

EXPERIMENTS WITH CONTINUOUS REINFORCEMENT IN CONCRETE PAVEMENTS

H. D. CASHELL, *Assistant Highway Engineer*

Public Roads Administration

AND

S. W. BENHAM, *Research Engineer*

Indiana Highway Commission

SYNOPSIS

Last year there were described before the Highway Research Board, cooperative experiments with continuously reinforced concrete pavement sections laid near Stilesville, Indiana. The present report contains the data obtained during the first two years of observation of these experimental sections.

Changes in pavement elevation have been generally small and there is nothing to indicate that these changes have affected the structural condition of the various sections.

The annual cycle of length change of the various sections shows that those approximately 150-ft. long move with as much freedom as the very short sections. The movement of sections greater than 150-ft. in length is apparently restrained by the subgrade and this restraint is progressively greater as the section length is increased.

In the long, heavily-reinforced sections many fine cracks have developed in the central area. In the sections of intermediate length containing $\frac{1}{4}$ -in. steel bars a moderate amount of cracking has developed, while only a very limited amount of cracking has occurred in the short sections containing welded wire fabric. While the width of the cracks is slightly greater in the sections containing the smaller amounts of longitudinal steel there is no evidence of spalling, raveling, disintegration, steel failure or other structural weakness at any of the cracks. A relation between the length of the section as constructed and the average slab length (or a distance between transverse cracks) appears to exist. So far, no relation has been found between the average slab length and either the type or the amount of longitudinal steel.

Relative roughness determinations over the various sections show that the surface of the sections was very smooth after about 18 months of service.

This is the second progress report describing the experimental reinforced concrete pavement investigation that is being conducted by the Public Roads Administration and the Indiana State Highway Commission. In the first report¹ the scope of the study was outlined in detail and the construction of the project was described. The present report contains a general discussion of the current condition of the reinforced pavement, with data showing the more important de-

velopments and trends that have become evident during its 2-year life. It is not the purpose of this report to draw definite conclusions regarding the relative merits of the various sections, but to present data that will show the observed behavior to date.

To aid in the better understanding of the data certain essential details of design that were presented in the first report will be repeated here. The number and length of the sections and the amount and type of reinforcement used in each are given in Tables 1, 2, and 3. It will be noted that the values of the calculated maximum steel stresses is such as to permit direct comparison between sections

¹Earl C. Sutherland and Sanford W. Benham, "Experiments with Continuous Reinforcement in Concrete Pavements," *Proceedings*, Highway Research Board, Vol. 19, 1939, *Public Roads*, Vol. 20, no. 11, January 1940.

containing different types as well as different percentages of longitudinal steel. It is apparent from these data that the

TABLE 1
 DETAILS OF STEEL REINFORCEMENT IN EXPERIMENTAL REINFORCED CONCRETE PAVEMENT
 Cold Drawn Wire (Welded Fabric)

Number of sections	Length of each section	Calculated maximum stress in steel	Reinforcement size and spacing		Weight of longitudinal steel
			Longitudinal	Transverse	
149-lb					
	<i>ft</i>	<i>lb per sq in</i>			<i>lb per 100 sq ft</i>
6	140	25,000	No 4-0	No 3	132
6	190	35,000	d = 0.3938 in	12 in c c	
6	250	45,000	4 in c c		
6	310	55,000			
107-lb					
6	90	25,000	No 4-0	No. 3	91
6	130	35,000	d = 0.3938 in.	12 in c c	
6	170	45,000	6 in c c		
6	200	55,000			
91-lb					
6	80	25,000	No 3-0	No 4	77
6	110	35,000	d = 0.3625 in	12 in c c.	
6	140	45,000	6 in c c		
6	170	55,000			
65-lb					
6	60	25,000	No 0	No 6	55
6	80	35,000	d = 0.3065 in	12 in c c	
6	100	45,000	6 in c c		
6	120	55,000			
45-lb					
6	30	25,000	No 3	No 6	35
6	50	35,000	d = 0.2437 in	12 in c c	
6	60	45,000	6 in c c		
6	80	55,000			
32-lb					
6	20	25,000	No 6	No 6	22
6	30	35,000	d = 0.1920 in	12 in c c	
6	40	45,000	6 in c c		
6	50	55,000			

NOTE—Sections are 10 ft wide

The average tensile strength of each of the different types and sizes of steel reinforcement yield points of both the billet and rail steel bars are appreciably higher than the

calculated maximum stresses shown in Tables 2 and 3.

In addition to the regular sections there were included four other sections in which special joint designs and different methods of reinforcing were employed. The essential common features of these four

transverse steel at this point and by greasing (5) Dowel bars for load transfer were placed across one-half of the weakened-plane joints of each section.

The distinguishing features between the four sections are as follows:

No. 1. Weakened-plane joints are of

TABLE 2
DETAILS OF STEEL REINFORCEMENT IN EXPERIMENTAL REINFORCED CONCRETE PAVEMENT
Billet Steel Bars (Intermediate Grade—Deformed)

Number of sections	Length of each section	Calculated maximum stress in steel	Reinforcement size and spacing		Weight of longitudinal steel
			Longitudinal	Transverse	
	<i>ft.</i>	<i>lb. per sq. in.</i>			<i>lb. per 100 sq. ft.</i>
2	360	15,000	1-in. round bars 6 in. c c	$\frac{1}{2}$ -in. round bars 24 in. c c.	534
2	600	25,000			
2	840	35,000			
2	1,080	45,000			
4	200	15,000	$\frac{3}{4}$ -in. round bars 6 in. c c.	$\frac{1}{2}$ -in. round bars 24 in. c c	300
4	340	25,000			
4	470	35,000			
4	610	45,000			
4	90	15,000	$\frac{1}{2}$ -in. round bars 6 in. c.c.	$\frac{1}{2}$ -in. round bars 24 in. c c	134
4	150	25,000			
4	210	35,000			
4	270	45,000			
6	50	15,000	$\frac{3}{4}$ -in. round bars 6 in. c.c.	$\frac{3}{4}$ -in. round bars 24 in. c c	75
6	80	25,000			
6	120	35,000			
6	150	45,000			
6	20	15,000	$\frac{1}{2}$ -in. round bars 6 in. c c.	$\frac{1}{2}$ -in. round bars 12 in. c c.	33
6	40	25,000			
6	50	35,000			
6	60	45,000			

NOTE—Sections are 10 ft. wide.

sections are. (1) Each section is 500 ft. long (2) Weakened-plane joints were placed at 10-ft. intervals in each. (3) Reinforcement consisted of welded fabric placed continuously through the weakened-plane joint. (4) The bond between the steel and the concrete was broken for a distance of 18 in. on each side of each weakened-plane joint by omitting the

the submerged type and the welded fabric reinforcement weights 91 lb. per square.

No. 2. This section is the same as no. 1, except that it is reinforced with a 45-lb. welded fabric.

No. 3. Weakened-plane joints are of the surface groove type and the reinforcement weights 91 lb. per square.

No. 4. The section is the same as no. 3,

except that it is reinforced with a 45-lb welded fabric

The amount of longitudinal steel in the 91-lb welded fabric is 77 lb, while that in the 45-lb welded fabric is 35 lb per square

The strength of the concrete was determined by compression tests on drilled

mately 1½ miles of this 6-mile project has been subject to heavy truck and passenger traffic for nearly two years, while the remaining 4½ miles has been under the same traffic for 1½ years

The schedule of observations that was described in the first report has been adhered to and, for information concern-

TABLE 3
 DETAILS OF STEEL REINFORCEMENT IN EXPERIMENTAL REINFORCED CONCRETE PAVEMENT
 Rail Steel Bars (Deformed)

Number of sections	Length of each section <i>ft</i>	Calculated maximum stress in steel <i>lb per sq in</i>	Reinforcement size and spacing		Weight of longitudinal steel <i>lb per 100 sq ft</i>
			Longitudinal	Transverse	
2	600	25,000	1-in round bars 6 in c c	½-in round bars 24 in c c	534
2	840	35,000			
2	1,080	45,000			
2	1,320	55,000			
4	340	25,000	¾-in round bars 6 in c c	½-in round bars 24 in c c	300
4	470	35,000			
4	610	45,000			
4	740	55,000			
4	150	25,000	½-in round bars 6 in c c	½-in round bars 24 in c c	134
4	210	35,000			
4	270	45,000			
4	330	55,000			
6	80	25,000	¾-in round bars 6 in c c	¾-in round bars 24 in c c	75
6	120	35,000			
6	150	45,000			
6	180	55,000			
6	40	25,000	¼-in round bars 6 in c c	¼-in round bars 12 in c c	33
6	50	35,000			
6	60	45,000			
6	80	55,000			

NOTE—Sections are 10 ft wide

cores at the age of six months. The average strength was found to be 6,360 lb. per sq. in. The average density of the concrete was 154 lb. per cu. ft

The experimental pavement was constructed during the months of September and October 1938 as a regular Federal-aid project, being a part of the transcontinental highway U S 40. Approx-

ing the details of this program, the reader is referred to the first report

Briefly, however, the schedule comprises

- 1 Measurement of changes in pavement elevation
- 2 Measurement of changes in length of the experimental sections.
- 3 Condition and crack surveys

In addition to these observations during the past year, measurements of the relative surface roughness of the various sections were made. The results of all of these various studies are presented in this report.

TABLE 4
TENSILE STRENGTH OF STEEL REINFORCEMENT
Welded Fabric

Weight	Average tensile strength	
	Longitudinal wires	Transverse wires
<i>lb. per sq.</i>	<i>lb. per sq. in.</i>	<i>lb. per sq. in.</i>
32	88,700	84,767
45	81,000	87,000
65	83,700	87,800
91	89,100	88,867
107	80,250	86,150
149	81,820	81,820

Billet Steel Bars

Diameter	Average tensile strength	
	Yield point	Ultimate
<i>in.</i>	<i>lb per sq. in.</i>	<i>lb. per sq. in.</i>
$\frac{1}{2}$	56,850	77,300
$\frac{3}{8}$	55,480	81,940
$\frac{1}{2}$	51,433	78,567
$\frac{3}{4}$	49,132	78,468
1	46,943	78,033

Rail Steel Bars

Diameter	Average tensile strength	
	Yield point	Ultimate
<i>in.</i>	<i>lb per sq. in.</i>	<i>lb per sq. in.</i>
$\frac{1}{2}$	60,250	84,600
$\frac{3}{8}$	66,650	93,625
$\frac{1}{2}$	68,768	115,312
$\frac{3}{4}$	64,428	113,255
1	63,342	113,202

PAVEMENT ELEVATIONS DETERMINED
PERIODICALLY

In connection with the presentation of the pavement elevation data certain pertinent physical characteristics and moisture determinations of the subgrade are

given in Table 5. The soil samples were taken from the finished subgrade at the depths indicated.

The first set of elevation measurements to establish the normal elevation of the pavement was started as soon as possible after the necessary bench marks had been established and the measuring points installed in the pavement.

Unfortunately, the first set of elevation measurements had been completed on only about $1\frac{1}{2}$ miles of the experimental pavement when the first freezing weather occurred, so it cannot be certain that the remaining portion was entirely undisturbed at the time of these first measurements. The winter of 1938-39 was generally mild in this area and frost did not penetrate more than a few inches at any time, however.

The second set of elevation measurements over the full length of the experimental sections was made during October 1939, the pavement being about one year old. It is believed that by this time the subgrade had attained a normal moisture condition throughout and the pavement slab was at an elevation normal for the season.

The third set of elevation measurements over the full length of the experimental sections was made in January 1940. This was a severe winter and the frost had penetrated to a depth of about 20 in. at the time of the measurements.

Other measurements of the elevation of certain selected sections of the pavement have been made from time to time.

In Figure 1 are shown the changes in pavement elevation that had occurred on typical sections at the end of the first year of pavement life, using the elevations determined in the fall of 1938 as a base. The moisture condition and other subgrade soil data at the time the pavement was placed are shown also on this graph. While no moisture determinations were made at the time the second set of elevation data were obtained it is only reason-

able that changes had occurred during the year since the concrete was placed and it is believed that the changes in pavement elevation that had developed during this period are caused by changes in the physical state of the subgrade soil

It will be noted that little change had occurred at any point in the 595-ft. sec-

while on the 1,310-ft section slight increases and slight decreases developed in certain areas during the first year period

The data in Figure 1 give a fair indication of the general order of the changes in elevation that were observed at the end of the first year. Over the entire length of the experimental sections no change in

TABLE 5
SUBGRADE SOIL DATA

	Silt	Clay	Liquid limit	Plasticity index	Moisture content		
					0-3 in below surface	3 in -12 in below surface	12 in -24 in. below surface
					%	%	%
Maximum	65	26 ^a	52	26	22.6	24.0	27.5
Minimum	20	7	19	4	6.1	8.9	8.1
Average	48	17	33	12	12.8	15.5	17.1

^a This maximum percentage was exceeded in two instances, however, but these cases were not considered as representative of the entire project

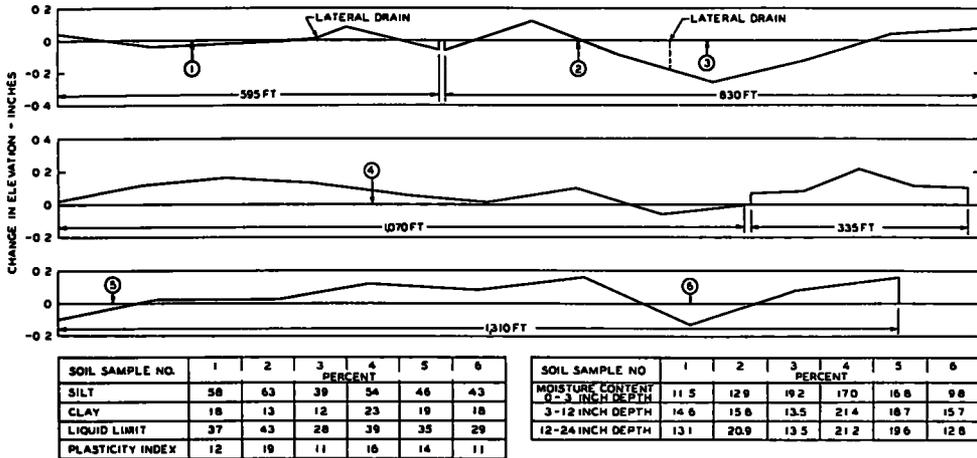


Figure 1. Changes in Elevation of Certain Sections of Pavement at End of First Year

tion In the 830-ft section the most noticeable change was a settlement of 0.2 in. near the center. During construction it was observed that the subgrade in this area was somewhat spongy at the time the concrete was placed. The figure shows that over much of the length of both the 335-ft and the 1,070-ft sections the elevation increased 0.1 to 0.2 in.,

elevation of more than 0.5 in. was found at this time.

Using as a datum the elevations measured on the pavement surface in October 1939, when presumably the sections had stabilized at their normal position for this season of the year, the position of certain selected sections are shown in Figures 2, 3 and 4 as they were found to be (1) in

January 1940 with the subgrade frozen deeply, (2) in May 1940 after thawing was complete, and (3) in October 1940 after the annual cycle of change was again completed.

In these figures the data are divided into

Figure 4 are relatively short sections reinforced with welded wire fabric.

It is of interest to note that the changes in elevation caused by freezing are

1. Of relatively small magnitude
2. Not uniform

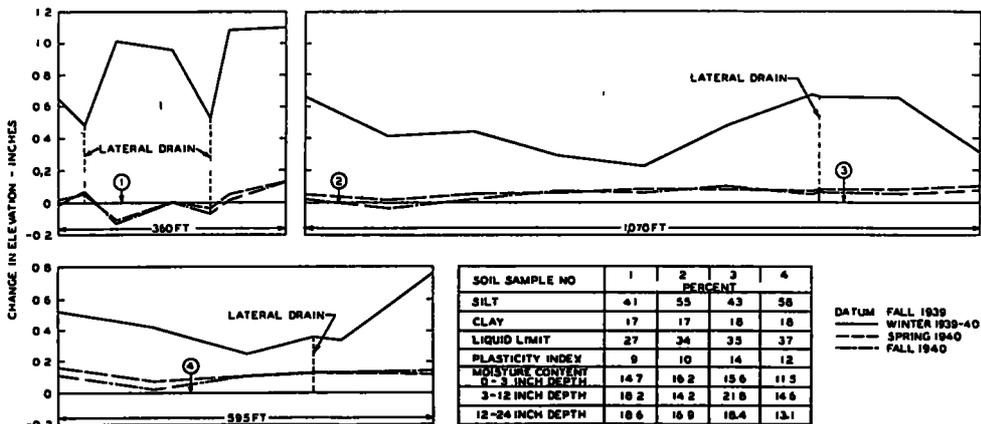


Figure 2. Seasonal changes in elevation of selected sections during the second year. One-inch bar, sections of considerable length

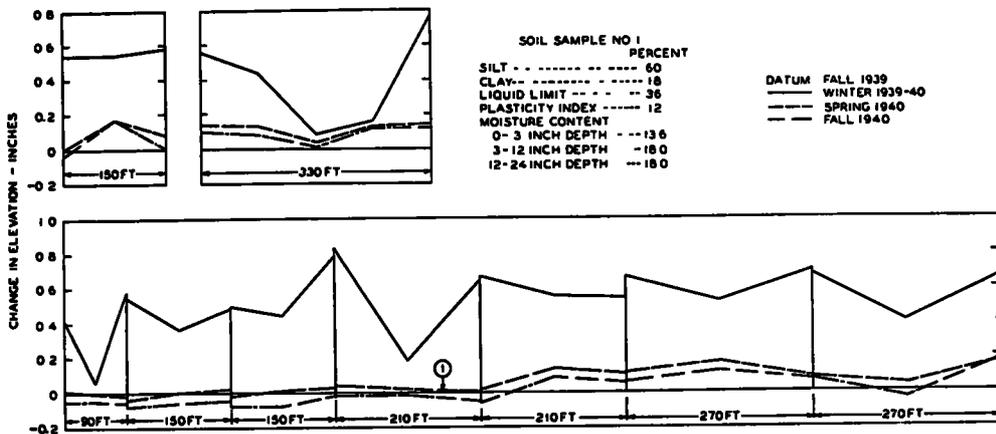


Figure 3. Seasonal changes in elevation of selected sections during the second year. One-half inch bars, intermediate length sections

three groupings on the basis of the amount of longitudinal reinforcement present (and indirectly the general length of the sections). In Figure 2 are sections containing 1-in. diameter bars and of considerable length; in Figure 3 are those containing 1/2-in. diameter bars and of intermediate section length, while in

3. Frequently greater at the expansion joints than elsewhere in the sections.

Figure 5 contains similar data showing changes in elevation caused by freezing at six joints in the central area of each of the four 500-ft. sections that have warping joints at 10-ft. intervals. The same general order and nonuniformity of heav-

ing is evident in these sections. It appears, however, that the warping joints

order of the frost heaving is not large, being generally within the range 0.2 to 1.0 in. It is not uniform, varying probably with the physical nature and condition of the subgrade soil. In this connection it is of interest to note that where lateral drains were placed under the 360-ft section there appears to have been a decrease in the magnitude of the frost heaving.

It is believed that the flexure caused by the nonuniformity of the frost heaving was not sufficient to fracture the sections and the condition surveys confirm this belief.

After the soil had completely thawed, the elevation of the pavement was, in general, slightly greater than before freezing occurred. Between May 1940 and October 1940 little or no change in pavement elevation developed.

The importance of subgrade uniformity and of tightly-sealed joints as aids to maintaining the structural integrity of concrete pavements exposed to freezing conditions is emphasized by these data.

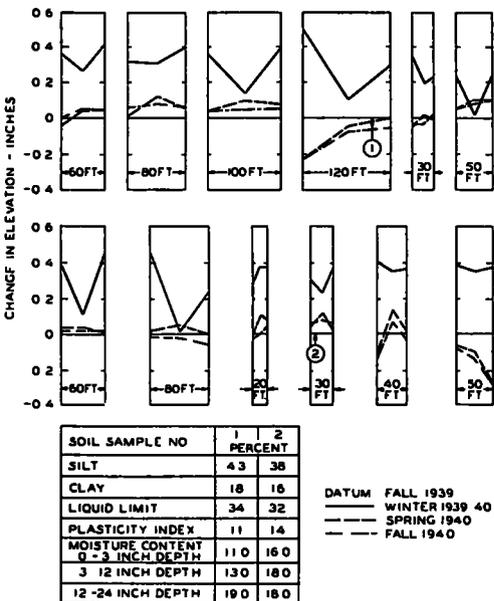


Figure 4 Seasonal changes in elevation of selected sections during the second year. Welded wire fabric, short sections.

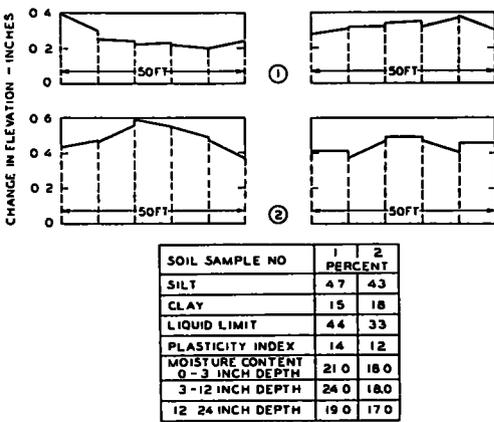


Figure 5. Increase in elevation caused by freezing of subgrade to a depth of 20 inches of sections containing 10-foot slabs.

were better sealed and did not aggravate the frost heaving as did the expansion joints in the longer sections

In spite of the deep freezing the general

ANNUAL CHANGES IN SECTION LENGTH NOT PROPORTIONAL TO LENGTH OF SECTION

As a part of the regular schedule, measurements are made of the daily and annual cycle of length change of a number of representative sections. In the case of the daily cycle the change is primarily that caused by the temperature change, but the annual cycle combines the length changes caused by temperature and moisture changes with any permanent change in length from other causes. In the present report only the annual cycle of length change will be discussed. Measurements of this movement are made at the expansion joints of one section of each length for each of three types of reinforcement, a total of 64 sections altogether.

In Figure 6, the broken line and the full line curves are the average maximum changes in length observed for sections of different length during the first and the

second years, respectively, of the pavement's life. The change in average pavement temperature accompanying these changes in length were 63°F. for the first year and 87°F. for the second year. For clarity in presentation, the points representing observed values for the first year are omitted from the graph. The two light weight straight lines, that appear to be tangent to the lower portion of the two curves, were drawn through the points for the shorter sections and thus

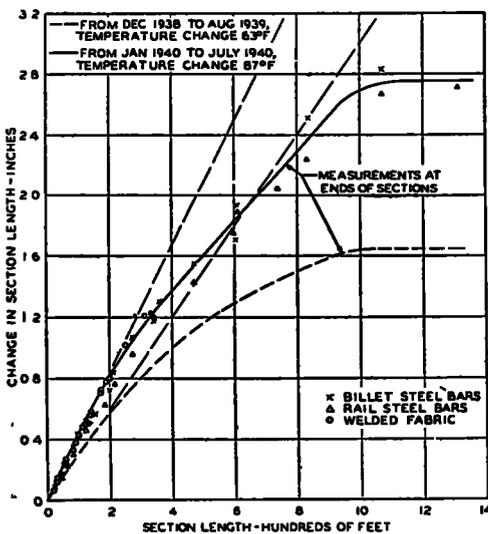


Figure 6. Relation between Section Length and Annual Change in Length

represent the relation for short sections that are comparatively free to expand and contract.

The type of reinforcement used in the various sections is denoted by the character of symbol and it is apparent that type of reinforcement exercises no significant influence on the magnitude of the length changes thus far observed.

The two curves represent length changes that accompanied temperature changes of quite different magnitude. When the two sets of data are reduced to a common temperature base, it is found that the length changes observed during

the second year, for sections exceeding 600 ft. in length, are appreciably greater than those during the first year. For example, take the extreme case of the 1,310-ft. section. During the first year the observed change in its length, as indicated by the broken line curve, was 1.64 in. Multiplying this by the temperature ratio 87/63 gives 2.27 in., the change in length that might be expected with an 87° change in temperature. During the second year, however, a change in length of 2.72 inches was observed. Thus, it appears that the change in length was affected by temperature

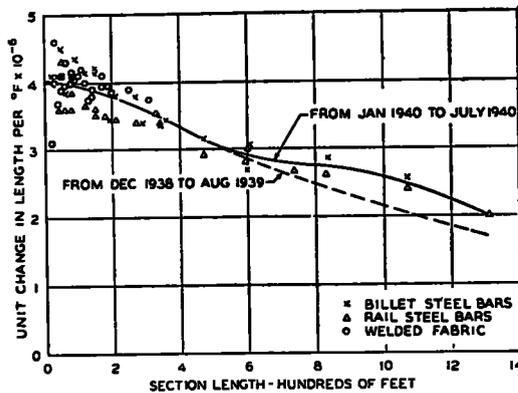


Figure 7. Relation between Section Length and Annual Expansion

and by other influences. It seems possible that the restraint offered by the subgrade may have been less after having been through an annual cycle of moisture and temperature change. The fact that the effect is most pronounced in sections between 700 and 1,000 ft. long and practically constant in those over 1,000 ft. of length indicates that it is more probably the result of changes in soil restraint than of other causes.

When the changes in length observed during the two annual cycles are reduced to unit values per degree temperature change and related to the corresponding section lengths, the curves shown in Figure 7 result. This figure shows how the

magnitude of the annual length change varies with the length of the section. The unit length change, while expressed in terms of temperature, is not actually a coefficient of thermal change alone but rather a coefficient of length change that involves temperature, moisture and perhaps other factors. The relation is useful in indicating the order of movement to be expected at the ends of pavement slabs of various lengths. It appears from this figure that for sections of about 150 ft or less in length the coefficient has a value of about 0.000004. As the length of section is increased to about 600 ft, the value of the coefficient is reduced to about 75 percent of that for short sections, while for sections 1,200 to 1,300 ft long it is reduced to about 50 percent.

In the discussion of Figure 6 it was pointed out that for the long sections the changes in length that accompanied a given temperature change were greater during the second year than during the first year. This is shown more clearly perhaps in Figure 7.

The annual longitudinal movements observed at the center, quarterpoints and ends of the 1,310-ft section are shown for each of the two years in Figure 8. The value shown for the quarterpoint and that shown for the end is in each case the average of the measurements at both quarterpoints and at both ends of this section. In this graph are shown also straight line relations between movement and section length as observed on the short and relatively unrestrained slabs during each annual period.

During the first year the movement at the quarterpoints was about 10 percent and at the ends about 40 percent of that which would be expected in a free slab of this length. During the second cycle the movement at the quarterpoints was about 33 percent and at the ends about 54 percent of that of the hypothetical unrestrained section. This is added evi-

dence that less restraint to longitudinal movement was present during the second cycle of length change.

Figures 9, 10 and 11 are typical crack survey sheets, including all data obtained in the six surveys made up to this time. These were made during the various seasons of each of the two years of the service life of the pavement. Figure 9 shows the crack formation in a section 1,070 ft in length reinforced with 1-in. diameter billet steel bars, Figure 10, sections 90, 150 and 330 ft in length reinforced with ½-in. diameter steel bars;

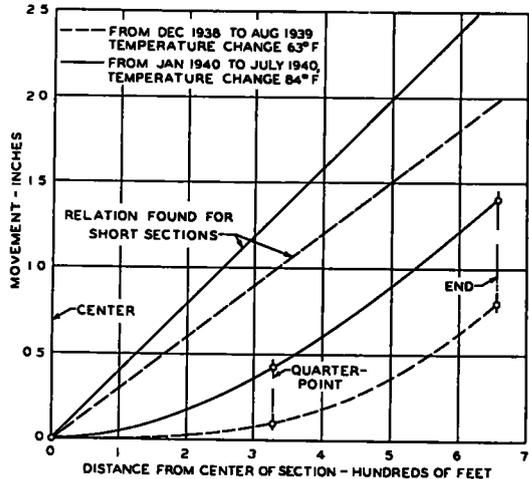


Figure 8. Annual Movement at the Center, Quarter-point and End of a 1310-foot Section

and Figure 11, sections 20, 30, 40, 50, 60, 80, 100 and 120 ft long containing three different weights of welded wire fabric reinforcement as noted.

Referring to Figure 9, it will be noted that a very large number of cracks have formed in the central area of this long, heavily reinforced section. In this area cracks are frequently less than 2 ft apart but near the ends the spacing gradually becomes much greater. This manner of cracking was anticipated. The cracks are barely visible even on very close inspection and none has opened enough to indicate an inelastic elongation.

of the steel. At this time there is no spalling or disintegration and the section is structurally intact. Figure 12 is a recent photograph of a crack typical of

of cracks that have formed in a given length is much less than that found in the longer, more heavily reinforced sections. Of the three sections represented in Fig-

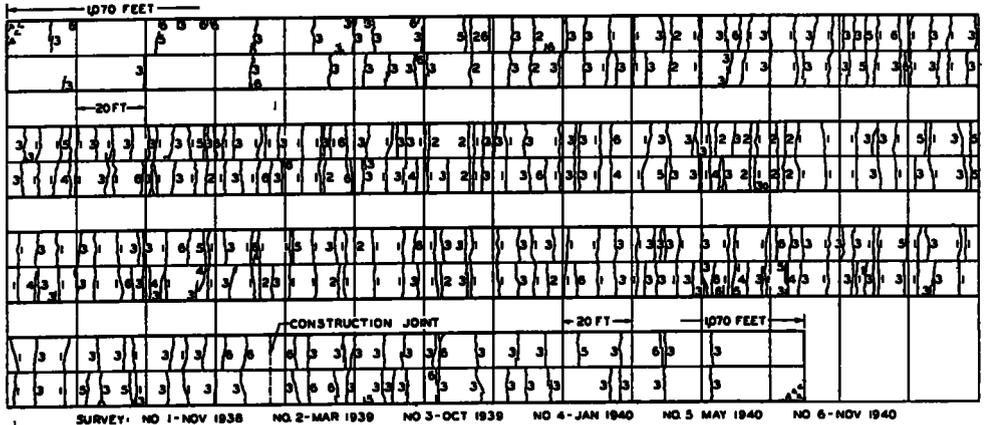


Figure 9. Typical crack survey sheet for long sections reinforced with one-inch diameter steel. Sections placed September-October, 1938

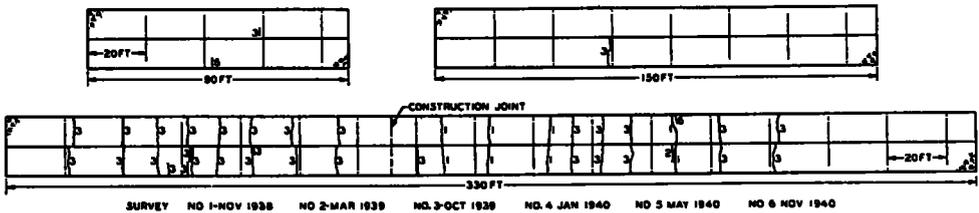


Figure 10. Typical crack survey sheet for intermediate length sections reinforced with 1/2-inch diameter steel. Sections placed September-October, 1938

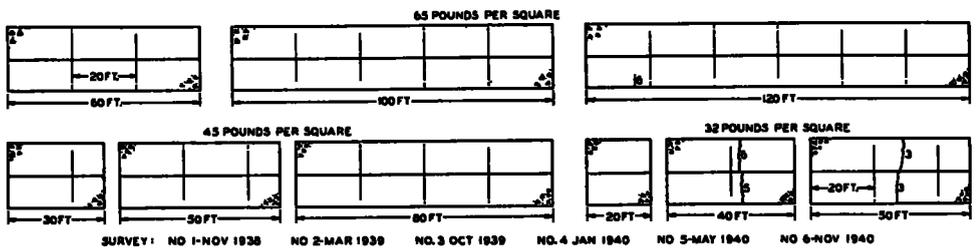


Figure 11. Typical crack survey sheet for short sections reinforced with welded fabric. Sections placed September-October 1938

those that formed early in the life of this section.

In the intermediate length sections shown in Figure 10, containing as they do much less reinforcement, the number

ure 10, only the 330-ft. section has an appreciable number of cracks discernible at this time. In the 150-ft. sections contains no full length cracks.

The cracks in this group appear to be slightly more open than those in the more heavily reinforced sections but the difference is slight and no quantitative data are available at this time. There is no spalling, disintegration or evidence of inelastic deformation of the steel in these intermediate length sections. Figure 13 is a photograph showing the present appearance of a typical crack in this part of the pavement.

As will be noted from Figure 11, little or no cracking has occurred to date in

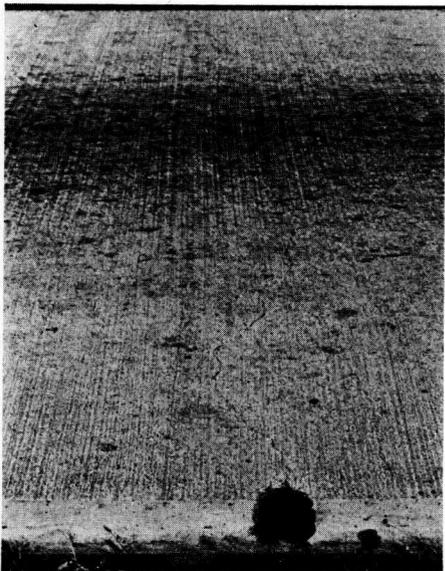


Figure 12. Present Condition of Typical Early Crack in Long Heavily Reinforced Section

the shorter sections reinforced with welded wire fabric. Of the nine sections represented in this figure only two have cracked. These are 40- and a 50-ft. sections reinforced with the 32-lb. fabric, the lightest weight used. One full-width crack has developed in each of these sections. Figure 14 shows the present appearance of one of these cracks. The cracks are open slightly but there is no spalling, disintegration or evidence of steel failure at this time.

Comparison of Figures 9, 10 and 11

indicate the presence of a relationship between the average slab length, or



Figure 13. Typical crack in section of intermediate length reinforced with $\frac{1}{2}$ -in diameter bars.



Figure 14. Present condition of crack in 40-foot section containing 32-pound wire fabric

number of cracks, and the length of the sections, or amount of longitudinal rein-

forcement. A study has been made of this relationship and in Figure 15 is shown the relation between length of section and the average slab length of the section as found in March 1939 and again in November 1940. The sections represented in this graph include three sizes of bar reinforcement and several weights of welded wire fabric. As in other figures, the points for the first survey have been omitted for the sake of clarity.

At the time of the March 1939 survey little or no cracking was to be found in

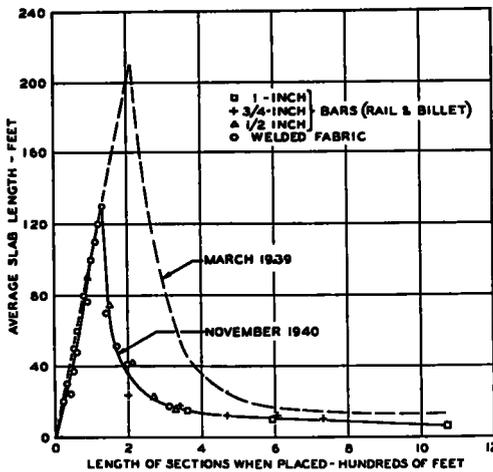


Figure 15. Relation between Length of Sections and Average Slab Length

sections having a length of 210 ft. or less. In sections of a length greater than 210 ft. cracking occurred and the frequency, as indicated by the average slab length, increased rapidly with section length. For example, at the time of this survey the average uncracked slab length of the 250-ft. sections was approximately 120 ft., that for the 600-ft. sections was about 16 ft., and that for the 1,070-ft. sections was about 13 ft.

By November 1940 a considerable change had occurred. The average length of the uncracked slabs had been reduced to about 130 ft. The average

slab length of the 250-ft. sections had been reduced to about 23 ft., the 600-ft. sections to about 10 ft., and the 1,070-ft. sections to about 6 ft.

While it might be inferred from this graph that the average slab length is not influenced by the amount of longitudinal steel present, it is believed desirable to await further developments before attempting to draw any conclusion regarding this point.

Figure 16 was constructed to show the manner in which the cracking developed in the sections of various lengths, particularly with respect to time of year. In this graph the long sections are reinforced longitudinally with 1-in. diameter bars, the intermediate sections with $\frac{1}{2}$ -in. diameter bars, while the short sections contain the three lighter weights of welded fabric (32, 45 and 65 lb. per square). The condition at the time of each of the six surveys is shown. The first survey was made after the completion of the curing period and within about one month after the section was laid. At this time about 40 percent of the cracking that now exists was present in the long sections and about 20 percent in the intermediate length sections. By March 1939 there had been but little change although the pavement had passed through a winter. The next survey in October 1939 showed a very great change in all groups, however. Since October 1939 there has been only a gradual increase in the number of cracks in all of the different length sections. The rate of cracking during this period has been greater for the shorter sections, although so few cracks have occurred that this is probably not significant. This graph indicates that the severe freezing of December 1939 and January 1940 had no noticeable influence on the rate of cracking.

The tensile stress in the concrete caused by the resistance offered by the subgrade is apparently responsible for most of the

cracking that has occurred in the longer sections of the pavement. This is indicated by the fact that comparatively little cracking has developed thus far in either the shorter sections or in the ends of the longer sections. In long slabs reinforced with continuously bonded longitudinal steel, the tensile stresses in the concrete caused by subgrade resistance are relieved when a crack or rupture occurs. The forces that caused the stresses are transmitted across the rupture plane by the steel and are transferred back to the concrete by the bond between it and the steel. The distance

ture fell below that point during the winter. This being the case, it is natural to expect further that cracking from subgrade restraint would develop during the winter. It was shown by Figure 16 that the greater part of the cracking was found after the hot weather of summer, rather than after the cold weather of winter as might have been expected. It is, of course, possible that incipient cracks started during the winter do not become discernible for some months. Whether or not this is true has not been established. It is possible that the residual stresses mentioned above would

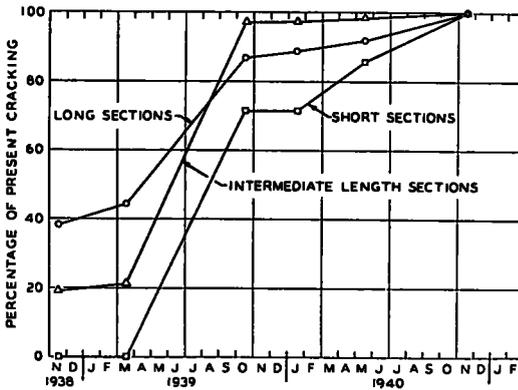


Figure 16. Rate of Crack Development

required for this transfer depends upon the magnitude of the force and the quality of the bond available. This explains why cracks have formed at such close intervals in the long sections with large amounts of reinforcement and at greater intervals in the shorter sections containing relatively small amounts of reinforcement.

Since the pavement was laid in the fall of the year, it might be expected that, in the long sections that are restrained, there would be a residual compressive stress during the summer when the temperature rises above that at which the concrete was placed and a corresponding residual tensile stress when the tempera-

ture fell below that point during the winter. If this happened, the highest tensile stresses would probably be the combined stresses that develop during the daily temperature cycle in the summer months.

The occasional cracking that has developed in the shorter sections and in the end areas is probably the result of combined load and warping stresses as the restraint of the subgrade could not produce critical tensile stress in sections of such length. Also the cracking in the shorter sections apparently occurred during the summer when warping stresses are high.

In connection with the study of cracking of the various sections of the experi-

mental pavement, there has been afforded an opportunity to observe the influence of traffic on the development and condition of the cracks. This 2-lane pavement is one-half of a dual highway; consequently, the right hand lane carries the greatest number of vehicles and practically all of the heavy trucks, the left hand lane being used largely for passing. While it might be argued that the two slabs are tied together at the center joint and thus cannot act independently, still it would be expected that if heavy traffic played an important part in the development of the transverse cracking, some difference in the condition of the two lanes would exist. None has been found.

SECTIONS CONTAINING 10-ft. SLABS GIVEN SPECIAL STUDY

It will be recalled that in the experimental pavement were four sections each

pavement, and this record is shown in Figure 17. It is noted that only two cracks were found at the time of the removal of the burlap and only two more during the remainder of the curing period. The others occurred gradually until by the end of the first year complete fractures had developed at all of the joints.

Measurements are being made periodically of the changes in width that take place, both at the expansion joints and at the warping joints, in these 500-ft. sections and, from these, certain trends have been observed.

1. The weakened-plane joints near the center of the section open and close slightly with temperature but there appears to be no tendency for progressive increase in width.

2. The weakened-plane joints near the ends of the sections show a tendency toward a progressive increase in width and this tendency seems to be

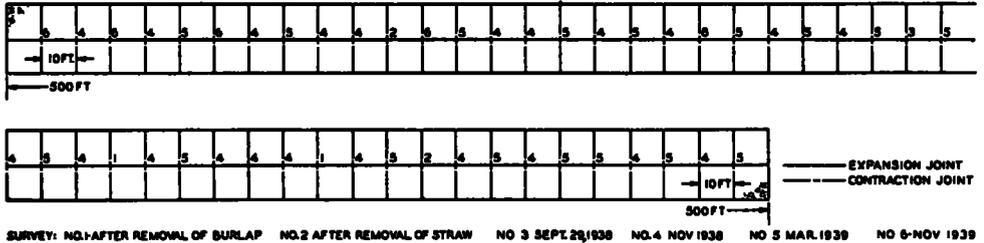


Figure 17. Progressive cracking of submerged plane of weakness contraction joints. Section placed September 8, 1938

500 ft. in length, in which contraction or warping joints were placed at 10-ft. intervals. Two of these sections contained 45-lb. wire fabric; the other two 91-lb. fabric. The fabric was continuous through the warping joints although the bond was broken for 36 in. These joints were planes of weakness formed by grooves in the bottom of the pavement in two sections and in the upper surface in the other two sections.

A record was kept of the time at which the cracks appeared over the grooves that had been formed in the bottom of the

greater in the sections with the groove in the lower surface of the pavement than in those that have the grooves in the upper surface.

3. There seems to be a tendency toward a progressive closing of the expansion joints. This tendency is apparently more pronounced in the sections containing the lighter reinforcement.

The changes in length of each of the four 500-ft. sections as measured at the ends for the two annual cycles are given in Table 6.

TABLE 6

ANNUAL CHANGES IN LENGTH OF 500-FT. SECTIONS WITH WEAKENED-PLANE JOINTS AT 10-FT. INTERVALS

Section number	Weight of reinforcement <i>lb. per sq.</i>	Type of weakened-plane joint	Time of observation		Temperature difference <i>deg. F.</i>	Change in length <i>in.</i>
			Winter	Summer		
1	91	Submerged	1938-1939	1939	60	1.10
			1939-1940	1940	84	1.47
2	45	Submerged	1938-1939	1939	60	1.33
			1939-1940	1940	84	1.41
3	91	Surface	1938-1939	1939	60	0.74
			1939-1940	1940	84	1.23
4	45	Surface	1938-1939	1939	60	0.83
			1939-1940	1940	84	1.05

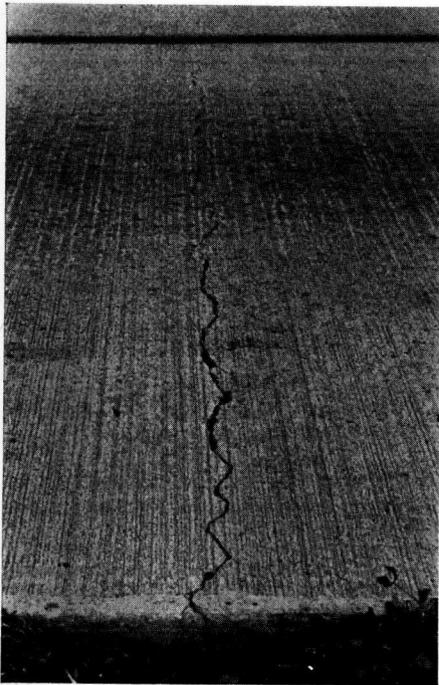


Figure 18. Typical Crack over Submerged Parting Strip in Lane Carrying Heavy Traffic

Figure 19. Companion Crack in Lane Carrying Light Traffic

The changes in length are not caused entirely by variation in temperature and

moisture because, as stated, there has been a slight progressive opening of some of the plane-of-weakness joints. It will be noted in this table that the change in temperature during the first year was smaller than that during the second and that there is a difference in the length changes of the same general order. Using the coefficient of 0.000004, as explained earlier, the observed changes in length of these 500-ft. sections indicate that a certain amount of restraint was present during expansion and contraction.

Figures 18 and 19 show the appearance of cracks over the submerged grooves in the right hand and the left hand lanes, respectively. These cracks have opened slightly and the edges have become slightly rounded. This condition is more noticeable in the right hand lane.

Those weakened-plane joints formed under a groove in the upper surface appear to be in perfect condition at this time.

SURFACE ROUGHNESS OF THE SECTIONS COMPARED

Recently a new instrument for indicating the relative roughness of road surfaces has been developed by the Public Roads Administration. The roughness of the surface is indicated by an index expressed in inches per mile of pavement length. With this apparatus it is possible to compare the surface roughness of sections of various lengths.²

The relative roughness index as determined during August 1940 for the various sections of the experimental reinforced pavement is shown in Figure 20, plotted with respect to section length. The pavement at this time was nearly two years old. It will be noted that in this graph different symbols are used to distinguish between sections reinforced with the different types of steel.

A study of this figure indicates that

- 1 The pavement as a whole is smooth (with this apparatus, index

² See page 621.

values of the order of 80 to 120 represent smooth surfaces, 200 and above rough surfaces).

2. The different types and weights of reinforcement have had no noticeable influence on the relative roughness of the various sections.

3. With modern methods of construction and proper care, the number or spacing of joints in a concrete pavement apparently need not affect its surface roughness.

The roughness index for the four special sections with weakened-plane joints at

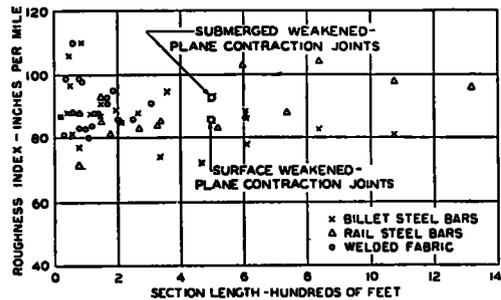


Figure 20. Relative roughness of various sections. Values obtained with Public Roads roughness indicator. (80-120 smooth surfaces, 200 and over, rough surfaces.)

10-ft. intervals is shown on the graph as a section length of 500 ft., the distance between expansion joints. Two points are shown, one for the two sections with submerged joints and one for the two with surface joints. These sections appear to be no rougher than sections of equal length having no intermediate joints. In fact, their surface roughness appears to be about the average for the experimental pavement as a whole.

It should be pointed out that any effect of the design of the various sections on their smoothness will probably become more evident as time passes and that the data presented in Figure 20 are intended to furnish a basis for future comparisons.

SUMMARY

It has been shown that in the long, heavily-reinforced sections many fine transverse cracks have developed in the central area. Frequently, these cracks are no more than 2 ft apart. At all times and in all cases the cracks have remained tightly closed and no spalling, raveling or disintegration has appeared at any of them so far.

In the sections of intermediate length containing the $\frac{1}{2}$ -in diameter bars a moderate amount of transverse cracking has developed in the longer sections with but relatively little in the shorter sections. In this group of sections the cracks are open slightly more than those in the sections containing the $\frac{3}{4}$ -in and 1-in diameter bars, but there is as yet no sign of spalling, raveling, disintegration, or of inelastic deformation of the steel.

Only a very limited amount of transverse cracking has occurred in the sections containing the welded wire fabric. The cracks that are present are open slightly more than those in the more heavily reinforced sections but here also no evidence of spalling, raveling, disintegration or structural weakness has been found.

There appears to be a relation between the length of the section as constructed and the average slab length (or distance between transverse cracks). So far there appears to be no relation between the average slab length and either the type or the amount of longitudinal steel.

The amount of change in elevation observed from season to season has been generally small (less than 1 in) and has not been uniform. There is nothing to indicate that it has affected the structural condition of the various sections.

In the four special 500-ft sections containing 10-ft slabs separated by plane-of-weakness type joints, the sections as a whole are in excellent condition. The joints in which the surface groove was used are apparently perfect, while those formed by a submerged parting strip have opened and raveled slightly.

Relative roughness determinations over the experimental pavement shows that the surface of all of the sections was very smooth after about 18 months of service. The sections containing planes of weakness at 10-ft intervals were as smooth as those in which the joints were 1,000 ft or more apart.