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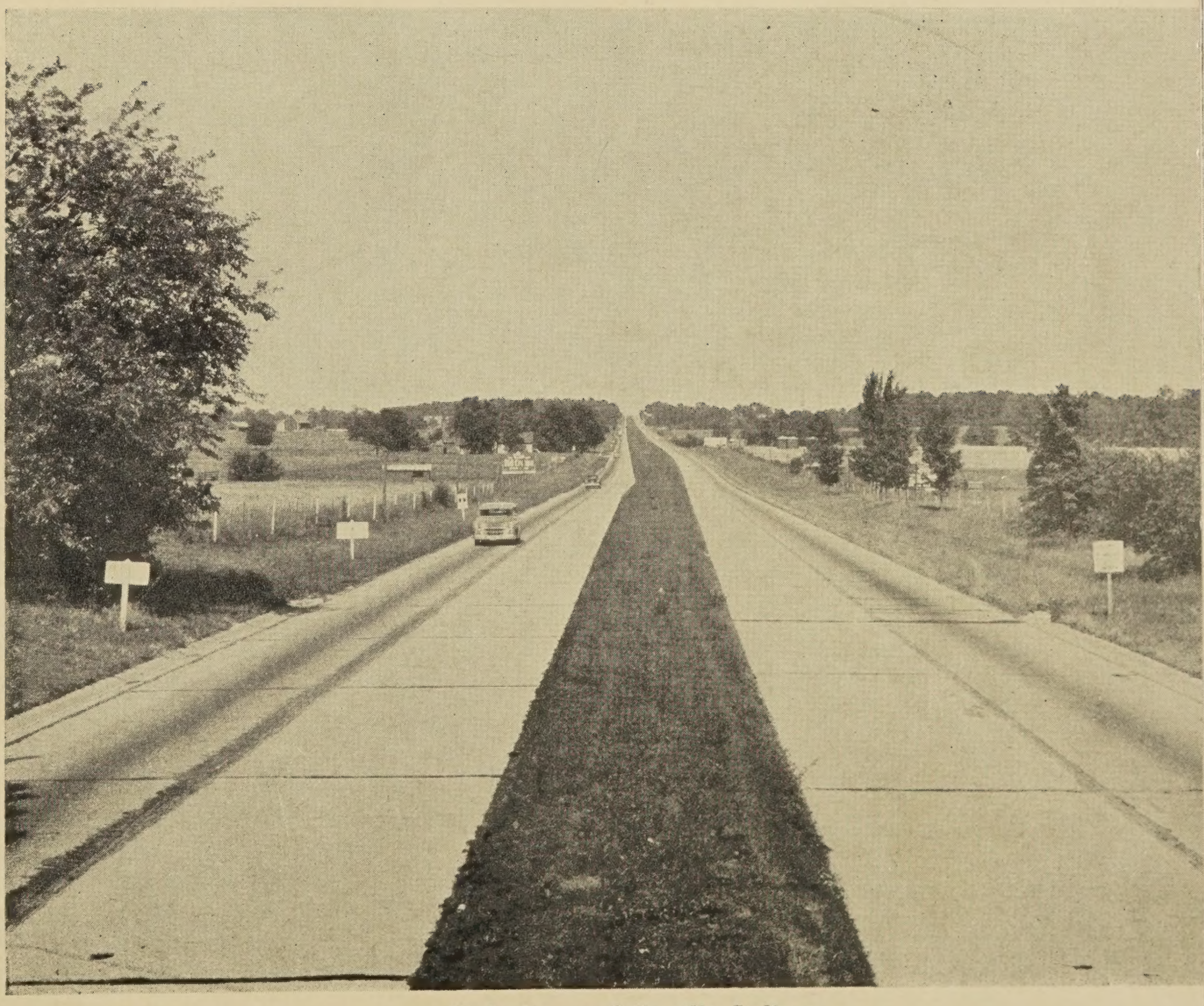

U. S. 40 near Stilesville, Indiana

Public Roads

A JOURNAL OF HIGHWAY RESEARCH

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Edgar A. Stromberg, *Editor*

IN THIS ISSUE

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Continuous Reinforcement in Concrete Pavement—after 15 1/2 years

A Cooperative Investigation by the Indiana State Highway Department and the Bureau of Public Roads

Reported by HARRY D. CASHELL, Highway Physical Research Engineer, Bureau of Public Roads, and WILMER E. TESKE, Research Engineer, Indiana State Highway Department

In 1938 there was constructed near Stilesville, Indiana, as a cooperative research project, a reinforced concrete pavement containing a number of sections, ranging in length from 20 to 1,310 feet. Three types of steel were used, and the amount of longitudinal reinforcement was varied from 0.07 to 1.82 percent among the sections. The purpose of the research was to obtain information on the possibilities for reducing the number of transverse joints in concrete pavement through the use of longitudinal steel reinforcement.

Observation of the experimental pavement sections after 15½ years of service indicates that, with the proper use of longitudinal reinforcement, any spacing of transverse joints within the range studied will give satisfactory performance, without failure of the steel or adverse effects on the concrete.

In the long, heavily reinforced sections numerous closely spaced transverse cracks have developed, but these have not opened and are not detrimental to surface smoothness or pavement life. In fact, an outstanding impression of the pavement is the superficial nature and structurally harmless character of transverse cracks held closed by continuous longitudinal reinforcement. Irrespective of section length, all cracks held closed by reinforcement have been highly resistant to pumping, free of faulting, and have required little or no maintenance.

Longitudinal reinforcement in very large amounts can be used without danger of cracking of the concrete above the steel, buckling failures, or disintegration of the concrete. Longitudinal reinforcement in small amount, 0.11 percent or less, should be used with caution in pavements subjected to heavy truck traffic.

The performance of the longest sections indicates that continuously reinforced pavements will be less susceptible to pumping than pavements of other designs, although under certain conditions of traffic and subgrade they will not be immune from pumping along the longitudinal free edge.

This investigation was planned primarily to determine the extent to which various types and amounts of longitudinal steel reinforcement could be used to reduce the number of transverse joints in concrete pavements. Thus its purpose was to produce information mainly on structural performance. The general excellence of the performance of the pavement sections over a period of more than 15 years raises a question regarding the economic benefits of reinforcing steel that cannot be answered at this time or by this investigation alone. However, subsequently there have been constructed several other continuously reinforced pavements of varying designs which are being observed and reported upon. It is believed that as time develops more information, it may eventually become possible to evaluate the relative economics of continuously reinforced pavement and that of more usual designs.

THIS is the fifth of a series of reports of a cooperative research investigation undertaken in 1938 by the Indiana State Highway Department and the Bureau of Public Roads to study the effects of varying amounts of continuous longitudinal steel reinforcement in portland cement concrete pavement sections of various lengths. Preceding reports (*1–4*)[1] have described in detail the design and construction of the project and the performance and behavior of the sections during the first 10 years of service. The present report describes the condition of the various sections as observed during a performance survey conducted in the spring of 1954 when the pavement was 15½ years old. On the assumption that the reader is either familiar with this investigation or can easily obtain previously published information about it, only those data essential for clarification are repeated in this report.

The experimental reinforced sections, ranging in length from 20 to 1,310 feet, were constructed near Stilesville, about 30 miles west of Indianapolis, Ind., as part of the eastbound lanes of the divided highway U. S. 40. The continuous steel reinforcement included rail-steel bars, billet-steel bars, and wire fabric, of varying sizes and weights such as to provide percentages of longitudinal steel ranging from 0.07 to 1.82 (see table 1).

In addition to the regular sections listed in table 1, four special 500-foot sections were constructed in which weakened-plane joints were spaced at 10-foot intervals and the bond between the longitudinal steel and the concrete was broken purposely for a distance of 18 inches on each side of each joint.

In compliance with 1938 standard specifications, the pavement is 20 feet wide with a 9–7–9-inch thickened-edge type cross section. Construction was directly over a natural fine-grained soil (table 2) common to the Indianapolis area and now known to be highly susceptible to pumping.

Traffic flow (fig. 1) on U. S. 40 in the immediate vicinity of the experimental sections has increased steadily since 1938, reaching in 1953 an estimated annual average daily volume (in both directions) of nearly 8,000 vehicles, trucks and buses comprising approximately 25 percent of the total.

Scope of Performance Survey

The 15½-year performance survey of the experimental pavement consisted primarily of a critical examination of the various sections for possible inherent characteristics and weaknesses that might affect or shorten their service life. During the survey attention was particularly focused on: (1) The effect of transverse cracking on surface deterioration and concrete durability; (2) the manner in which the various types and quantities of longitudinal steel performed their structural function of holding cracks tightly and permanently closed; (3) the susceptibility of the sections to pumping and the influence of pumping at the joints, cracks, and edges of the pavement; (4) the maintenance require-

[1] Numbers in parentheses refer to the bibliography, p. 141.

ments of the sections; (5) the effect of traffic on pavement behavior and condition as indicated by a comparison between the heavily traveled outer lane and the more lightly traveled passing or inner lane; and (6) the surface smoothness of the sections.

Conclusions

Constructed on a pumping-susceptible soil and subjected to relatively heavy traffic for 15½ years, the experimental sections have by their behavior and condition provided basic information applicable to the ultimate performance of reinforced concrete pavement. The most significant conclusions to be drawn from the results of this investigation follow:

Regular sections

1. Sections of any length can be reinforced with continuous longitudinal steel in sufficient amount to maintain all transverse cracks in a tightly closed condition without adverse effect on the concrete.

2. The length of a continuously reinforced section containing adequate steel has a pronounced effect on the pattern of transverse crack development. In sections up to approximately 150 feet in length the cracks will be comparatively few and variably spaced. In the end regions of longer sections the same condition will exist while in the central region of long sections numerous closely spaced cracks will form.

3. The rate of crack development and the crack frequency will have little effect on the service life of adequately reinforced sections.

4. Surface widths of cracks held closed by continuous reinforcement will increase gradually with time by raveling and wearing superficially under exposure and the action of traffic; however, this condition will not impair the durability of the concrete and will require little maintenance.

5. Cracks held closed by continuous reinforcement will be highly resistant to pumping, practically free of faulting, and will seldom develop surface roughness.

6. Welded wire fabric as light as 32 pounds per 100 square feet and longitudinal bar reinforcement as light as ¼-inch bars spaced at 6-inch centers appear to be structurally incapable of performing the intended function of holding transverse cracks permanently closed in pavement sections subjected to heavy traffic.

7. A continuously reinforced concrete pavement without joints will be less susceptible to the damaging effects of pumping than rigid pavements of usual current designs but, under certain conditions of subgrade type and traffic, will not be immune from pumping action at the longitudinal free edge of the pavement.

Special sections

1. Preservation of pavement continuity is an essential requirement of the design comprising short, constructed slabs held together by relatively lightweight reinforcement.

2. To preserve continuity of the pavement surface, longitudinal reinforcement heavier than that provided by wire fabric of 91 pounds per 100 square feet would be required if shear bars are omitted at the weakened-plane joints. If shear bars are included in the design, however, pavement continuity can be preserved with an amount of longitudinal reinforcement somewhat less than that provided by the 91-pound fabric.

3. As long as continuity exists, the pavement will be free from all but very slight faulting at the weakened-plane joints, of acceptable surface smoothness, and highly resistant to pumping.

4. The submerged type, weakened-plane joint with a copper seal enveloping the bottom parting strip appears to provide more protection against the entrance of water to the subgrade than that obtained with the surface-

Table 1.—Details of reinforcement in the experimental sections

Number of sections for each length [1]	Length of each section [2]	Calculated maximum stress in steel [3]	Weight of reinforcement	Reinforcement size and spacing: Longitudinal, Diameter[4]	Longitudinal, Spacing c. to c.	Transverse, Diameter[4]	Transverse, Spacing c. to c.	Percentage of longitudinal steel [5]	Average tensile strength of longitudinal steel: Yield point	Ultimate
	Feet	*Lb. per sq. in.*	*Lb. per 100 sq. ft.*		*Inches*		*Inches*	*Percent*	*Lb. per sq. in.*	*Lb. per sq. in.*
Rail-Steel Bars (Deformed)										
2	600 840 1,080 1,320	25,000 35,000 45,000 55,000	567	1-in.	6	½-in.	24	1.82	63,000	113,200
4	340 470 610 740	25,000 35,000 45,000 55,000	334	¾-in.	6	½-in.	24	1.02	64,400	113,300
4	150 210 270 330	25,000 35,000 45,000 55,000	167	½-in.	6	½-in.	24	.45	68,800	115,300
6	80 120 150 180	25,000 35,000 45,000 55,000	94	⅜-in.	6	⅜-in.	24	.26	66,700	93,600
6	40 50 60 80	25,000 35,000 45,000 55,000	50	¼-in.	6	¼-in.	12	.11	60,300	84,600
Billet-Steel Bars (Deformed), Intermediate Grade										
2	360 600 840 1,080	15,000 25,000 35,000 45,000	567	1-in.	6	½-in.	24	1.82	46,900	78,000
4	200 340 470 610	15,000 25,000 35,000 45,000	334	¾-in.	6	½-in.	24	1.02	49,100	78,500
4	90 150 210 270	15,000 25,000 35,000 45,000	167	½-in.	6	½-in.	24	.45	51,400	78,600
6	50 80 120 150	15,000 25,000 35,000 45,000	94	⅜-in.	6	⅜-in.	24	.26	55,500	81,900
6	20 40 50 60	15,000 25,000 35,000 45,000	50	¼-in.	6	¼-in.	12	.11	56,900	77,300
Wire Fabric (Cold-Drawn Wires)										
6	140 190 250 310	25,000 35,000 45,000 55,000	149	No. 0000	4	No. 3	12	0.42	----------	81,800
6	90 130 170 200	25,000 35,000 45,000 55,000	107	No. 0000	6	No. 3	12	.28	----------	80,300
6	80 110 140 170	25,000 35,000 45,000 55,000	91	No. 000	6	No. 4	12	.24	----------	89,100
6	60 80 100 120	25,000 35,000 45,000 55,000	65	No. 0	6	No. 6	12	.17	----------	83,700
6	30 50 60 80	25,000 35,000 45,000 55,000	45	No. 3	6	No. 6	12	.11	----------	81,000
6	20 30 40 50	25,000 35,000 45,000 55,000	32	No. 6	6	No. 6	12	.07	----------	88,700

[1] The term "section" as used in this report refers to a lane or 10-foot width of pavement; thus the number "2" indicates a pair of sections, one being on each side of the center joint.

[2] The lengths of the longer sections are nominal lengths and may be either 5 or 10 feet greater than the actual length in cases where a pair of bridge-type joints were installed.

[3] Calculated by subgrade resistance method with coefficient of resistance equal to 1½ times the weight of the pavement.

[4] The rail-steel and billet-steel reinforcement were round bars. The diameters of the wires in the fabric were as follows: No. 0000, 0.3938 inch; No. 000, 0.3625 inch; No. 0, 0.3065 inch; No. 3, 0.2437 inch; No. 4, 0.2253 inch; No. 6, 0.1920 inch.

[5] Cross-sectional area of the longitudinal steel expressed as a percentage of the cross-sectional area of the concrete slab.

Table 2.—Subgrade soil data [1]

Total soil samples for each depth	Location below surface	Material retained on No. 270 sieve	Plasticity index	Moisture content
	Inches	*Percent*	*Percent*	*Percent*
SECTIONS CONTAINING RAIL-STEEL BARS				
18	0–4	19	12	13.2
	4–12	19	13	16.1
	12–24	21	13	18.1
SECTIONS CONTAINING BILLET-STEEL BARS				
15	0–4	24	11	12.6
	4–12	23	12	15.6
	12–24	24	12	18.1
SECTIONS CONTAINING WELDED-WIRE FABRIC				
12	0–4	36	10	11.2
	4–12	33	12	13.4
	12–24	32	13	14.1

[1] Average data from tests on samples taken from the finished subgrade just prior to placing concrete.

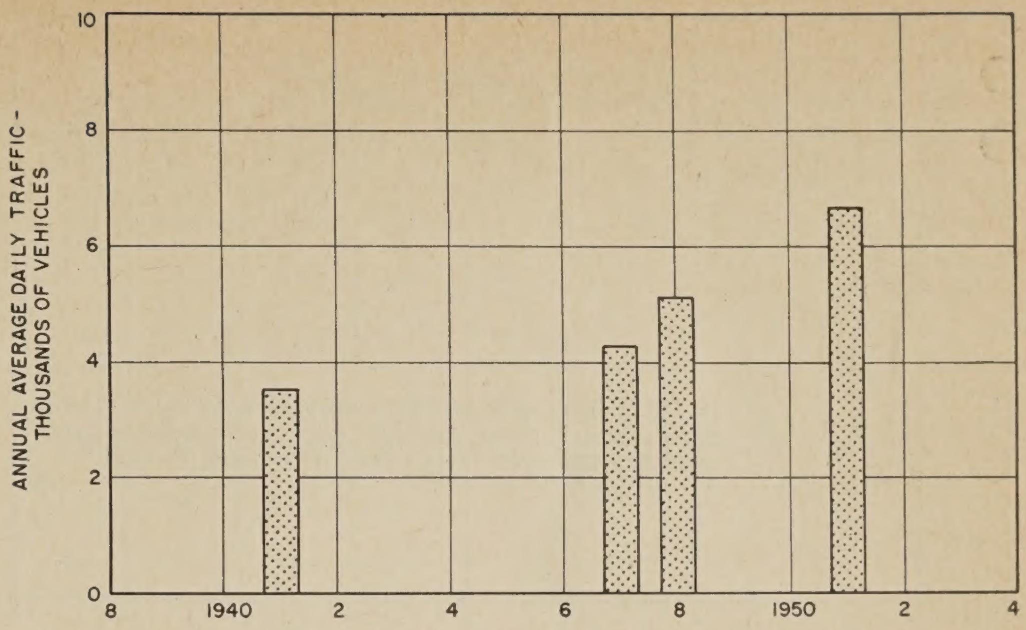


Figure 1.—Traffic volume on U. S. 40 in the immediate vicinity of the experimental pavement.

groove type of joint. However, the fractures that form above the parting strips will be meandering in character and unsightly in appearance.

5. Elimination of expansion joints and the consequent minimizing of progressive opening of the weakened-plane joints would be advantageous to pavements of this design.

Development of Cracking

Crack development during the first 10 years of pavement life has been carefully recorded and fully described in preceding published reports; consequently, only data indicative of the general trend of cracking are reported here.

Typical examples of crack patterns that formed during the 15½-year period of service are shown in figure 2. To emphasize the more recent fractures, only those that appeared within the final time period covering the last 5½ years are labeled with their survey number (7).

The data of figure 2, although limited, give a good idea of the crack development existing in the range of section lengths comprising the experimental pavement. Briefly, the shorter sections are comparatively free of fractures. As the length of section increases, however, cracking is more frequent until in the central region of the longest sections the crack interval is often less than 2 feet.

Figures 3 and 4 show the development of cracking over the 15½-year period in two selected cases, a 310-foot section and the critical central region of the 1,310-foot section. In this report, unless otherwise noted, fractures less than 5 feet long and those that occurred at the extreme ends of sections as a result of pumping at the joints are not considered in the various analyses of cracking.

Figure 3 indicates the manner in which the fractures appeared with respect to time. As will be noted, the rate of cracking was very high during the first year following construction, after which the rate was comparatively low, remaining rather uniform for the intermediate-length section and diminishing progressively with time in the case of the central area of the long section. Of special interest is the fact that 13 percent of the cracks now present in the central 400 feet of the 1,310-foot section formed during the last 5½ years. This suggests a continued high stress condition in the concrete in that region, with continued bond between the steel and the concrete.

Figure 4 shows the effect of pavement age on the average distance between cracks. Of interest is the average crack interval of 2.3 feet (range from 1 to 6 feet) now existent in the central portion of the 1,310-foot section reinforced with 1.82 percent longitudinal steel.

In the discussion of figures 3 and 4 attention has been directed purposely to crack development in the central portion of the 1,310-foot section, because it is indicated that cracking

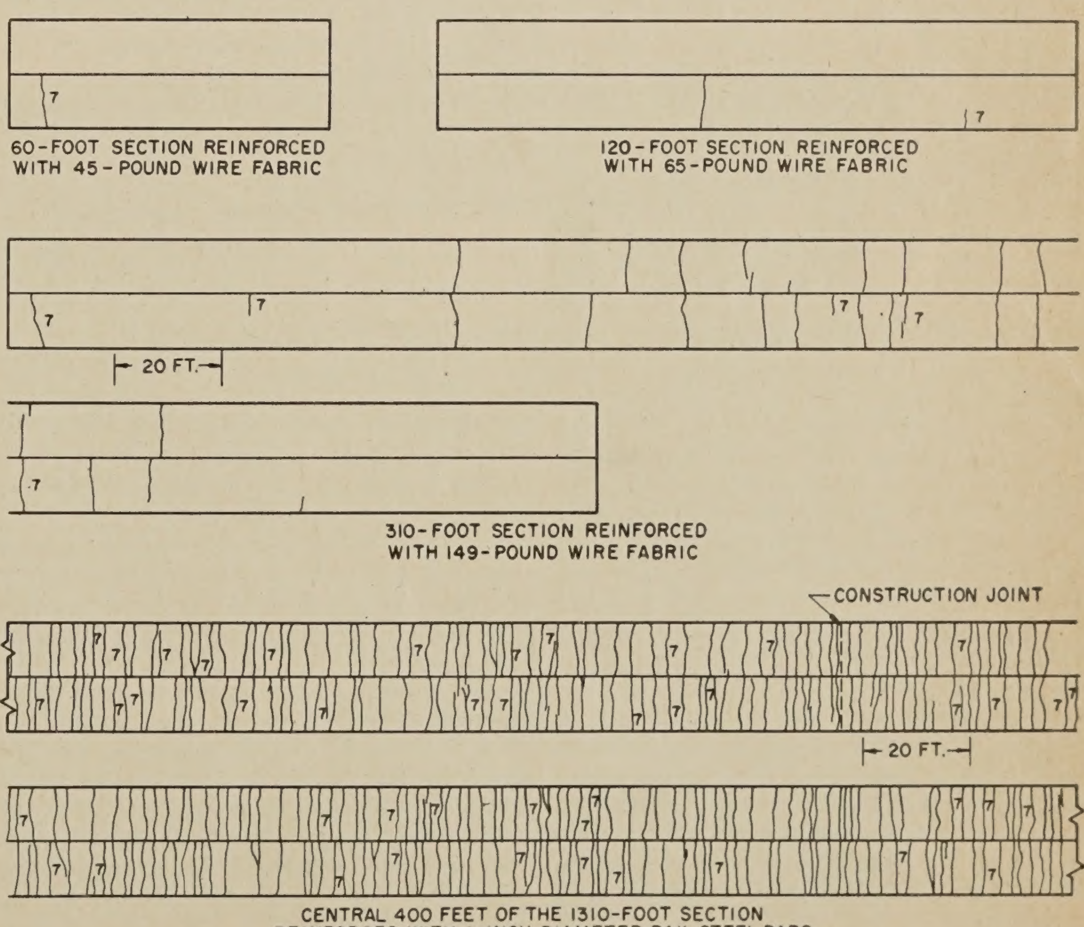


Figure 2.—Typical crack patterns in sections of various lengths after 15½ years. (Fractures numbered 7 occurred between the sixth and seventh crack surveys, October 1948 and April 1954.)

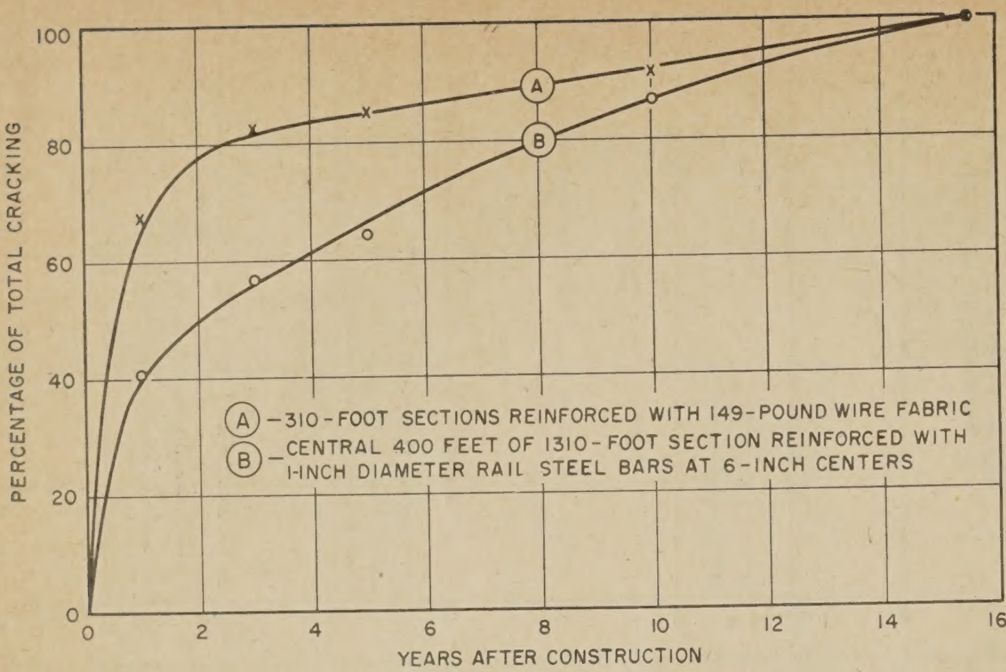


Figure 3.—Rate of crack development during the first $15^1/_2$ years of pavement life.

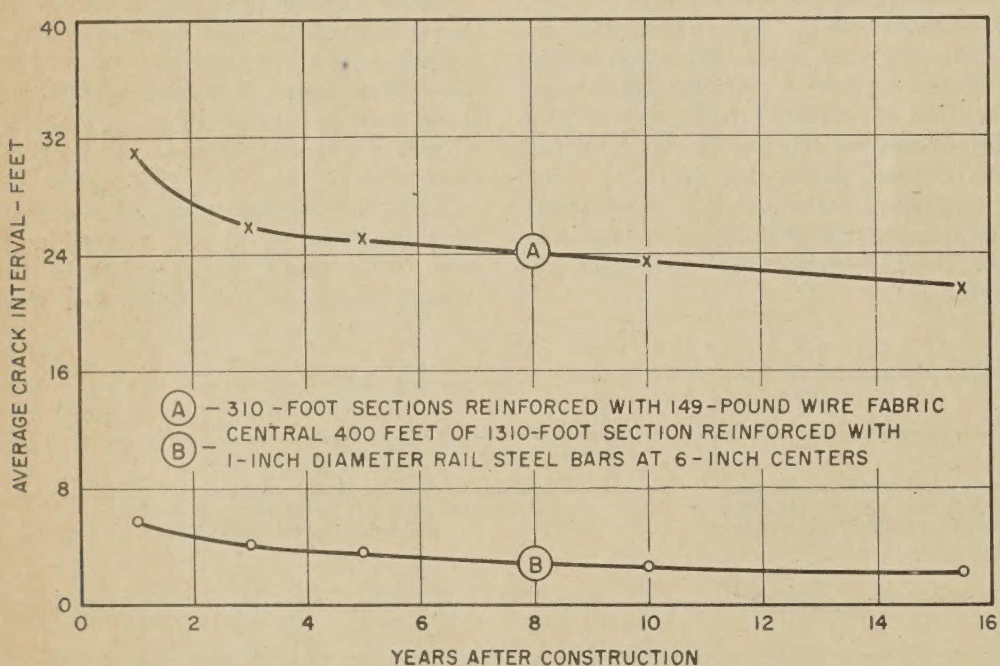


Figure 4.—Relation between average transverse crack interval and age of pavement.

in this area approximates closely that which would develop in the critical area of a pavement of infinite length continuously reinforced with 1.82 percent steel. Other, more recent researches (*5–10*) have shown, however, that continuous pavement without joints can be reinforced adequately with considerably less longitudinal steel than the 1.82 percent used in the 1,310-foot sections. Comparison between the results of the later researches and the one under discussion indicates that cracks will form at somewhat greater intervals in the critical region of continuous pavement containing lesser (and hence more economical) amounts of longitudinal steel than in the central portion of the heavily reinforced 1,310-foot section. This is as might be expected.

Discussion of cracking has thus far been confined largely to that which develops in continuously reinforced sections of considerable length. An analysis of the crack data obtained from shorter sections reinforced with various weights of welded wire fabric is shown in figure 5. In this figure the average crack interval or slab length, at pavement age of 15½ years, is plotted against section length as constructed. Slab length is defined as the distance between two expansion joints, two transverse cracks or an expansion joint and a crack.

The curves of figure 5, despite limitations, suggest a general pattern of cracking for reinforced sections up to approximately 250 feet in length; that is, the average slab length increases with an increase in section length until a peak value is reached, beyond which there is a rapid decrease in the average length of slabs. For conditions existing in the sections under discussion, the longest average slab lengths are found at a section length of about 130 feet.

It is indicated that, for weights of wire fabric of 91 pounds per 100 square feet or less, the relation between section length and average slab length is unaffected by the amount of reinforcement present. For greater weights of reinforcement, however, there appears to be a pronounced effect. For example, in the case of a 140-foot section, the average slab length was 70 feet for welded fabric ranging in weight from 45 to 91 pounds per 100 square feet, whereas the average slab length for the 107- and 149-pound fabric was 86 and 120 feet, respectively.

Character and Effect of Cracking

An outstanding impression of this and all previous condition surveys is the superficial nature and structurally harmless character of transverse cracks held closed by continuous longitudinal steel. The vast number of fractures that occurred in the longer, more heavily reinforced sections, however shocking when considered numerically, have not weakened materially the structural continuity of the pavement. Irrespective of crack incidence or rate of crack development, all sections, except those reinforced with the lightest amount of each type of steel, have continued in service free from distress at the cracks other than inconsequential edge raveling and very limited damage caused by localized scaling and spalling.

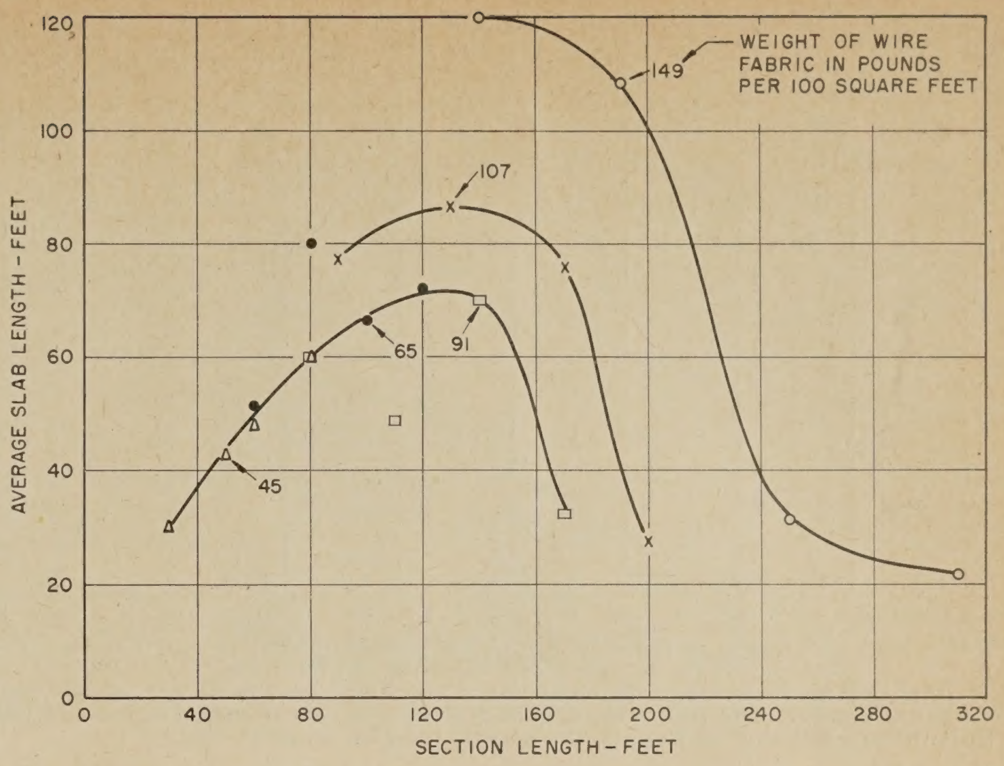
Over the years, exposure and the action of traffic have produced various degrees of raveling and wearing of the surface edges of the transverse cracks. At present, especially in the long, heavily reinforced sections, a few of the earlier and many of the more recently formed fractures are almost imperceptible at the surface of the pavement, being discernible only by extremely close inspection. In contrast, other fractures in the same sections and of the same age group are quite conspicuous at the surface of the pavement, having raveled and rounded to widths which, at the surface, average approximately one-eighth inch.

Cracks in the lightly reinforced short and moderate-length sections are, in general, more readily seen than those in the more heavily reinforced longer sections and, for a given long section, cracks in the central region are more prominent than those in the end regions.

Figure 6 shows the surface condition of the pavement at several transverse cracks as observed in the outside wheel path of the heavily traveled lane. These photographs, taken in 1954, are of fractures that occurred at an early age in the central portions of the longest sections reinforced with 1-inch diameter rail-steel bars, ½-inch diameter rail-steel bars, 149-pound wire fabric, and 91-pound wire fabric, the percentages of longitudinal reinforcement being 1.82, 0.45, 0.42, and 0.24, respectively. By selection, the surface widths of the fractures shown are representative of the widest resulting from raveling that were observed in each respective group of sections.

The cracks shown in figure 6, although restricted in length, serve to illustrate several conditions or characteristics of cracking that

Figure 5 (Right).—*Relations between weight of wire fabric, section length, and average crack interval or slab length.*



were quite obvious when actually seen in the pavement, namely:

1. The surface width of an individual crack is variable along its length.

2. The surface widths of cracks in the shorter, more lightly reinforced sections are wider, on the average, than those of cracks in the heavily reinforced longer sections.

3. The extent of raveling or wearing now present at the edges of cracks held closed by continuous longitudinal reinforcement can hardly be considered as detrimental to surface smoothness or to pavement life.

Another very important structural characteristic existing at all cracks held closed by continuous reinforcement, but not apparent in figure 6, is the fineness of the real widths of the cracks themselves; that is, widths which, unlike those observed at the surface, are unaffected by raveling and wearing of the crack edges. The real widths of all cracks are many times smaller than their respective surface widths. Like their surface widths, the real widths increase with a decrease in the percentage of longitudinal reinforcement, other conditions being equal.

The erratic surface raveling of the cracks throughout their lengths naturally makes it impossible to establish exact values of their surface widths. Nevertheless, to disclose behavior trends, if any, a procedure of measurement was adopted which gives estimated values of the average surface widths of cracks. Essentially, this procedure consisted of dividing a crack extending the width of a lane into three equal segments, then making a width measurement in each segment at a point judged to be average. The value obtained by averaging the three measurements is considered to represent the average surface width of the crack for the particular lane. Although this method is rather crude, it is believed that the averages of a number of such measured values have significance in relative comparisons.

At pavement ages of 10 and 15½ years, measured values of the average surface widths of numerous cracks were obtained in the manner described. Figure 7 shows, for each of the two ages, the relation established by plotting values obtained in the heavily traveled lane against corresponding percentages of longitudinal reinforcement. Each plotted value represents an average of a number of fractures that formed at an early age in the central area of the longest section of a group of similarly reinforced sections.

Comparisons available in figure 7 indicate that the surface widths of cracks tend to decrease with an increase in the amount of longitudinal steel in spite of the fact that the heavier the reinforcement the longer the length of section. As expected, the surface widths of cracks tend to increase with pavement age. It is of interest to note, however, that during the last 5½ years the rate of surface raveling

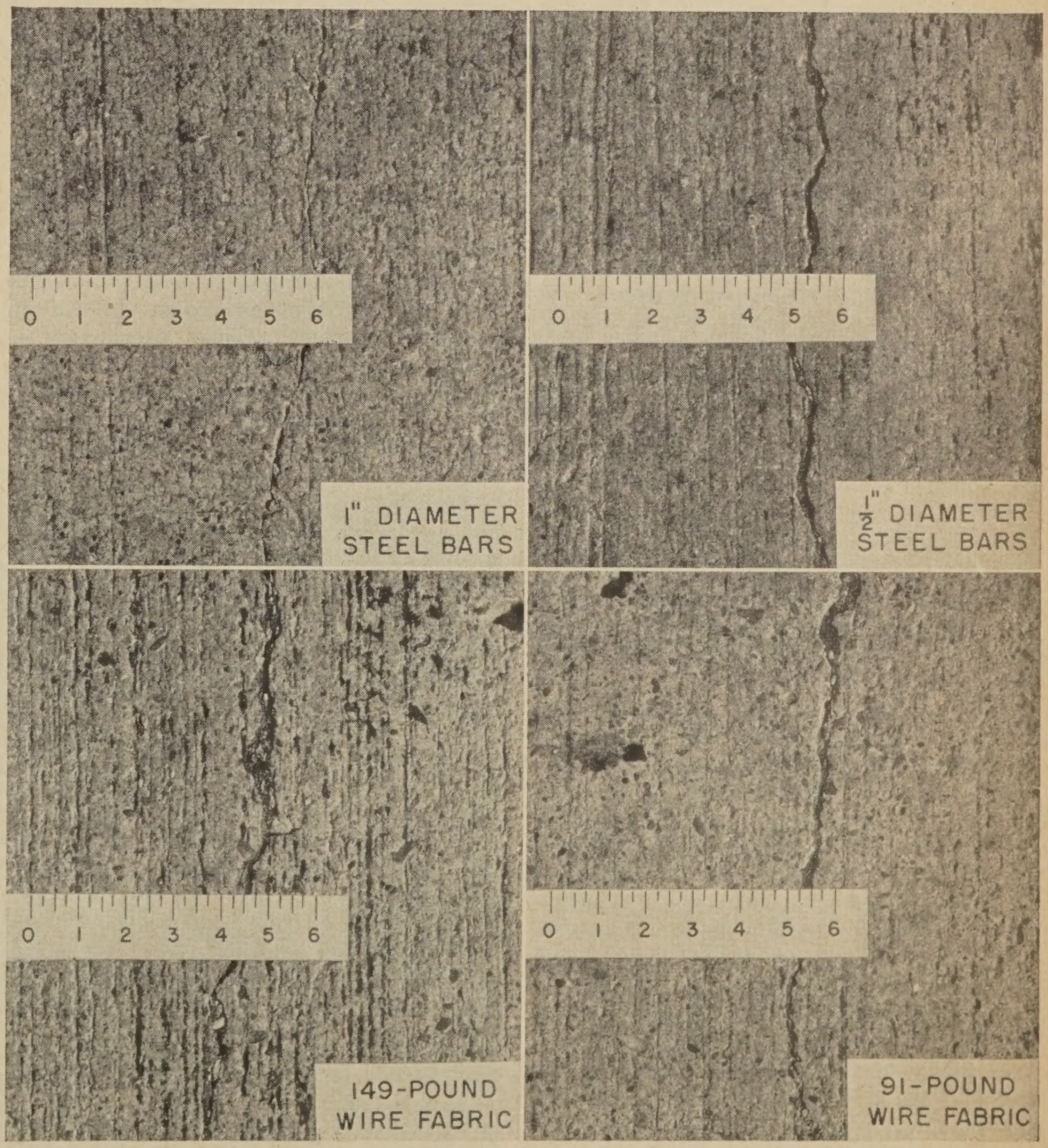


Figure 6.—Surface condition at cracks typical of those that developed at an early age in the central portion of the longest section of each group of similarly reinforced sections (these were in the heavily traveled lane, after 15½ years of service).

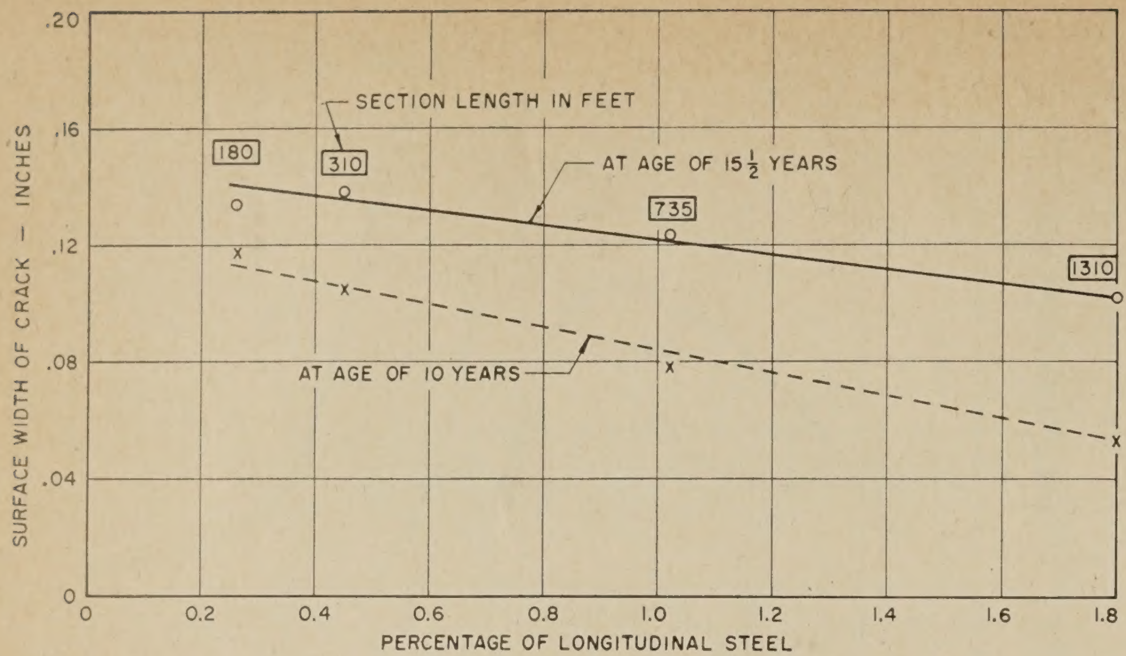


Figure 7.—Effect of percentage of longitudinal steel and pavement age on the surface widths of cracks. The values shown are of fractures that occurred at an early age in the central portion of sections in the heavily traveled lane.

sections it was assumed that subgrade resistance would be constant and could be expressed as a coefficient equal to 1½ times the weight of the pavement. On this basis, the section lengths given in table 1 would develop the listed calculated maximum stresses in the steel, and the yield-point values that were anticipated for each of the three types of reinforcement would have been approached closely in the longest section of each group. This was expected to produce, under repeated stressing, inelastic elongation and possible breakage of the steel with a consequent opening of the cracks.

However, the performance survey at the end of 15½ years showed that all percentages of longitudinal steel of 0.17 and greater had been able to maintain in a closed condition all cracks in their respective group of sections. It is apparent, therefore, that the design assumptions of the experimental sections were too conservative to determine, as was intended, the limiting length of section for each of the selected steel sizes shown in table 1. Comparisons were further complicated by the fact that tests on the steels used showed that, in general, the yield-point values were considerably higher than had been anticipated.

As observed in table 1, the longitudinal steel incorporated in the various sections ranged from 0.07 to 1.82 percent, or from a minimum equivalent to the lightest used in pavement design to a maximum exceeding any other known pavement installation.

After 15½ years of service the performance of the sections containing the maximum percentage of steel indicated definitely that longitudinal reinforcement, when positioned near the mid-depth of the pavement slab, can be used in very large amounts without danger of cracking above the members, failures caused by buckling, or disintegration of the surrounding concrete.

of the selected cracks in the more heavily reinforced sections has been higher than that of the selected cracks in the shorter sections containing the lighter reinforcement. This trend is the opposite of earlier developments but, at present, seems to have little significance.

Damage and Maintenance of Cracks

Concrete deterioration, other than the natural raveling and wearing just reported, was extremely rare at all cracks held closed by continuous reinforcement. Of the few cases of more than superficial damage observed at the cracks, the worst is pictured in figure 8. This type of damage, classified as surface spalling, was first noticed during the 15½-year performance survey.

Surface scaling is another type of pavement distress that was first observed during the last survey. Currently, the scaling is confined to scattered pavement areas, is light in depth, and appears to be more prevalent in the immediate vicinity of cracks and joints than elsewhere.

With reference to scaling, it should be mentioned that during the last four winters calcium chloride, as an additive to sand or cinders for ice control, has been applied to the experimental pavement in indeterminate amounts whenever conditions warranted its use. The light scale observed in 1954 may have been caused by this treatment. Whether or not the many transverse cracks will accelerate its development can be, for the present, only a matter of speculation.

With the exception of isolated cases of spalling, such as that shown in figure 8, it is the opinion of all those who have examined critically the more heavily reinforced sections that the inconsequential surface widths and the fineness of the transverse cracks themselves definitely preclude the need for bituminous maintenance. Opinion has been divided, however, with respect to maintenance of the closed cracks in the sections containing the more conventional amounts of reinforcement.

Performance and Limitation of Reinforcement

For many years the required amount of longitudinal steel reinforcement for pavement sections has been computed by an analytical method based on the possible maximum tensile stress that could be induced in the steel by subgradé resistance during contraction of fractured sections. In the application of this method to the design of the experimental

Figure 8.—Extreme case of spalling at a crack in a section reinforced with heavy steel bars. Even minor spalling at such cracks is unusual.

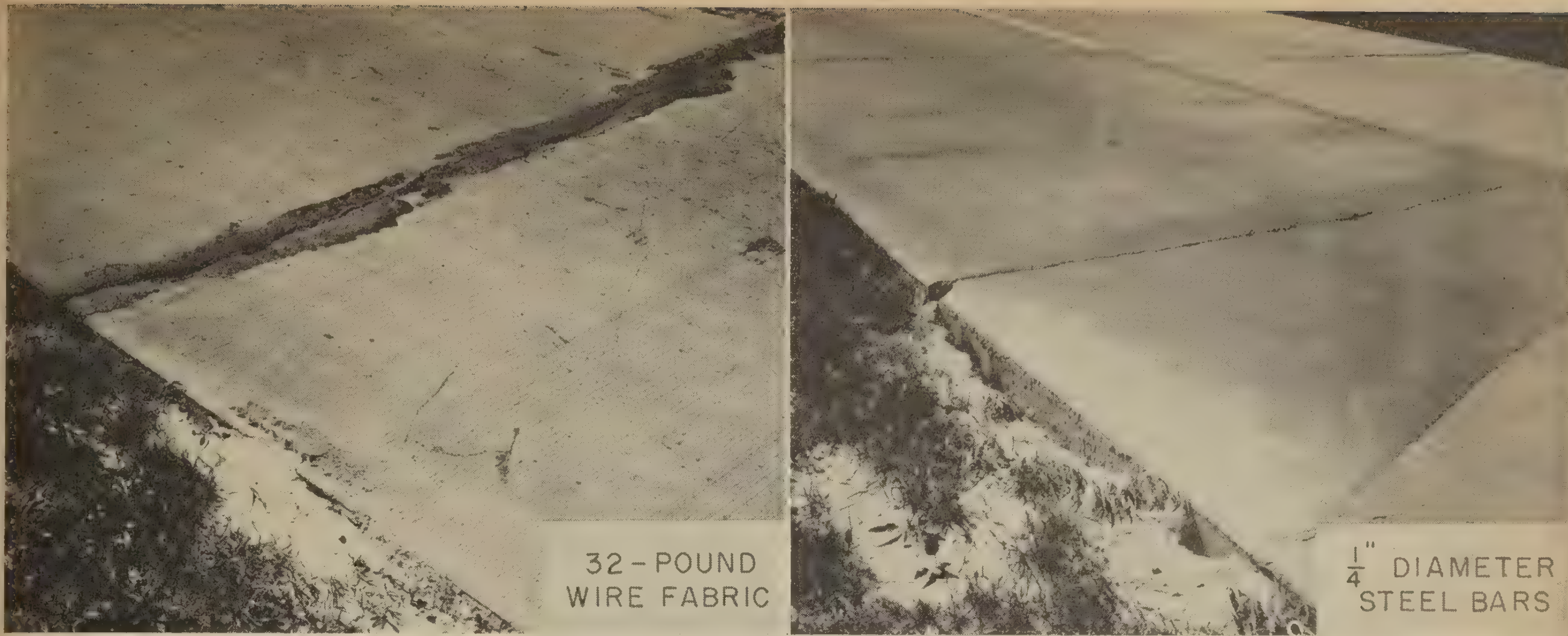


Figure 9.—Cracks at which the reinforcing steel failed. Steel failures in the heavily traveled lane were generally followed by pumping and faulting.

As implied earlier, a number of open cracks, indicative of steel failures, developed in sections containing the lighter percentages of longitudinal steel (0.11 and 0.07 percent). Figure 9 shows two of these failures that appeared in the heavily traveled lane sometime between the 10-year and 15½-year performance surveys. In this lane, pumping and faulting developed rapidly after the cracks opened and bituminous maintenance was soon needed to alleviate surface roughness.

The development of steel failures in the sections containing longitudinal reinforcement of 0.11 percent or less is shown in table 3. Of interest is, first, the length of time required for the steel to rupture after a crack had formed and, second, the fact that section length exerted little influence on the occurrence of the ruptures.

As indicated in table 3, steel failures were first observed during the 8-year performance survey. At that time three breaks were noted in the heavily traveled lane, all at cracks in sections reinforced with the 32-pound wire fabric (0.07 percent longitudinal steel). Although two of these cracks were present at pavement age of 1 year and the other at 5 years the steel did not fail until sometime between the fifth and eighth years. At the end of 15½ years of service, seven additional steel failures were observed in the sections containing the 32-pound wire fabric, four at cracks in the heavily traveled lane and three at cracks in the passing lane. Two of the cracks in the heavily traveled lane were present at pavement age of 5 years and the other two at 10 years, whereas two of the cracks in the passing lane were first seen at the end of 1 year and the other at 10 years. Of the cracks at which steel breakage was found, three were in 30-, three in 40-, and four in 50-foot sections.

The steel failures that occurred at cracks in sections reinforced with ¼-inch diameter rail- and billet-steel bars (0.11 percent longitudinal steel) took even longer to develop than those in sections containing the 32-pound wire fabric.

All of the five failures in these sections were

Figure 10.—The bridge-type joint, and early pumping at such a joint.

Table 3.—Steel failures at cracks in the experimental sections

Failure location			Year after construction [1] when—	
Section length	Pavement lane		Crack first observed	Steel failure first observed
Feet	Outer	Inner		
Sections Containing 32-Pound Welded-Wire Fabric				
30	X	------	5	8
30	X	------	10	15½
30	------	X	10	15½
40	X	------	1	8
40	X	------	5	15½
40	------	X	1	15½
50	X	------	1	8
50	X	------	5	15½
50	X	------	10	15½
50	------	X	1	15½
Sections Containing ¼-Inch-Diameter Billet-Steel Bars				
20	X	------	3	15½
40	X	------	10	15½
Sections Containing ¼-Inch-Diameter Rail-Steel Bars				
60	X	------	1	15½
80	X	------	5	15½
80	------	X	5	15½

[1] Performance surveys were made shortly after construction and at the end of 1, 3, 5, 8, 10, and 15½ years.

Figure 11.—Condition after $15^1/_2$ years of a double bridge-type expansion joint, typical of the majority. Loosening of the steel cover plate, pumping, and faulting developed at an early age at most of these joints in the heavily traveled lane.

first observed during the 15½-year performance survey. Four were at cracks in the heavily traveled lane and one at a crack in the passing lane. One of these cracks was present at pavement age of 1 year, one at 3, two at 5, and the fifth at 10 years. Of the five steel failures (three for rail steel and two for billet steel), one each occurred in the group of 20-, 40-, and 60-foot sections and two occurred in the group of 80-foot sections.

The crack survey data provide a comparison between the behavior of the longitudinal steel in the sections containing the 32-pound wire fabric and the longitudinal steel in the sections containing the slightly heavier ¼-inch diameter rail- and billet-steel bars. At the time of the 5-year survey, six cracks had formed in the heavily traveled lane of the sections reinforced with the 32-pound wire fabric and nine such cracks had formed in the sections reinforced with the ¼-inch diameter steel bars. The 15½-year performance survey indicated that the reinforcement had failed at five of the six cracks referred to in the sections reinforced with the wire fabric while, in contrast, the reinforcement had failed at only three of the nine cracks that had occurred during the first 5 years in the sections reinforced with the steel bars. This difference in performance is probably a reflection of the difference in the percentage of longitudinal steel in the two groups of sections.

It is evident from table 1 that sections reinforced with the 45-pound wire fabric contain the same percentage of longitudinal steel as those reinforced with the ¼-inch diameter bars. At the end of 15½ years only four cracks were observed in the sections containing the 45-pound wire fabric. Crack survey data disclose that one of these was first seen at the end of 5 years, two at 10 years, and the fourth at 15½ years. All were in closed condition.

The exact cause or causes of the steel failures which have been described are not known. However, their occurrence irrespective of section length and their predominance in the heavily traveled lane, despite tie-bars in the longitudinal joint, point to repeated stresses induced by traffic loads as a major factor in their development. The nature of the failures suggests the need for extreme caution and a consideration of the possible effects of live-load stresses in the use of longitudinal reinforcement as light as 0.11 percent.

Development and Effect of Pumping

By the end of 15½ years, pumping had affected various parts of the experimental pavement. In the following discussion of this development it will be of interest to keep in mind the steady increase in traffic volume recorded during the life of the experimental sections (fig. 1).

Bridge-type expansion joints

Early in the life of the pavement, pumping began to appear at some of the bridge-type expansion joints (fig. 10) which were designed to provide the wider openings between the longer sections. These joints had no effective means of load transfer, except the steel cover plate, and consequently, under traffic, permitted slab deflections considerably larger than those occurring at any other part of the constructed pavement. After 5 years of service many of the joints of this type were pumping, faulting was noticeable, and flexural cracking, caused by loss of subgrade support through pumping, had occurred in the end areas of several sections. At 15½ years, nearly all of the bridge-type joints in the heavily traveled lane were subject to pumping and, at many, flexural cracking, serious settlement, and severe faulting of the slab ends had developed. Of all companion joints in the passing lane, however, only three were affected by pumping.

Figure 11 illustrates typically the general condition of the pavement existing at the majority of the double bridge-type expansion joints. When the photograph was taken, in the spring of 1954, most of the double and many of the single bridge-type joints were sources of acute surface roughness in spite of rather extensive maintenance. At 15½ years these joints had reached the stage where major repairs were badly needed and such repairs were on immediate schedule. Although the action of pumping contributed materially to the poor condition of these joints, it must be recognized that all joints, regardless of type, which separate long sections, undergo large changes in width and, even when pumping is controlled, are susceptible to functional defects which contribute to surface roughness.

Doweled expansion joints

Seven years after construction, incipient pumping appeared at several of the conventional doweled expansion joints which separate the shorter sections. The provision for load transfer in the joints consisted of ¾-inch diameter dowels spaced at 12-inch centers. After 10 years, pumping was observed at a number of these joints, but the action was still so slight that faulting was negligible and flexural cracking of the slab ends had not occurred. At the end of 15½ years, however, the performance survey showed that pumping at the doweled joints in the heavily traveled lane had progressed to the point of causing considerable structural damage. Evidence of pumping was observed at more than half of the joints, approximately one-third had pumped to the extent that flexural cracking had developed in the slab ends, and faulting, as much as ½ inch, was present at the outside corners of several. In contrast, pumping was completely absent and faulting was negligible at the same type of joint in the passing lane.

In concluding the discussion of pumping and expansion joints, it is of special interest to note that a comparison of the described service performances of the bridge-type joints and the doweled joints indicates that load-transfer devices have considerable value in resisting and delaying the action of pumping. It is also of interest that all percentages of longitudinal reinforcing steel of 0.11 or greater have, thus far, held closed all fractures that occurred, as a result of pumping, in the pavement areas adjacent to the various expansion joints.

Construction joints

Construction joints constitute another structural feature that has been affected by pumping. Essentially, two types of construction joints were used in the experimental pavement: one type in the sections reinforced with the welded wire fabric; the other in the sections reinforced with the deformed bars. In the first, the wire fabric ended at the header board and ⅝-inch-diameter deformed tie-bars

4 feet long and spaced at 2-foot centers, were installed to hold the adjoining slabs together. In the second, the bar reinforcement was extended through the header board.

Of 11 construction joints of the first type, the 15½-year survey of the heavily traveled lane showed that (1) five joints were subject to pumping, one to the extent of flexural cracking, (2) widths ranged from tightly closed to ¾ inch, (3) faulting had developed at nearly all, the maximum being ¾ inch, and (4) moderate surface spalling of the edges requiring some maintenance was present at the majority. In the passing lane pumping had not appeared at any of the joints, but widths were consistent with those in the heavily traveled lane and slight faulting and minor spalling had developed. Figure 12 shows the condition at one of these joints which, as may be observed, had opened appreciably. Apparently the tie-bars crossing this type of joint did not develop sufficient bond or lacked the strength to perform properly their intended function of maintaining adjoining slabs in close contact.

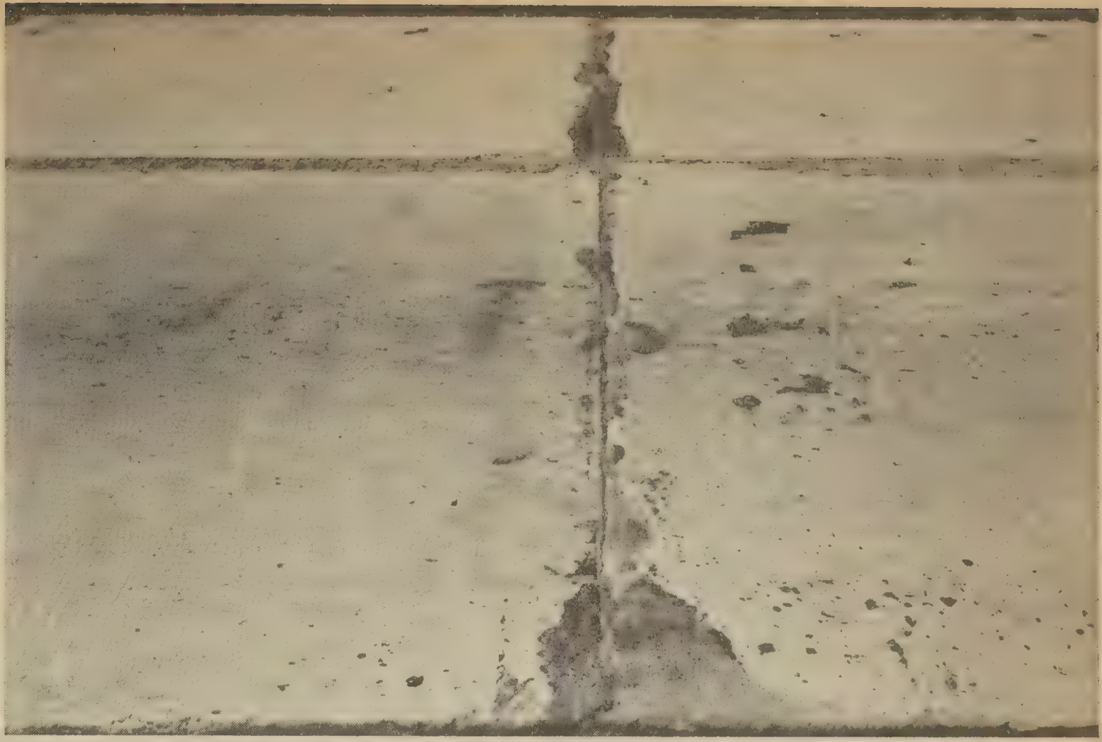


Figure 12.—Condition after 15½ years of a construction joint in sections reinforced with wire fabric. Tie bars were used to hold adjoining slabs together.

Under the same conditions 22 of the 25 construction joints of the second type—that is, those containing continuous reinforcement—were found to be structurally sound, tightly closed, and free from pumping. The condition of the pavement at one of these joints, installed in the central portion of a section reinforced with 1-inch diameter bars, is shown in figure 13.

Of the three unsound construction joints of the second type, one each was located in sections reinforced with ¼-, ⅜-, and ½-inch diameter billet-steel bars. All three of the joints were open ⅜ to ½ inch, indicating failure of the reinforcing steel crossing them and, in the heavily traveled lane, all had pumped and faulted. These joint failures occurred sometime after the tenth year of pavement life. Quite perplexing is the failure that occurred at the construction joint in the section reinforced with the ½-inch diameter bars (0.45 percent longitudinal steel). This joint was located only 69 feet from the end of a 270-foot section.

Inspection of the pavement in the vicinity of all construction joints through which the reinforcement was continuous showed that these joints had little effect on the crack pattern normal to that part of the section in which they were located. This behavior differs from the abnormal concentration of cracking which has been observed in the concrete placed immediately ahead of the joint in question when construction was resumed on certain other continuously reinforced pavements (*5–10*). Since there is evidence that the method of curing might have exerted some influence on the excessive cracking reported in the pavement adjacent to the construction joints of the other researches, it appears desirable to mention that the pavement under discussion was cured initially with wet burlap and then wet straw for a total of 7 days.

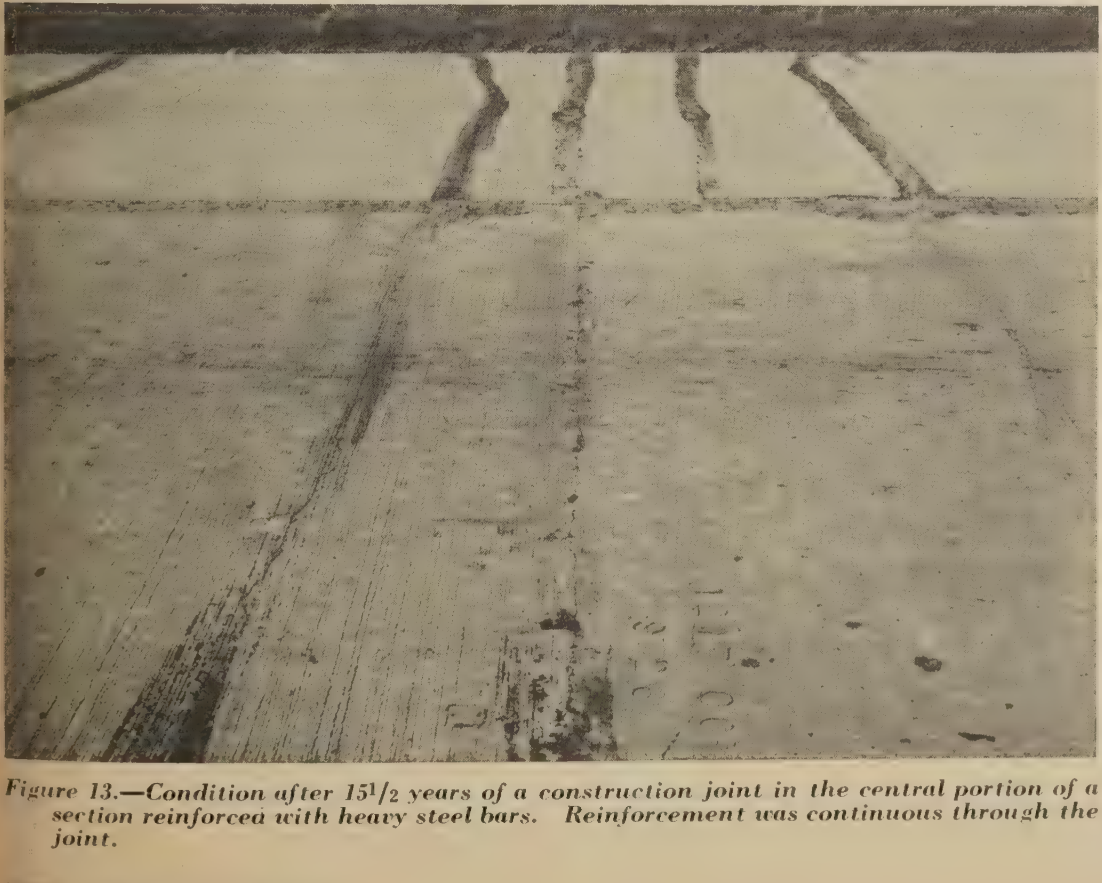


Figure 13.—Condition after 15½ years of a construction joint in the central portion of a section reinforced with heavy steel bars. Reinforcement was continuous through the joint.

Transverse cracks

Pumping in various stages was noted at a number of the previously reported open cracks that formed in the sections reinforced with the lighter amounts of steel. Specifically, the 15½-year survey showed that of 11 such cracks in the heavily traveled lane, 9 were subject to pumping, flexural cracking of the slab ends had occurred at 4, and, in some cases, faulting was quite pronounced. Of four open cracks in the passing lane, slight evidence of pumping was observed at one. Two examples of the condition described may be seen in figure 9.

The appearance of pumping at the cracks shortly after the reinforcing steel ruptured is indicative of the structural weakness resulting from this type of failure and emphasizes the importance of maintaining in closed condition all cracks in reinforced concrete sections.

In contrast to the action at open cracks, neither pumping nor faulting has developed at any of the large number of transverse cracks held closed by continous reinforcement. Considering the prevalence of pumping and faulting elsewhere in the pavement, this per-

Figure 14.—Condition after $15^1/_2$ years: Slab failure in heavily traveled lane near center of 830-foot section reinforced with 1-inch rail-steel bars. Faulting at longitudinal joint and edge pumping preceded structural breakdown.

formance indicates the watertight character and the inherent structural strength of cracks maintained in closed condition by reinforcing steel.

Longitudinal free edge

Pumping along the free edge of the pavement some distance from the ends of a section was first observed during the 10-year performance survey. At that time the only area affected was in the heavily traveled lane near the middle of an 830-foot section reinforced with 1-inch-diameter bars. In the immediate vicinity of pumping, abnormal raveling or chipping was noted at the surface edges of three closely spaced transverse cracks, indicating that the pavement at that point had been deflected considerably by heavy loads. The underlying cause of the excessive deflection is pointed out by notes taken during construction which describe the subgrade at this point as soft, spongy, and unstable to such an extent that the side forms had to be supported by mudsills of heavy planking during placement of the concrete.

Under continued pumping and deflection the narrow segments of the pavement within the boundaries of the three transverse cracks soon shattered and the broken pieces settled and faulted. In spite of considerable surface maintenance this failure became progressively worse and at the time of the last survey had developed to the condition shown in figure 14. As indicated in the photograph, the adjacent pavement of the passing lane is entirely free from similar distress.

To date, the described failure is the only one of its nature to appear in any of the experimental sections. During the last survey, however, several areas of potential trouble were noted in the same section in which the failure developed. The worst of these is shown in figure 15. Typical of the areas were an open and slightly faulted longitudinal joint, indicating slight settlement of the heavily traveled lane, and an excessive raveling or chipping of the edges of transverse cracks, indicating abnormal and localized deflection of the pavement under heavy loads. Except for a complete absence of pumping, these areas resemble closely the early stages of the failure just reported.

At the time of the 15½-year survey, evidence of pumping was observed at four additional locations along the free edge of the pavement, all being in the heavily traveled lane of relatively long sections. The action, however, had been very slight and the pavement in the areas was by no means in immediate structural jeopardy. Figure 16 shows the most advanced stage of edge pumping observed at any of the locations. An exceptionally low shoulder existed at all four of the pumping locations and three of the four, like that of the photograph, were within 100 feet of the ends of long sections where transverse cracking was minimum.

Effect of Traffic

Throughout the report, reference has been made repeatedly to either the heavily traveled or the passing lane. Consequently, it is probably needless to recall that the experimental two-lane pavement is one-half of a rural, divided highway; and, typically, the outer lane carries the greater number of vehicles and practically all of the heavy trucks, the inner lane being used largely for passing. Such a distribution of traffic naturally provides an excellent opportunity to observe the effect of repetition of heavy loads on the structural performance and condition of the various sections.

Development of cracking

The 10-year crack survey showed that 53 percent of the transverse cracks then present in both lanes of the pavement had formed in

Figure 15.—Condition after $15^1/_2$ years: Potential failure in the central portion of 830-foo section reinforced with 1-inch rail-steel bars. Slight faulting at the longitudina joint indicates settlement of the heavily traveled lane. This development is approxi mately 50 feet east of the failed area shown in figure 14.

the heavily traveled outer lane. A similar survey at the end of 15½ years indicated that (1) of the total number of cracks in the central area of the 1,310-foot section, only 51 percent were in the heavily traveled lane and (2) of the total number of cracks (those caused by pumping omitted) in all sections of 200 feet and less, 60 percent were in the heavily traveled lane. Thus it appears that repetition of traffic loads has exerted some influence on the development of transverse cracks, particularly in the shorter sections. In the restrained, multifractured central regions of long sections the influence is very slight, however.

Surface widths of cracks

In all of the later crack surveys it has been quite apparent that the greater volume of traffic using the outer lane causes considerably more raveling and wearing of the edges of the transverse cracks than the lighter traffic on the passing lane. From data obtained at the end of 15½ years, figure 17 was prepared to compare the effect of traffic on the surface widths of cracks measured in the two lanes of the pavement. As indicated by the figure, the difference between lanes is appreciable, the average surface widths of cracks in the heavily traveled lane being approximately three times those of companion cracks in the passing lane. In addition to the described difference in crack raveling, all spalling, such as that shown in figure 8, is confined to the heavily traveled lane.

Pumping

Since one of the conditions necessary for the development of pumping is the repetition of heavy loads, it is natural to expect that evidence of pumping would be most pronounced in the lane of the experimental pavement carrying the greater number of heavy trucks. A review of reported data discloses that rather serious pumping developed at a considerable number of transverse joints and open cracks in the heavily traveled lane in contrast to only four cases of slight pumping action at such points in the passing lane. From this it might be concluded that the need for provisions to prevent or control pumping is greater for the heavily traveled lanes of divided highways than for the passing lanes.

The difference in the present condition of the two lanes of the experimental pavement indicates an inherent difference in the structural requirements of the inner and outer lanes of the pavement on divided highways and suggests the possibility of differences in design to compensate for the characteristic distribution of traffic on that type of pavement.

Pavement Smoothness

Since the advent of the automobile the general public has been deeply interested in the riding quality of the roads over which it travels. Each vehicle affords a means for evaluating and comparing the smoothness or roughness of pavements and every motorist has become a critic of riding comfort. As a result, a continuous smooth riding surface is a requisite of modern highways and, within economic limits, the common goal of all pavement design.

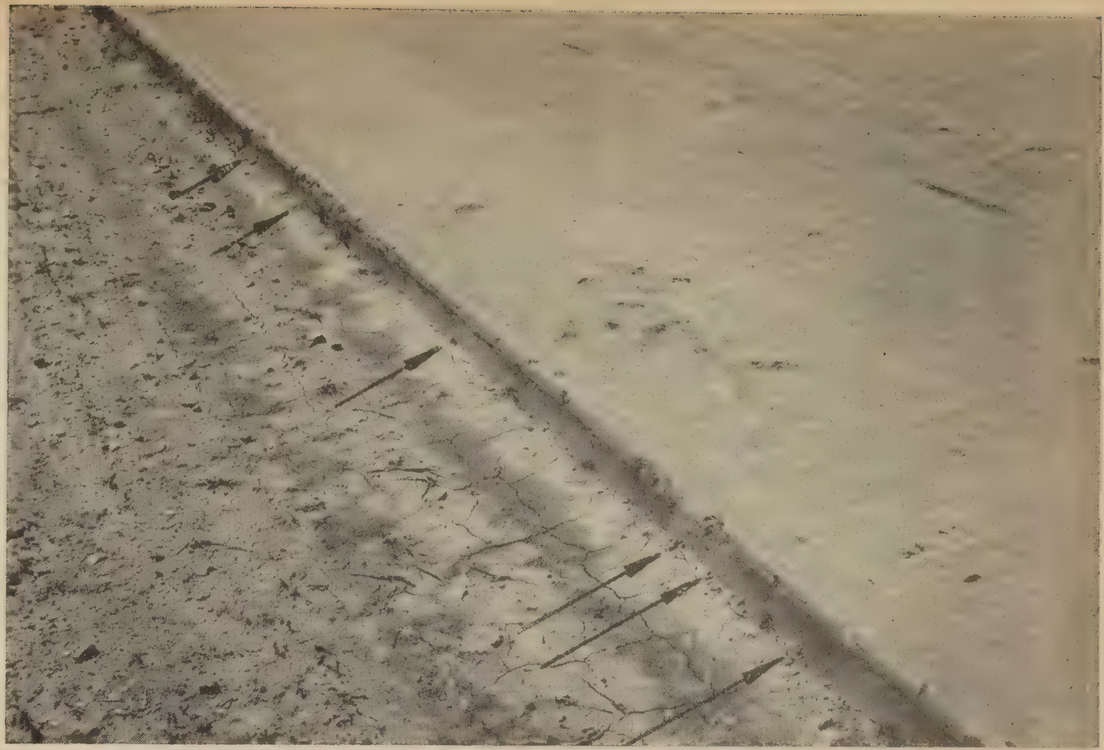


Figure 16.—Early stage of edge pumping observed at pavement age of 15½ years. This condition developed over a 50-foot length near the east end of a long, heavily reinforced section. The arrows point to tiny pump holes.

During the last survey, motoring at legal speed over the experimental pavement resulted in the following impressions: Starting in the heavily traveled lane and at the beginning of a long section, the ride was pleasantly smooth with only an occasional faint sensation of dipping. At the first double bridge-type joint, however, an abrupt jolt or shock accompanied by vehicle vibrations was felt. Smooth riding continued again until another joint of similar type was encountered. Passing on to the intermediate-length sections separated by the single bridge-type joints, the impressions just described were repeated but on a more moderate scale, the effect of joint roughness being less but at closer intervals. Continuing to shorter sections and the conventional expansion joints, a slight bump and pitching motion was felt at some of the joints, and at nearly all of them an annoying clicking sound was heard, suggesting that the sealing material was no longer flush with the surface of the pavement. Travel over the very short, lightly reinforced sections containing open cracks was accompanied by a succession of light bumps and slight pitching.

In motoring over the passing lane, it was noted that disturbances at most joints were far less severe than those encountered at adjacent joints in the heavily traveled lane. In contrast, however, with the exception of damaged areas, there was no impression of a

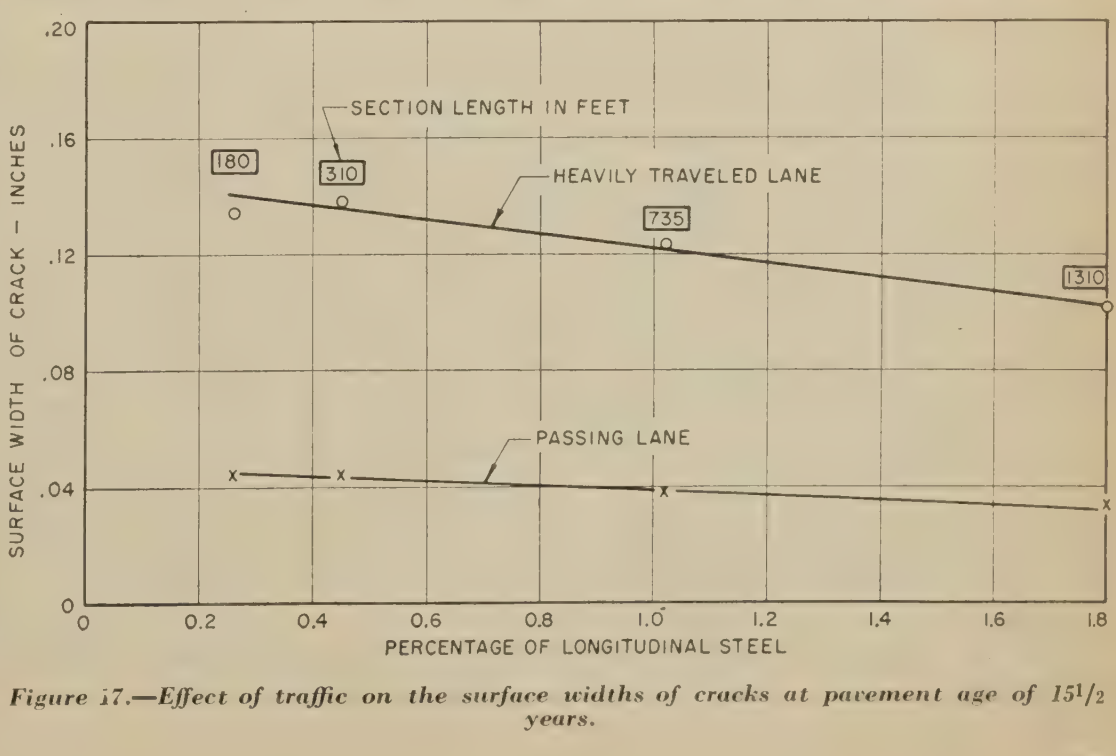


Figure 17.—Effect of traffic on the surface widths of cracks at pavement age of 15½ years.

Table 4.—Comparison of the roughness indexes of the various groups of similarly reinforced sections with the average index of the pavement between joints of the long, heavily reinforced sections [1]

Section length: Group average	Percentage of longitudinal steel in section	Ratio of roughness index of a given group of sections to that of pavement between joints of long sections	
		Outer lane	Inner lane
Feet	*Percent*		
Sections Containing Rail-Steel Bars			
960	1.82	1.1:1	1.0:1
540	1.02	1.1:1	1.0:1
240	.45	1.2:1	1.0:1
133	.26	1.0:1	1.0:1
58	.11	1.3:1	0.9:1
Sections Containing Billet-Steel Bars			
720	1.82	1.1:1	1.0:1
405	1.02	1.1:1	0.9:1
180	.45	1.2:1	1.0:1
100	.26	1.2:1	1.0:1
43	.11	1.3:1	1.0:1
Sections Containing Welded-Wire Fabric			
223	0.42	1.2:1	1.0:1
148	.28	1.1:1	1.0:1
125	.24	1.1:1	1.2:1
90	.17	1.1:1	1.2:1
55	.11	1.1:1	1.0:1
35	.07	1.4:1	1.4:1

[1] All roughness indexes were determined at pavement age of 15½ years.

difference between lanes in the riding quality of the pavement other than at the joints.

From the motorist's viewpoint the long stretches of pavement between the expansion joints of the heavily reinforced sections left little to be desired in riding comfort, indicating that the many cracks that formed in these sections have not affected the surface smoothness of the pavement.

Another, more analytical approach to the relative riding quality of the various sections was provided by the road surface roughness indicator developed some years ago by the Bureau of Public Roads (*11*). With this device it is possible to compare the surface roughness of sections or groups of sections by means of an index expressed in inches per mile.

At the end of 15½ years, roughness indexes were obtained for each group of similarly reinforced sections listed in table 1. In addition, a weighted average index was established for the pavement located between the joints of the long, heavily reinforced sections by excluding 50 feet of pavement on each side of the transverse joints separating these sections. This index should approximate closely that which would have been obtained had these sections been constructed as continuously reinforced pavement without joints.

The results of the 15½-year roughness survey are given in table 4. In this table the indexes determined for each of the various groups of similarly reinforced sections are compared with the index representative of continuous pavement without joints. The section length listed in the first column of the table is the average of the range in section lengths included in each group of sections and indicates the average spacing of transverse joints.

It is apparent in table 4 that, in spite of a rather narrow range in the surface roughness of the various groups of sections, certain trends exist which support the impressions previously described. For example, in the outer, heavily traveled lane, the roughest pavement surface is shown for the groups of very short sections reinforced with the lightest amount of each type of steel. As discussed earlier, open cracks developed in the sections of these groups. Also, in the same lane, the ratios for the groups of long, heavily reinforced sections reflect the roughness existing at the bridge-type joints; whereas those for the groups of shorter sections indicate that the surface of the basic pavement with its large number of transverse cracks is somewhat smoother than that of pavement containing conventional expansion joints. In the inner or passing lane, the majority of the groups of sections have the same surface smoothness as that of the basic pavement, suggesting that, under certain conditions, pavements with expansion joints can retain surface smoothness equal to those of continuously reinforced pavements without joints.

Another interesting relation disclosed by the roughness indexes determined at the end of 15½ years, but not apparent in table 4, is the fact that the pavement located between the joints of the long sections in the heavily traveled lane was of approximately the same smoothness as that of companion pavement in the passing lane, in spite of the fact that the surface widths of the cracks in the heavily traveled lane were, on the average, three times those in the passing lane.

Table 5.—Distinguishing features of the four 500-foot special sections [1]

Length of section	Spacing of weakened-plane joints	Type of weakened-plane joint	Weight of reinforcement
Feet	*Feet*		*Lb. per 100 sq. ft.*
500	10	Surface-groove	91
500	10	do	45
500	10	Submerged	91
500	10	do	45

[1] Bond between the steel and concrete was purposely destroyed for 18 inches on each side of each joint. Shear bars consisting of ¾-inch diameter dowels, 18 inches long, spaced at 12-inch centers, were placed in one-half of each of the four sections. Copper seals enveloped the bottom parting strips of the submerged type, weakened-plane joints.

Behavior of Special Sections

It may be recalled that four special 500-foot sections containing weakened-plane joints at 10-foot intervals were included in the experimental pavement to develop information on the practicability of a design in which trans-

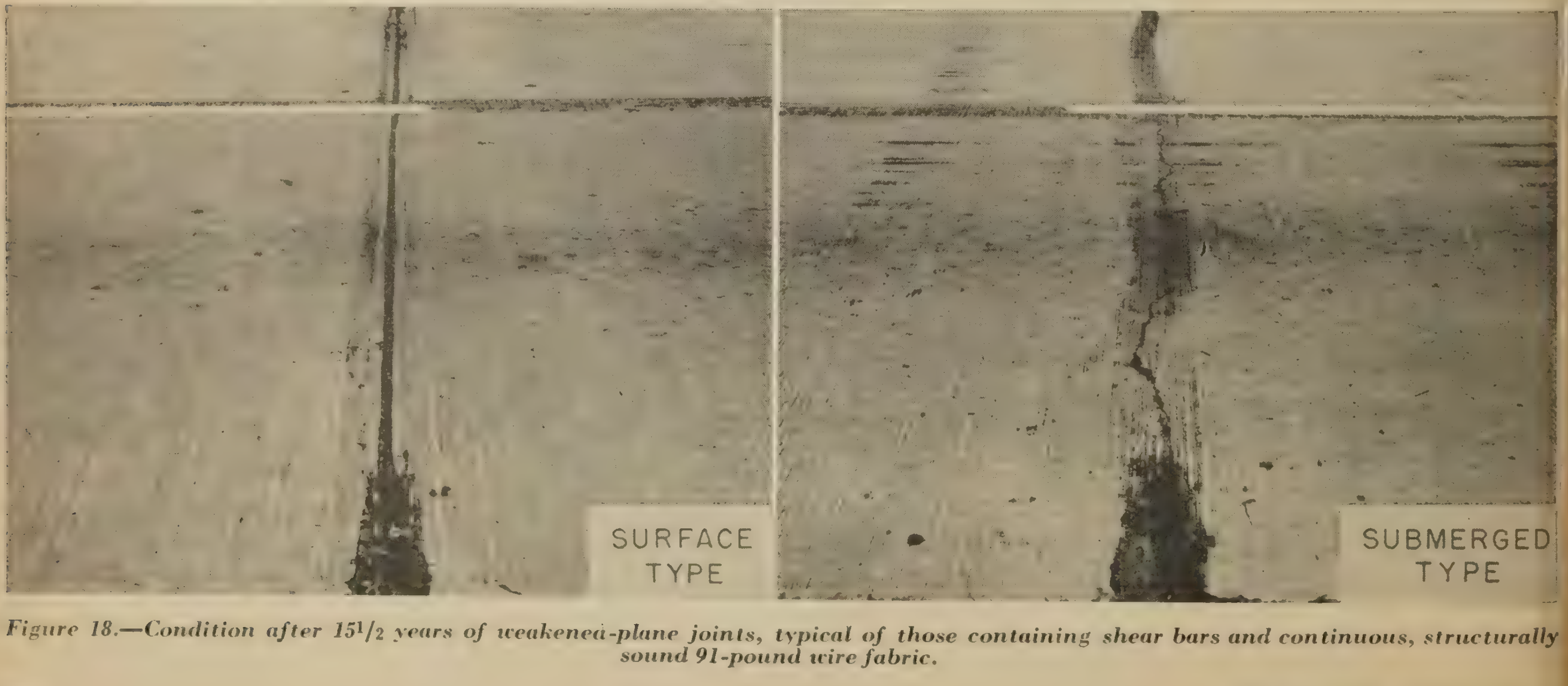


Figure 18.—Condition after 15½ years of weakened-plane joints, typical of those containing shear bars and continuous, structurally sound 91-pound wire fabric.

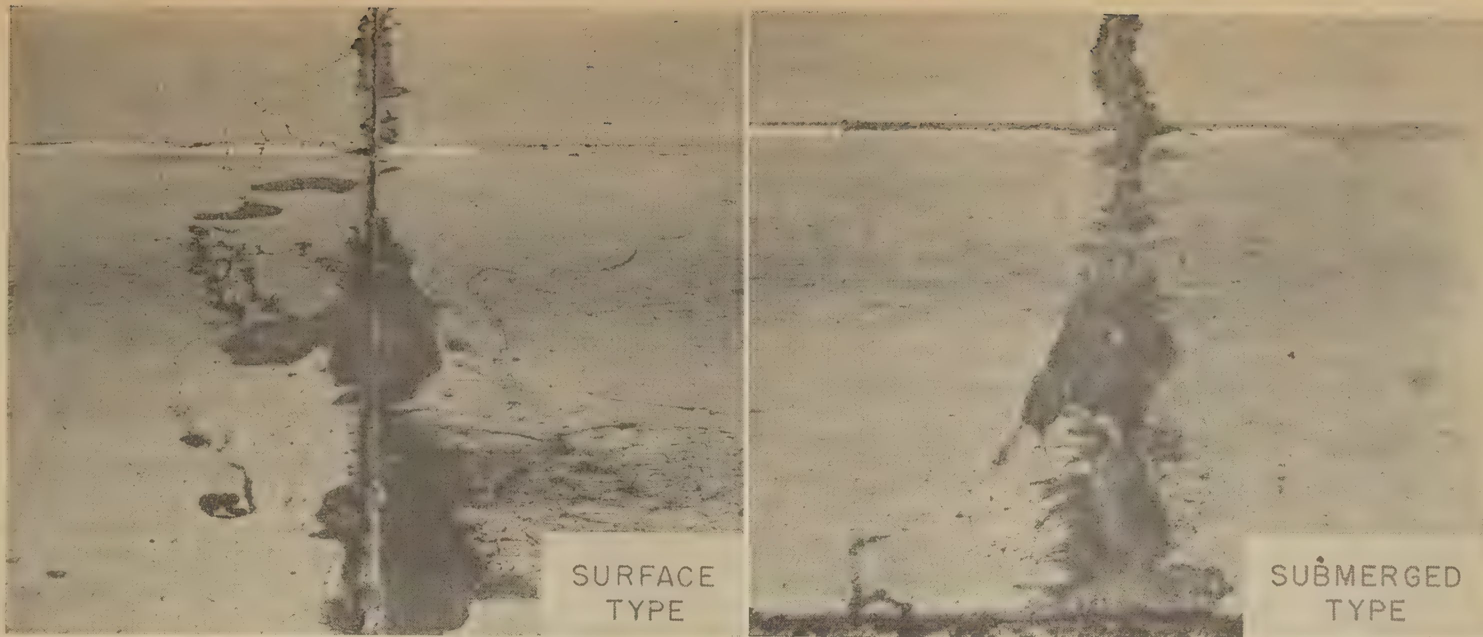


Figure 19.—Condition after 15½ years of weakened-plane joints, typical of those without shear bars and at which the reinforcing steel failed.

verse crack control is effected through the use of short constructed slabs with pavement continuity provided by continuous, relatively lightweight, longitudinal reinforcement. As explained in earlier reports, the basic feature of the proposed design is the deliberate breaking of the bond between the steel and the concrete for a distance of 18 inches on each side of each joint. Through this feature the reinforcing steel can elongate appreciably at each joint without exceeding its yield point, making it possible, during contraction periods, to provide a certain degree of relief from tensile stresses induced by subgrade resistance. For example, during a sudden drop in pavement temperature when subgrade resistance is relatively great, the reinforcing steel can elongate and permit the slab units to contract about their individual centers. Then, subsequently, when the resistance subsides, the steel can contract and draw the units together.

The distinguishing features of the four special 500-foot sections, together with general design details, are given in table 5. The performance of these sections was expected to furnish information on (1) the overall effect of purposely destroying the bond between the steel and the concrete in the manner described, (2) the amount of longitudinal steel necessary for proper functioning of the proposed design, (3) the benefit of shear units in the weakened-plane joints, and (4) the relative value of the two types of weakened-plane joints.

With these objectives in mind, the four special sections were subjected to a close examination during the 15½-year performance survey.

Surface condition of joints

Figure 18 shows the 15½-year surface condition of the two types of weakened-plane joints installed in the special sections. The photographs are of joints in the heavily traveled lane and the condition illustrated is typical of that now present at joints containing shear bars and unbroken 91-pound wire fabric. A well-sealed joint of good appearance is typical of the weakened-plane joint of the surface-groove type. All structurally sound joints of this type have continued in excellent condition and have required little maintenance. Their behavior indicates that, if pavement continuity is maintained, the comparatively small length changes of the 10-foot slabs are conducive to well-sealed conditions.

Likewise, except where steel failures have occurred, all weakened-plane joints of the submerged type, although rather unsightly in appearance, have continued to remain in excellent condition structurally. The fractures that formed above the parting strips of these joints are, in general, irregular and meandering in character, and, under exposure and the action of traffic, they have raveled and chipped to widths wider than those that developed in the regular sections reinforced with comparable percentages of steel. For example, at the end of 15½ years, the average measured surface width of fractures at structurally sound submerged joints containing the 91-pound fabric was approximately 0.3 inch in the heavily traveled lane or about twice the average surface width of fractures in the same lane of equivalently reinforced, regular sections.

In contrast to the favorable condition found at the joints which were structurally sound, figure 19 shows the present state of surface deterioration typical of that existing in the heavily traveled lane at joints, constructed without shear bars, at which the longitudinal steel was either broken or stressed beyond the yield point. Wherever the steel failed at the weakened-plane joints, relatively wide separations (up to ⅜ inch) quickly developed, and raveling and spalling increased appreciably.

Steel failures

The results of that part of the 15½-year examination relating to failures of the longitudinal steel crossing the weakened-plane joints are given in table 6. The data of this table indicate that, in the heavily traveled lane, the reinforcement was either broken or stressed beyond the yield point at 40 of the 196 weakened-plane joints incorporated in the four special sections. Of the 40 steel failures, 37 occurred at joints without shear units (dowels) indicating, rather definitely, that shear forces caused by loads passing over the joints were primarily responsible for the failure. Apparently, the elongation of the 36-inch length of unbonded steel at each weakened-plane joint permitted a separation of the slab ends sufficient to destroy or reduce whatever shear resistance aggregate interlock may have provided and to transfer all or part of the function of resisting shear to the relatively small members of the welded wire fabric.

Considering only the 37 failures that occurred at the joints without shear units, it is noted that 28 appeared in sections reinforced with the 45-pound and 9 in those reinforced with the 91-pound fabric. This

Table 6.—Steel failures and pumping at joints in the heavily traveled lane of the special sections [1] at the end of 15½ years

Weight of reinforcement *Lb. per 100 sq. ft.*	Shear bars	Number of joints with steel failures	Number of pumping joints
SURFACE-TYPE JOINT			
91	Yes	0	0
91	No	7	8
45	Yes	0	2
45	No	15	12
SUBMERGED-TYPE JOINT			
91	Yes	0	0
91	No	2	0
45	Yes	3	0
45	No	13	2

[1] Table gives values for half sections. Either 24 or 25 joints in each half section.

shows that although the 91-pound fabric provided better shear resistance than the 45-pound fabric, the No. 000 gage wires of the heavier fabric were not adequate to provide the shear resistance necessary for good structural performance under conditions such as obtained in these tests.

Of interest is the fact that all of the three steel failures which occurred at the doweled joints in the heavily traveled lane were in the half of the section containing the 45-pound wire fabric and the submerged type, weakened-plane joints. In accounting for these failures, it is possible for a progressive separation to develop at a joint and cause a residual tensile stress in the reinforcing steel. When this happens the relatively lightweight reinforcement, as used in the 500-foot special sections, may be subjected, during contraction periods, to tensile stresses sufficiently large to cause failures. In this connection, data presented in the 10-year report indicated that of the two types of weakened-plane joints, the submerged type developed the greater residual openings.

From a consideration of the causes of the steel failures that have been described it appears that elimination of expansion joints would be advantageous to pavements of the design of the special sections. This would control the progressive opening of the weakened-plane joints and minimize shear failures by maintenance of more positive aggregate interlock.

Pumping and faulting

The distribution of pumping joints in the heavily traveled lane of the special sections is shown in the last column of table 6. At the end of 15½ years, evidence of pumping was observed at nearly all of the impaired joints of the surface-groove type but, conversely, except in two cases, there was little evidence of this action at those of the submerged type. When joints of the submerged type were installed, a copper seal which enveloped the bottom parting strip was incorporated in their design. It may be that these seals have continued to prevent the leakage of free water to the subgrade despite the wide separations that followed the steel failures.

Of particular interest is the complete absence of pumping at all joints in the halves of the two sections which contain shear bars and the 91-pound wire fabric. Considering that the special sections were constructed on a subgrade soil of proved susceptibility to pumping, it is indicated that structurally sound pavements of this design are highly resistant to pumping.

As would be expected, tilting of the 10-foot slabs and consequent faulting at the joints was quite evident at all weakened-plane joints at which the reinforcing steel failed. Because of pumping, this condition was most severe at those of the surface-groove type. Faulting in amounts up to ⅝ inch was measured at the impaired joints and, in several areas, the pavement had been patched with asphalt to restore surface smoothness.

Riding quality

During the last survey, motoring over the heavily traveled lane of the four special sections left the impression that the halves containing shear bars were of acceptable surface smoothness, but not as pleasantly smooth as the long stretches of pavement between joints of the heavily reinforced regular sections. On the other hand, the halves without shear units were, in places, disagreeably rough. The two halves reinforced with the 45-pound wire fabric, in which the majority of the steel failures occurred, were exceptionally bumpy.

Table 7.—Comparison of the roughness indexes of the various halves of the special sections with the average index of the pavement between joints of the long, regular sections [1]

Weight of reinforcement *Lb. per 100 sq. ft.*	Shear bars	Ratio of roughness index of a given half of a special section [2] to that of pavement between joints of long, regular sections: Outer lane	Inner lane
SURFACE-TYPE JOINT			
91	Yes	1.2:1	1.2:1
91	No	1.8:1	1.3:1
45	Yes	1.2:1	1.2:1
45	No	3.2:1	1.6:1
SUBMERGED-TYPE JOINT			
91	Yes	1.3:1	1.3:1
91	No	1.6:1	1.5:1
45	Yes	1.2:1	1.3:1
45	No	2.1:1	1.6:1

[1] All roughness indexes were determined at pavement age of 15½ years.
[2] Each roughness index is based on 250 feet of pavement.

Roughness indexes of the four 500-foot special sections were determined at the same time as those of the regular sections. These indexes provide a means for evaluating the effects on surface roughness of the features listed in table 5. Comparisons of the roughness index of each half of each of the four special sections with the average index established for the pavement between joints of the long, heavily reinforced regular sections are given in table 7. All roughness indexes compared in this table were determined at pavement age of 15½ years.

Considering the heavily traveled outer lane, it is apparent from table 7 that the surfaces of the four halves of the special sections containing shear bars in the weakened-plane joints were, after 15½ years: (1) 20 to 30 percent rougher than the surface of the pavement between the joints of the long, regular sections, (2) of nearly the same roughness, irrespective of type of joint or the amount of longitudinal steel crossing the joints, and (3) smoother, markedly so in two cases, than the surfaces of the four halves with no shear units in the joints.

A comparison of surface roughness confined specifically to the heavily traveled lane and the four halves of the special sections without shear bars in the weakened-plane joints indicates that, for comparable percentages of reinforcing steel, the halves containing the submerged type joint have, with time, less surface roughness than those containing the surface-groove type, and, for the same type of joint, the halves of sections reinforced with the 91-pound fabric have, with time, considerably smoother surfaces than those reinforced with the 45-pound fabric.

Interlane comparisons at the end of 15½ years disclose that traffic has had little effect on the surface roughness of the four halves of the special sections with shear bars in the joints. However, in the halves without shear units, the surfaces of the sections in the heavily traveled lane have, with one exception, become appreciably rougher with time than those of their companion sections in the passing or inner lane. The one exception is the half of the section containing submerged type joints and the 91-pound wire fabric. In the heavily traveled lane of this half only two steel failures occurred and pumping was completely absent.

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(2) *Progress in experiments with continuous reinforcement in concrete pavements,* by H. D. Cashell and S. W. Benham. Public Roads, vol. 22, No. 3, May 1941. *Also,* Proceedings, Highway Research Board, vol. 20, 1940.

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Revisions to the Manual on Uniform Traffic Control Devices

Important changes in the design of traffic signs and other traffic control devices have recently been published in *Revisions to the Manual on Uniform Traffic Control Devices for Streets and Highways,* printed for the Bureau of Public Roads by the Government Printing Office.

For many years the *Manual on Uniform Traffic Control Devices* has been the standard guide for American traffic engineers in the design and application of traffic control devices but, like any other standard, it must change to keep pace with a changing world. The responsibility for its periodic revision lies with the National Joint Committee on Uniform Traffic Control Devices, a group of experts representing the American Association of State Highway Officials, the Institute of Traffic Engineers, and the National Committee on Uniform Traffic Laws and Ordinances. The latest edition of the Manual was published in 1948. The Joint Committee met during 1953 to review the standards and to recommend revisions on the basis of another 5 years' experience. Its recommendations for revision have been approved by the three parent organizations and are now published in pamphlet form.

The *Manual on Uniform Traffic Control Devices for Streets and Highways, including the revisions supplement,* is sold by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 90 cents a copy. As a separate publication, the *Revisions to the Manual on Uniform Traffic Control Devices for Streets and Highways* is available from the same source at 15 cents a copy.

The principal changes brought about by the revisions, most of them affecting traffic signs, are as follows:

1. A red stop sign, with white lettering, and with at least the lettering reflectorized, replaces the former standard yellow sign. No contrasting panels or supplementary messages are permitted.

2. A "Yield Right of Way" sign is adopted for use at certain intersections where a full stop is not required. This sign is a yellow equilateral triangle, with one point downward.

3. "No Passing" and "End No Passing Zone" signs are replaced by signs reading "Do Not Pass" and "Pass With Care", respectively.

4. The cardinal direction marker is to read "North", "South", etc., rather than "Northbound", etc.

5. The minimum mounting height to the bottom of signs in rural areas is increased to 5 feet, to avoid road splatter.

6. Warning signs are to be placed further in advance of dangers ahead.

7. The border around signs is now optional rather than mandatory.

8. Railroad-crossing pavement markings are confined to the right-hand portion of the pavement.

9. Traffic signal installations must show at least two signal faces visible on each approach to an intersection.

10. The minimum traffic "warrants" (vehicular and pedestrian volumes) justifying traffic signal installation are raised in certain respects.

Construction Review

The Departments of Commerce and Labor have joined efforts in production of a new periodical, *Construction Review,* which will serve as a comprehensive and authoritative source of information on the construction industry. The new monthly publication, which will start with the January 1955 issue, replaces the Labor Department's *Construction* and the Commerce Department's *Construction and Building Materials.*

Construction Review is available by purchase from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. The subscription rate is $3.00 per year, and single copies are priced at 30 cents.

Construction Review brings together virtually all current statistics pertaining to construction which are compiled by the Federal Government, plus some nongovernmental material. Statistical series include value of new construction put in place, new nonfarm dwelling units started, building permit valuation, contract awards, construction cost indexes, wage scales, wholesale prices and production of building materials, contract construction employment, etc. The publication will also report on specific aspects of construction.

Annual Report of the Bureau of Public Roads, Fiscal Year 1954

The *Annual Report of the Bureau of Public Roads, Fiscal Year 1954*, is now available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 30 cents a copy.

Covering the fiscal year ended June 30, 1954, the report deals with many vital aspects of highway transportation. As the principal roadbuilding agency of the Federal Government, the Bureau supervises the expenditure of funds authorized to aid the States in highway construction. It also supervises highway construction in National forests and parks and furnishes highway engineering assistance to other Federal agencies. In addition, the Bureau carries on a broad program of research dealing with the problems of highway improvement and traffic control.

The report discusses all phases of the Federal-aid construction program, which reached new high levels in 1954. Included are improvements on the National System of Interstate Highways, on primary and urban highways, and on farm-to-market roads. Outstanding Federal-aid projects are described. The report also reviews factors affecting progress, new highway legislation, foreign activities, including progress on the Inter-American Highway, and work in the field of highway safety.

The work done in fiscal year 1954 was financed by Federal-aid funds of $575 million authorized for the year and remaining balances of prior authorizations, together with State and local matching funds. All classes of Federal and Federal-aid projects completed during the year had a combined length of 20,989 miles. The decrease of 11 percent in total mileage completed from the all-time record of the previous year was due to a greater dollar volume of work in urban areas where costs per mile are high. The total cost of projects completed during the year amounted to $1,106 million, of which $585 million was Federal aid. The total was 2 percent greater than the previous year.

The 20,989-mile total included 4,488 miles of highways and 995 bridges on the Federal-aid primary system outside of cities (principal intercity routes), 767 miles of highways and 453 bridges on urban portions of the primary system, 14,995 miles of highways and 1,631 bridges on secondary or farm-to-market roads, and 739 miles of highways in National forests, parks, parkways, and flood-relief projects. At railway-highway grade crossings 193 hazardous crossings were eliminated, 21 inadequate grade-crossing structures were reconstructed, and 315 crossings were protected by the installation of flashing lights or other safety devices.

Research activities covered by the report include highway design standards, bridge design, and joint planning of location of highways and airports, and development of highway improvement programs for urban areas. A section of the report deals with parking meters—their financing, revenues, installation costs, and related matters. The report presents the results of physical research involving soils and related problems directly affecting improved road construction and lower costs.

In reviewing recent developments, the report points out that the most significant trend of the year was the increasingly strong and widespread demand that steps be taken to make our highway systems adequate within the shortest possible period—with particular emphasis on the need for improved main arteries between urban areas and for expressways in cities.

Criteria for Prestressed Concrete Bridges

The Bureau of Public Roads recently issued a new publication, *Criteria for Prestressed Concrete Bridges*, which is available by purchase from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 15 cents a copy.

The criteria presented in the 31-page pamphlet were developed in the hope that they may be useful until such time as more complete specifications, covering the subject in far greater detail, may be presented to the civil engineering profession by American specification and code writing bodies.

Included in the publication are criteria on the design, materials, and construction of prestressed concrete bridges, and explanatory discussions of the criteria.

The Bureau recognized in 1952 that the prestressed method of concrete construction had great possibilities in the building of better and more economical highway bridges of reinforced concrete, and that in many instances prestressed concrete might become a competitor of structural steel also.

There were no American standard codes governing the design of prestressed concrete bridges at that time. In recognition of the need for a guide to design that would provide structures acceptable for Federal-aid projects, the Bureau, in March 1952, prepared and distributed a *Design Criteria for Prestressed Concrete Bridges* (*Post Tensioning*). Although the scope of the criteria were very limited, the issue attracted considerable attention, and many constructive comments and suggestions were received from American and European engineers engaged in prestressed concrete design and construction.

On the basis of these comments and suggestions, a rough draft of a new and greatly enlarged criteria, covering design, materials, and construction, was prepared and submitted in September 1953 to a number of authorities in the field both in this country and abroad. Thoroughly revised in the light of their comments, the criteria, together with supporting discussion and source references, now appear in the new publication.

Uniform Vehicle Code

A new one-volume edition of the *Uniform Vehicle Code* was recently published by the National Committee on Uniform Traffic Laws and Ordinances. The Code, formulated in 1926 and revised periodically in the light of new developments and practical experience, provides a reliable guide for the use of the legislatures of the States in the development of Nationwide uniform traffic regulation.

The *Uniform Vehicle Code* (revised 1954) is a consolidation, rearrangement, and revision of the material heretofore included in five separate acts, formerly published by the U. S. Government Printing Office. The Code is now incorporated in a single act of 19 chapters, and the new arrangement will facilitate study of present laws in comparison with the provisions recommended as a guide for uniformity. The table of contents provides a key to the section numbering in the previous five individual acts.

The new 197-page *Uniform Vehicle Code* is published and sold by the National Committee on Uniform Traffic Laws and Ordinances, 1604 K Street, N. W., Washington 6, D. C. Single copies are priced at 75 cents, plus 8 cents for postage and handling, making a total charge per copy of 83 cents. The Committee, on request, will quote prices for quantity orders.

The *Model Traffic Ordinance* (revised 1953), companion publication to the Uniform Vehicle Code with particular application to cities, continues to be available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at 20 cents a copy.

U. S. GOVERNMENT PRINTING OFFICE: 1955

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PUBLICATIONS of the Bureau of Public Roads

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- 1941, 15 cents. 1948, 20 cents.
- 1942, 10 cents. 1949, 25 cents.

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- 1943; 1944; 1945; 1946; 1947.
- (*Free from Bureau of Public Roads*)

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- 1950, 25 cents. 1952, 25 cents. 1954, 30 cents.
- 1951, 35 cents. 1953, 25 cents.

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- 1945, 35 cents. 1948, 65 cents. 1951, 60 cents.
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- 1947, 45 cents. 1950 (out of print).

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- Part 1.—Nonuniformity of State Motor-Vehicle Traffic Laws, 15 cents.

PUBLICATIONS (Cont'd)

- Part 2.—Skilled Investigation at the Scene of the Accident Needed to Develop Causes. 10 cents.
- Part 3.—Inadequacy of State Motor-Vehicle Accident Reporting. 10 cents.
- Part 4.—Official Inspection of Vehicles. 10 cents.
- Part 5.—Case Histories of Fatal Highway Accidents. 10 cents.
- Part 6.—The Accident-Prone Driver. 10 cents.

Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft (1943). $2.00.
Public Control of Highway Access and Roadside Development (1947). 35 cents.
Public Land Acquisition for Highway Purposes (1943). 10 cents.
Results of Physical Tests of Road-Building Aggregate (1953). $1.00.
Roadside Improvement, No. 191MP (1934). 10 cents.
Selected Bibliography on Highway Finance (1951). 60 cents.
Specifications for Construction of Roads and Bridges in National Forests and National Parks, FP-41 (1948). $1.50.
Standard Plans for Highway Bridge Superstructures (1953). $1.25.
Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces (1943). 10 cents.
Transition Curves for Highways (1940). $1.75.

MAPS

State Transportation Map series (available for 39 States). Uniform sheets 26 by 36 inches, scale 1 inch equals 4 miles. Shows in colors Federal-aid and State highways with surface types, principal connecting roads, railroads, airports, waterways, National and State forests, parks, and other reservations. Prices and number of sheets for each State vary—see Superintendent of Documents price list 53.
United States System of Numbered Highways together with the Federal-Aid Highway System (also shows in color National forests, parks, and other reservations). 5 by 7 feet (in 2 sheets), scale 1 inch equals 37 miles. $1.25.
United States System of Numbered Highways. 28 by 42 inches, scale 1 inch equals 78 miles. 20 cents.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

Bibliography on Automobile Parking in the United States (1946).
Bibliography on Highway Lighting (1937).
Bibliography on Highway Safety (1938).
Bibliography on Land Acquisition for Public Roads (1947).
Bibliography on Roadside Control (1949).
Express Highways in the United States: a Bibliography (1945).
Indexes to PUBLIC ROADS, volumes 17–19 and 23.
Title Sheets for PUBLIC ROADS, volumes 24–27.

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DEPARTMENT OF COMMERCE - BUREAU OF PUBLIC ROADS

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

FOR OFFICIAL USE

AS OF DECEMBER 31, 1954

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM: Programmed Only			Plans Approved, Construction Not Started			Construction Under Way			Total		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$16,148	$15,533	$8,172	461.6	$4,223	$2,539	20.2	$43,967	$21,942	544.2	$63,723	$32,653	1,026.0
Arizona	5,998	8,535	5,747	126.2	1,124	784	4.1	6,611	4,610	128.0	16,270	11,141	258.3
Arkansas	13,076	8,045	4,539	325.4	6,047	3,172	173.6	14,336	7,078	300.6	28,428	14,789	799.6
California	14,012	30,646	16,180	167.6	15,536	8,216	55.9	118,824	58,204	294.5	165,006	82,600	518.0
Colorado	15,244	6,999	4,046	112.7	3,203	1,748	60.9	15,307	8,359	135.0	25,509	14,153	308.6
Connecticut	16,218	537	268	1.7	2,861	1,414	3.2	9,927	4,769	8.2	13,325	6,451	13.1
Delaware	4,658	841	422	4.0	2,582	1,285	9.5	6,597	3,656	23.3	10,020	5,363	36.8
Florida	13,280	19,018	9,737	222.4	7,466	3,853	50.2	20,541	10,558	337.6	47,025	24,148	610.2
Georgia	19,622	12,118	6,153	220.0	16,172	6,849	73.1	48,661	23,417	929.7	76,951	36,419	1,222.8
Idaho	4,292	9,657	6,163	130.4	2,489	1,549	50.5	12,125	7,633	170.7	24,271	15,345	351.6
Illinois	36,349	39,876	20,995	540.1	11,213	5,616	59.0	63,993	33,592	306.7	115,082	60,203	905.8
Indiana	20,917	38,462	19,263	168.4	18,661	9,566	128.1	25,618	13,809	92.4	82,741	42,638	388.9
Iowa	12,431	17,713	9,557	444.4	8,398	4,520	146.1	16,967	9,401	757.5	43,078	23,478	1,348.0
Kansas	16,160	9,384	4,759	744.0	3,293	1,671	60.0	21,596	11,102	962.2	34,273	17,532	1,766.2
Kentucky	15,080	9,988	5,406	61.4	4,789	2,433	102.8	25,481	12,807	225.1	40,258	20,646	389.3
Louisiana	15,803	10,409	5,193	135.4	8,860	4,430	33.8	23,636	10,656	102.8	42,905	20,279	272.0
Maine	6,242	7,102	3,801	41.3	1,655	834	20.0	14,453	7,309	115.1	23,210	11,944	176.4
Maryland	11,483	12,876	6,567	53.6	7,938	3,830	15.6	8,454	4,685	51.3	29,268	15,082	120.5
Massachusetts	18,071	3,754	1,867	20.2	8,146	4,005	6.7	52,575	24,689	42.4	64,475	30,561	69.3
Michigan	23,633	36,350	18,946	468.9	9,274	4,665	129.4	34,980	17,667	207.6	80,604	41,278	805.9
Minnesota	22,084	9,533	4,990	552.7	3,164	1,754	97.0	15,876	8,565	390.1	28,573	15,309	1,039.8
Mississippi	9,544	15,037	7,337	497.1	5,691	2,976	154.0	20,745	10,663	405.4	41,473	20,976	1,056.5
Missouri	15,844	29,837	15,742	1,094.1	6,582	3,728	30.7	57,245	29,260	747.7	93,664	48,730	1,872.5
Montana	15,657	11,838	7,163	270.3	3,202	1,961	47.2	22,092	13,585	425.2	37,132	22,709	742.7
Nebraska	18,182	16,360	8,579	720.6	9,725	5,720	121.9	15,538	8,542	525.4	41,623	22,841	1,367.9
Nevada	10,535	5,610	4,744	130.4	719	599	15.0	3,757	3,122	41.5	10,086	8,465	186.9
New Hampshire	5,851	1,958	1,154	10.5	284	145	1.6	6,421	3,137	35.3	8,663	4,436	47.4
New Jersey	22,614	8,025	4,012	43.8	3,233	1,595	3.4	15,380	7,096	29.1	26,638	12,703	76.3
New Mexico	7,035	6,234	3,845	198.4	2,225	1,434	15.0	9,613	6,136	159.5	18,072	11,415	372.9
New York	45,080	47,215	24,766	84.7	49,686	24,955	18.1	200,108	93,170	338.0	297,009	142,891	440.8
North Carolina	21,675	16,519	7,842	315.6	4,010	1,939	63.5	39,899	18,596	475.5	60,428	28,377	854.6
North Dakota	10,822	8,869	4,520	842.0	877	452	144.2	4,906	2,462	281.6	14,652	7,434	1,267.8
Ohio	31,807	30,266	14,849	74.8	10,018	4,075	18.3	72,242	34,439	158.8	112,526	53,363	251.9
Oklahoma	22,869	7,305	4,128	180.0	10,067	5,273	133.0	19,638	10,264	312.2	37,010	19,665	625.2
Oregon	9,076	4,605	2,769	61.1	3,612	2,262	51.8	11,194	6,830	132.7	19,411	11,861	245.6
Pennsylvania	46,122	1,613	807	1.6	22,843	11,193	20.8	83,967	41,498	159.7	108,423	53,498	182.1
Rhode Island	3,820	8,935	4,467	32.0	2,527	1,263	1.5	4,855	2,434	16.8	16,317	8,164	50.3
South Carolina	12,515	10,757	5,784	187.0	3,589	1,779	20.1	14,748	7,727	259.7	29,094	15,290	466.8
South Dakota	7,428	16,169	9,151	703.8	2,096	1,174	132.7	6,134	3,470	290.6	24,399	13,795	1,127.1
Tennessee	20,439	12,907	6,407	300.7	4,613	2,306	54.8	33,067	15,020	329.6	50,587	23,733	685.1
Texas	48,678	10,800	6,368	247.2	9,441	4,922	130.0	72,583	38,568	1,111.0	92,824	49,858	1,488.2
Utah	8,720	2,800	2,080	46.9	2,556	1,907	62.3	3,616	2,837	21.0	8,972	6,824	130.2
Vermont	4,849	1,134	570	17.6	429	224	2.2	7,113	3,542	62.0	8,676	4,336	81.8
Virginia	17,275	11,317	5,700	179.4	6,844	3,399	117.7	21,315	9,906	138.4	39,476	19,005	435.5
Washington	13,711	8,650	4,994	80.1	2,681	1,425	59.5	17,268	8,873	113.1	28,599	15,292	252.7
West Virginia	12,434	11,313	5,745	78.8	2,545	1,287	3.4	13,614	6,824	51.6	27,472	13,856	133.8
Wisconsin	18,886	21,265	10,735	260.1	521	300		24,907	12,587	262.5	46,693	23,622	522.6
Wyoming	5,601	5,109	3,287	99.1	1,758	1,151	15.6	7,507	4,708	146.0	14,374	9,146	260.7
Hawaii	4,519	2,980	1,490	2.8	1,058	351	2.2	5,788	2,715	15.1	9,826	4,556	20.1
District of Columbia	5,642	5,934	2,967	7.9	2,132	1,055	.6	13,620	6,477	1.2	21,686	10,499	9.7
Puerto Rico	9,683	6,557	3,193	39.2	1,187	572	4.2	15,382	6,867	42.4	23,126	10,632	85.8
TOTAL	807,714	655,294	347,966	11,810.0	323,845	166,155	2,745.0	1,444,787	725,863	13,213.6	2,423,926	1,239,984	27,768.6