3-DG	-	-	-	0.8	-	-	0.4	-	-
5-DG	-	-	-	0.2	-	-	-	0.2	-
8-DG	-	-	-	-	-	-	-	-	-
3-SC	-	0.6	1.1	0.8	-	-	0.8	0.6	-
5-SC	-	0.2	0.4	0.8	-	-	0.6	0.4	0.4
CM-5	-	0.5	0.5	0.6	-	-	0.5	0.3	-
CM-7	-	-	0.7	0.5	-	-	0.5	0.5	-
CM-9	-	-	0.2	0.3	0.1	-	0.2	0.3	-
CM-11	-	0.2	0.7	0.7	-	-	0.5	0.1	-
NS	0.1	0.1	0.7	0.8	0.1	0.1	0.7	0.1	0.7

TABLE 7

OCCURRENCES OF EDGE PUMPING PER 100 FEET OF UNCURBED LENGTH

Sub-base	1953		1954	1955		1956			1957
	Mar.	May	Mar.	Apr.	Oct.	Jan.	Mar.	Dec.	May
(a) 20-Ft Slabs									
3-OT	-	-	-	-	-	-	-	-	-
5-OT	-	-	-	-	-	-	-	-	-
8-OT	-	-	-	-	-	-	-	-	-
3-DG	-	0.9	0.4	0.1	0.1	-	0.1	-	-
5-DG	-	-	-	-	-	-	-	-	-
8-DG	-	0.4	0.1	-	-	-	-	-	-
3-SC	-	1.4	2.7	3.5	3.8	1.8	5.7	5.2	3.0
5-SC	-	1.0	2.5	1.3	3.1	1.3	6.6	5.6	4.2
CM-5	0.3	3.4	3.5	4.5	5.4	1.2	8.8	6.5	2.9
CM-7	9.5	5.1	2.6	5.3	4.4	1.2	10.0	6.0	5.8
CM-9	0.4	3.5	1.2	4.2	4.6	0.7	4.0	3.1	4.2
CM-11	0.2	1.6	1.0	2.6	4.2	0.8	9.0	6.4	6.6
NS	-	1.7	3.4	7.7	8.7	7.4	10.0	7.7	7.4
(b) 100-Ft Slabs									
3-OT	-	-	-	-	1.4	-	-	-	-
5-OT	-	-	-	-	1.0	-	-	-	-
8-OT	-	-	-	-	0.4	-	-	-	-
3-DG	-	-	-	0.4	4.4	-	-	-	-
5-DG	-	-	-	0.2	3.4	-	-	-	-
8-DG	-	-	-	-	0.4	-	-	-	-
3-SC	-	1.1	0.8	0.8	0.3	0.3	0.3	-	1.4
5-SC	0.1	0.4	0.4	0.8	0.6	0.2	-	-	-
CM-5	-	1.0	0.9	0.3	1.1	0.3	0.3	-	0.2
CM-7	-	1.7	2.4	0.6	1.1	0.4	0.2	-	0.2
CM-9	-	0.5	1.4	0.3	1.4	0.6	0.2	0.1	0.1
CM-11	-	0.6	0.7	0.2	0.5	0.1	0.2	-	-
NS	0.1	0.9	1.4	0.8	3.4	0.2	0.5	0.2	1.0

TABLE 8

NUMBER OF BLOWHOLES AT EDGE PER 100 FEET OF UNCURBED LENGTH

Sub-base	1953		1954	1955		1956			1957
	Mar.	May	Mar.	Apr.	Oct.	Jan.	Mar.	Dec.	May
(a) 20-Ft Slabs									
3-OT	0.1	0.3	4.6	2.9	10.2	3.5	12.2	0.7	0.9
5-OT	0.2	1.7	2.4	1.0	15.5	7.2	-	0.7	0.2
8-OT	0.3	1.1	0.1	-	1.8	-	-	0.4	-
3-DG	-	6.8	11.9	40.3	44.7	13.5	30.4	10.0	2.6
5-DG	0.4	11.5	18.9	27.8	57.1	10.5	47.8	17.7	3.0
8-DG	1.1	13.3	17.8	23.6	26.8	10.3	49.8	10.9	1.7
3-SC	1.3	16.3	27.8	23.0	20.7	9.7	19.0	7.1	0.4
5-SC	0.8	20.6	12.1	20.6	24.6	7.0	31.4	11.6	5.5
CM-5	2.0	14.2	5.6	18.8	23.6	12.5	5.6	11.8	-
CM-7	9.1	10.0	12.8	20.5	7.5	9.6	9.1	5.4	-
CM-9	10.9	22.6	25.4	21.7	17.0	10.2	17.1	8.5	0.1
CM-11	2.8	13.2	13.0	27.0	25.4	5.6	10.0	5.2	6.2
NS	4.4	19.5	3.4	14.1	-	-	-	2.0	-
(b) 100-Ft Slabs									
3-OT	-	-	0.2	-	-	-	0.4	-	-
5-OT	-	-	2.2	0.2	-	-	1.4	-	-
8-OT	-	-	1.6	0.6	-	0.2	1.6	-	-
3-DG	-	0.8	10.2	8.4	6.8	4.0	-	3.2	4.4
5-DG	-	-	12.6	4.6	0.4	11.0	2.0	1.4	16.4
8-DG	-	3.0	18.4	6.2	0.8	7.6	1.8	5.4	10.0
3-SC	0.6	2.2	12.3	5.2	-	-	-	1.1	0.3
5-SC	0.9	2.9	3.4	2.4	-	0.4	-	-	5.0
CM-5	0.3	2.9	4.6	1.2	1.4	-	0.3	0.8	0.9
CM-7	1.5	9.8	2.1	3.5	-	0.6	0.1	6.4	-
CM-9	0.6	14.2	0.9	5.7	0.3	-	0.7	2.8	2.2
CM-11	4.1	9.6	8.0	3.9	0 2	-	0.2	1.6	0.4
NS	0.1	1.7	1.6	1.8	-	0.1	1.7	0.5	0.3

TABLE 9

LINEAL FEET OF BLOWING PER 100 FEET OF UNCURBED LENGTH

Sub-base	1953		1954	1955		1956			1957
	Mar.	May	Mar.	Apr.	Oct.	Jan.	Mar.	Dec.	May
(a) 20-Ft Slabs									
3-OT	-	-	-	-	-	0.5	-	-	2.8
5-OT	-	-	-	-	-	-	-	-	-
8-OT	-	-	-	-	-	-	-	-	-
3-DG	-	1.0	-	-	1.4	-	17.1	1.0	2.7
5-DG	-	1.7	-	-	-	-	12.8	15.1	2.2
8-DG	-	4.4	3.2	3.0	9.3	-	16.0	9.0	1.8
3-SC	-	1.8	-	5.9	18.8	10.1	7.8	3.3	23.2
5-SC	-	8.3	11.5	24.5	13.7	1.0	16.4	3.2	11.6
CM-5	-	6.1	2.1	4.5	11.1	14.5	9.2	21.6	22.9
CM-7	1.1	17.0	19.9	9.4	39.7	22.5	2.8	32.4	39.1
CM-9	0.3	24.9	8.4	4.2	4.4	7.5	30.8	31.5	49.1
CM-11	-	-	5.0	13.2	-	4.6	9.0	11.8	-
NS	-	-	8.7	-	-	-	-	-	16.1
(b) 100-Ft Slabs									
3-OT	-	-	-	-	12.0	-	-	-	-
5-OT	-	-	-	-	4.0	-	1.0	-	-
8-OT	-	-	-	-	5.0	1.0	2.0	-	2.0
3-DG	-	1.2	-	33.0	-	6.0	100.0	4.0	10.0
5-DG	-	-	-	18.0	0.6	2.0	69.0	-	2.0
8-DG	-	-	-	30.0	-	4.0	80.0	-	1.0
3-SC	-	11.0	2.2	0.8	23.4	5.5	64.8	2.8	11.8
5-SC	-	2.5	0.6	-	4.0	2.0	15.0	-	9.0
CM-5	-	5.1	1.1	2.3	6.0	2.0	27.5	2.7	3.9
CM-7	-	1.3	2.5	1.5	8.0	5.5	43.5	-	6.5
CM-9	-	1.2	0.8	-	3.0	1.2	54.0	2.4	9.8
CM-11	-	6.7	1.0	3.0	19.0	3.0	27.5	2.0	7.5
NS	-	-	1.3	1.7	-	0.5	4.5	-	2.0

TABLE 10

JOINT FAULTING

Sub-base	Number of Faults in Each Class[a]																	
	March 1954			April 1955			March 1956			May 1956			Dec 1956			May 1957		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
(a) 20-Ft Slabs																		
3-OT	1	-	-	6	-	-	25	6	1	23	10	-	31	12	-	27	10	-
5-OT	1	1	-	6	1	-	18	7	-	20	6	-	28	8	-	23	7	-
8-OT	4	1	-	9	1	-	18	6	-	25	5	-	26	9	-	24	9	-
3-DG	8	3	-	7	7	-	13	24	2	11	28	4	12	31	3	16	31	2
5-DG	2	2	-	7	3	-	13	21	1	16	25	2	23	21	3	19	25	2
8-DG	3	-	-	7	1	-	15	21	1	20	24	2	15	27	3	20	22	3
3-SC	2	-	-	5	2	-	17	16	-	15	24	1	16	22	2	17	19	3
5-SC	3	1	-	6	2	-	15	15	-	26	16	-	19	20	-	18	24	1
CM-5	7	4	-	8	8	-	19	16	4	17	24	2	15	26	3	8	28	6
CM-7	6	1	-	13	4	-	17	16	4	19	20	1	13	22	3	13	25	4
CM-9	5	3	-	10	8	-	17	20	6	18	25	3	16	27	1	10	28	9
CM-11	3	2	-	7	3	-	6	9	1	6	13	-	8	13	-	6	13	1
NS	4	2	-	7	7	-	10	8	1	9	11	1	6	15	1	6	14	3
(b) 100-Ft Slabs																		
3-OT	1	-	-	-	-	-	2	1	-	4	15	-	3	2	-	4	1	-
5-OT	1	-	-	3	-	-	7	3	-	6	5	-	7	3	1	7	4	-
8-OT	1	-	-	1	3	-	5	1	1	6	-	1	5	2	1	5	2	1
3-DG	-	-	-	4	-	-	4	5	1	2	7	1	1	8	1	1	8	1
5-DG	-	-	-	3	-	-	4	4	-	2	6	-	1	7	-	1	7	-
8-DG	2	-	-	2	1	-	3	3	2	4	4	-	4	5	-	3	5	1
3-SC	1	-	-	1	3	-	2	5	-	3	5	-	3	5	-	2	5	1
5-SC	-	-	-	2	-	-	6	1	-	6	2	-	2	6	-	3	6	-
CM-5	-	-	-	-	1	-	2	6	-	5	4	1	4	5	1	2	8	-
CM-7	1	-	-	-	2	-	3	5	2	2	5	2	3	5	2	1	7	2
CM-9	1	-	-	1	2	-	1	3	1	3	3	2	3	4	1	3	4	1
CM-11	1	-	-	2	2	-	2	5	1	-	8	1	2	7	1	2	7	1
NS	2	1	1[b]	1	3	1	5	2	1	4	5	1	4	3	-	2	3	2

[a] Class 1 = 1/16 in ; Class 2 = 1/8 to 3/16 in.; Class 3 = 1/4 in and greater.
[b] Broken slab

TABLE 11

TRANSVERSE CRACKS

Sub-base	Total Count of Transverse Cracks						
	Mar 1954	Apr 1955	Oct 1955	Jan 1956	Mar 1956	Dec 1956	May 1957
(a) 20-Ft Slabs[a]							
3-OT	-	-	-	-	-	7	20
5-OT	-	-	-	-	-	10	22
8-OT	-	-	1	1	1	16	33
3-DG	-	-	2	2	2	4	8
5-DG	-	-	1	1	1	6	12
8-DG	-	-	-	-	-	-	6
3-SC	-	-	-	1	2	16	19
5-SC	-	-	-	-	-	3	5
CM-5	-	1	2	2	2	19	22
CM-7	-	1	2	3	3	18	24
CM-9	-	-	4	4	8	22	36
CM-11[b]	-	-	-	-	-	8	12
NS[b]	-	-	3	3	4	24	27
(b) 100-Ft Slabs[c]							
3-OT	1	1	4	9	12	34	44
5-OT	1	2	11	11	13	28	50
8-OT	3	5	5	10	10	35	53
3-DG	5	8	9	10	10	23	41
5-DG	-	-	2	2	2	31	35
8-DG	1	4	7	15	15	30	43
3-SC	-	-	-	8	8	27	64
5-SC	-	1	1	4	4	16	60
CM-5	1	1	2	4	4	39	63
CM-7	-	1	2	7	7	44	68
CM-9	1	3	8	13	14	49	66
CM-11	-	1	7	10	12	31	55
NS	7[d]	8	10	11	12	25	32

[a] 50 slabs each treatment
[b] 25 slabs
[c] 10 slabs each treatment.
[d] Undersealed.

TABLE 12-A

MAXIMUM DEFLECTIONS,

31,500-LB TANDEM AXLE ALONG OUTER EDGE —AFTERNOON TESTS

Sub-base	Average Deflection (0 001 in)														
	Doweled Corner[a]										Free Edge				
	1953 An	1953 Lv	1954 Ap	1954 Lv	1955 Ap.	1955 Lv	1956 Ap	1956 Lv	1957 Ap.	1957 Lv	1953	1954	1955	1956	1957
(a) 20-Ft Slabs															
ΔT[b]	15 deg		10 deg		22 deg		13 deg		7 deg		15 deg	10 deg	22 deg	13 deg	7 deg
3-OT	9	10	28	25	21	17	13	15	35	26	11	17	15	16	15
5-OT	9	8	18	18	9	10	15	14	22	20	9	10	9	14	11
8-OT	12	13	23	22	14	14	13	12	18	16	14	16	10	13	12
3-DG	14	14	21	17	13	13	10	7	18	17	15	17	12	15	15
5-SG	12	10	16	14	11	9	14	9	18	17	13	13	13	16	19
8-DG	13	11	18	22	11	14	14	15	14	10	10	13	13	17	14
3-SC	10	11	22	25	15	13	19	16	26	25	11	15	12	15	15
5-SC	8	8	18	13	6	6	8	8	17	12	8	10	9	10	10
CM-5	6	10	25	21	15	15	11	14	30	30	14	19	16	17	17
CM-7	8	7	19	15	10	9	9	8	19	19	13	15	12	11	14
CM-9	9	7	14	19	9	13	8	10	15	24	11	10	9	8	9
CM-11	8	10	15	23	12	11	15	9	21	25	8	11	9	11	12
NS	24	21	32	39	29	31	18	19	58	47	22	20	21	19	20
(b) 100-Ft Slabs															
ΔT[b]	12 deg		12 deg		21 deg		14 deg		13 deg		12 deg	12 deg	21 deg	14 deg	13 deg
3-OT	20	19	21	17	6	9	7	9	9	7	20	13	12	11	8
5-OT	15	14	13	14	13	14	14	13	14	11	16	14	15	9	10
8-OT	20	13	11	13	15	14	9	11	10	11	9	10	10	9	7
3-DG	38	37	32	27	24	24	33	30	20	21	20	21	27	28	23
5-DG	25	23	15	14	18	16	22	19	13	13	9	15	16	17	15
8-DG	26	25	18	20	14	14	18	15	10	14	12	14	14	8	13
3-SC	21	24	34	43	23	27	11	11	10	5	13	15	12	14	12
5-SC	12	-	18	17	10	10	13	8	11	9	11	14	12	15	9
CM-5	16	15	14	10	13	11	21	17	18	13	12	11	13	15	13
CM-7	15	15	12	17	9	6	13	14	18	14	12	11	10	13	11
CM-9	14	12	15	14	16	14	19	22	16	17	12	11	13	15	10
CM-11	15	12	20	18	12	16	25	32	16	18	12	14	13	17	16
NS	102	95	73	83	27	26	62	62	41	42	20	21	23	26	21

[a] Ap. = Slab on which truck approaches joint, Lv = Slab on which truck leaves joint

[b] Temperature differential, F.

TABLE 12 B

MAXIMUM DEFLECTIONS,

31,500-LB TANDEM AXLE ALONG OUTER EDGE — MORNING TESTS

Sub-base	Average Deflection (0 001 in)														
	Doweled Corner										Free Edge				
	1953 Ap	1953 Lv	1954 Ap	1954 Lv.	1955 Ap.	1955 Lv	1956 Ap	1956 Lv	1957 Ap	1957 Lv	1953	1954	1955	1956	1957
(a) 20-Ft Slabs															
ΔT	-2 deg		-4 deg		4 deg		6 deg		4 deg		2 deg	0 deg	4 deg	6 deg	4 deg
3-OT	-	-	34	35	49	48	30	47	37	32	18	20	29	19	14
5-OT	-	-	23	33	45	61	31	37	26	24	14	16	27	13	13
8-OT	-	-	44	49	54	53	37	44	27	33	23	24	39	20	14
3-DG	-	-	28	44	27	27	34	30	26	19	18	20	21	16	17
5-DG	-	-	29	30	26	34	26	28	20	22	15	17	26	20	18
8-DG	-	-	25	31	20	22	25	27	13	12	14	19	22	21	14
3-SC	-	-	37	44	49	40	40	40	30	33	16	21	25	21	20
5-SC	-	-	39	41	42	47	18	25	21	26	14	18	33	15	11
CM-5	43	43	41	34	37	37	33	29	33	46	25	27	30	27	18
CM-7	34	34	27	30	47	46	26	24	21	20	21	24	22	16	15
CM-9	22	21	21	39	31	42	16	30	18	33	11	15	19	12	10
CM-11	-	-	26	36	46	45	30	38	23	28	21	17	32	14	19
NS	47	46	47	60	84	85	45	49	62	52	20	20	30	23	20
(b) 100-Ft Slabs															
ΔT	-2 deg		0 deg		-1 deg		3 deg		1 deg		1 deg	-1 deg	-1 deg	3 deg	1 deg
3-OT	-	-	41	35	61	56	45	43	24	19	26	29	39	26	12
5-OT	-	-	30	38	43	43	32	39	19	19	23	32	44	24	17
8-OT	-	-	30	42	70	59	34	39	17	18	13	23	36	24	15
3-DG	-	-	59	61	51	53	53	52	39	29	19	24	34	35	24
5-DG	-	-	26	31	43	41	47	42	17	18	17	20	29	21	21
8-DG	-	-	37	36	37	47	35	35	30	35	18	23	29	26	30
3-SC	45	49	50	75	74	102	22	16	20	21	15	18	30	21	19
5-SC	26	24	25	34	46	41	28	27	20	19	12	16	30	19	16
CM-5	28	27	26	29	41	39	41	50	29	26	14	13	24	18	20
CM-7	26	29	25	39	40	35	31	36	19	24	17	17	27	21	18
CM-9	34	31	33	43	68	64	41	43	25	24	15	15	36	19	17
CM-11	39	36	30	28	53	69	47	53	38	41	17	15	29	22	22
NS	-	-	92	113	75	87	93	94	68	75	18	25	39	33	28

TABLE 13

MAXIMUM DEFLECTIONS AND STRAINS UNDER MOVING LOADS

Sub-base	20-Ft Slabs							100-Ft Slabs						
	Temp. Diff.	Defl. (0.001 in.)			Strain (millionths)			Temp. Diff.	Defl. (0.001 in.)			Strain (millionths)		
		Corner[a]		Edge	Corner[a]		Edge		Corner[a]		Edge	Corner[a]		Edge
	F	Ap.	Lv.		Ap.	Lv.		F	Ap.	Lv.		Ap.	Lv.	
1953														
5-OT	4	15	16	12	27	26	29	11	13	11	16	28	37	38
5-DG	4	18	16	25	33	30	41	6	14	16	12	32	32	31
5-SC	-2	54	34	23	41	39	31	8	22	24	21	33	34	38
CM-7	0	26	26	21	28	28	36	15	36	26	23	33	31	39
NS	0	31	30	22	41	40	36	9	61	60	15	33	47	39
1954														
5-OT	5	29	25	-	27	23	-	6	23	26	15	27	26	31
5-DG	8	11	18	20	34	26	31	6	21	31	12	29	27	25
5-SC	4	24	28	-	25	29	-	2	23	28	23	30	29	28
CM-7	4	22	24	-	29	28	-	2	20	22	14	32	30	-
NS	6	36	48	-	31	33	-	8	57	75	27	38	40	39
1955														
5-OT	10	28	27	18	36	33	36	15	14	15	15	33	30	37
5-DG	10	24	24	27	38	45	47	15	26	25	18	43	37	38
5-SC	10	22	22	17	40	40	33	12	24	25	20	37	37	38
CM-5	4	33	37	25	40	40	38	12	23	22	19	32	33	31
NS	4	78	85	32	38	44	48	15	32	32	28	47	45	47
1956														
5-OT	-4	35	47	20	30	37	38	3	23	24	15	24	31	-
5-DG	-4	33	34	30	39	54	48	3	47	44	28	27	-	-
5-SC	-4	24	33	20	35	52	41	3	24	22	18	28	31	32
CM-5	1	30	33	28	33	39	45	3	25	42	17	37	38	34
NS	1	51	48	30	33	38	42	3	87	90	30	31	-	53
1957														
5-OT[b]	-5	40	42	26	29	33	38	0	33	62	35	32	38	39
5-DG[b]	-2	27	25	28	39	45	42	0	80	55	58	38	48	48
5-SC[b]	0	21	26	18	35	41	34	3	20	19	25	35	33	42
CM-7[b]	0	39	33	39	32	39	40	5	34	29	29	36	44	44
NS[b]	3	85	78	33	41	48	44	5	102	68	103	40	54	50

[a] Ap. = Slab on which truck approaches joint; Lv. = Slab on which truck leaves joint.
[b] In 1957 the subbases tested under 100-ft slabs were 3-OT, 3-DG, 5-SC, and CM-9.