PERFORMANCE OF VARIOUS THICKNESSES OF PORTLAND CEMENT CONCRETE PAVEMENT

30-Year Report

Iowa Highway Research Board
Project HR-9

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DEPARTMENT OF TRANSPORTATION
IOWA
Highway Division

in cooperation with
Greene County
Secondary Road Department

ernon Marks and John I. Helmers

IOWA HIGHWAY RESEARCH BOARD

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Performance of Various Thicknesses of Portland Cement Concrete Pavement

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ABSTRACT

If adequately designed and high quality material and good construction practices are used, portland cement concrete is very durable. This is demonstrated by the oldest pavement in Iowa (second oldest in the U.S.) paved in 1904, which performed well for 70 years without resurfacing. The design thickness is an important factor in both the performance and cost of pavement.

The objective of this paper is to provide a 30-year performance evaluation of a pavement constructed to determine the required design thickness for low volume secondary roadways.

In 1951 Greene County and the Iowa Highway Research Board of the Iowa Department of Transportation initiated a four-mile (6.4 km) demonstration project to evaluate thicknesses ranging from 4-1/2" (11.4 cm) to 6" (15.2 cm).

The project, consisting of 10 research sections, was formed pavement placed on a gravel roadbed with very little preparation except for redistribution of the loose aggregate. Eight sections were non-reinforced except for centerline tie bars and no contraction joints were used. Mesh reinforcing and contraction joints spaced at 29' 7" (9.02 m) intervals were used in two 4-1/2" (11.4 cm) thick sections. The only air entrained section was non-reinforced.

The pavement performed well over its 30-year life carrying a light volume of traffic and did not require major maintenance. There was substantial cracking with average slab length varying directly with thickness. The 4-1/2" (11.4 cm) thick non-air entrained, mesh-reinforced pavement with contraction joints has performed the best.

INTRODUCTION

Iowa's portland cement concrete paving began in 1904 with one-half block in the town of LeMars (second oldest pavement in the U.S.). This two lift pavement was 6-1/2" (16.5 cm) thick with the top 1-1/2" (3.8 cm) having a greater cement factor than the bottom 5" (12.7 cm). The joints were formed at 6' (1.83 m) intervals skewed 45° from each side, resulting in a diamond pattern. The texture was obtained by scoring the surface in 4" (10.2 cm) squares. This pavement performed well for 70 years without resurfacing and demonstrates the potential of pcc pavement.

Many miles of portland cement concrete pavement were constructed in the late 1920s and early 1930s during a campaign to "get Iowa out of the mud".

Iowa, a state of 56,290 square miles (145,791 square kilometres) and only 8 urban areas with population over 50,000, now has 112,257 miles of roadway (180,660 km) with surface types as shown in Table 1. In 1951, excluding municipal roads, there were 8,248 miles (13,274 km) of hard surfacing, 58,598 miles (94,304 km) of gravel and 35,523 miles (57,169 km) with no surfacing. The 94,121 miles (151,473 km) of roadway without hard surface, and the belief that adequate design, high quality material and good construction are essential for durable concrete were the impetus for research project HR-9.

Substantial research has been conducted into structural requirements, with studies of flexural fatigue as a function of design thickness being completed in the 1920s. This research was used in the development of the 1933 Portland Cement Association (PCA) design curve for pavement. The Iowa DOT is presently using the 1966 PCA design procedure.

OBJECTIVE

The objective of the research project was to determine to what thickness portland cement concrete (pcc) pavement could be reduced, with corresponding cost reduction, while providing a high quality surface of long life for low volume secondary roadways. The objective of this report is to provide a 30-year performance evaluation of the experimental pcc roadway.

PROJECT IDENTIFICATION

Greene County is located in central Iowa approximately 50 miles northwest of Des Moines. The project is four miles (6.4 km) long on County Road E-33 from Iowa Highway 4 to Farlin.

Signs showing the thickness and reinforcing of the pavement were installed along the north right-of-way line of the project. They were placed at the ends of the sections, and arrows on the signs pointed to the section to which the information applied. These signs are still present on the project as an aid to observers in locating the various sections and evaluating the present condition.

A non-conformity of the signs' text and the terms used in this report is that the non-reinforced sections are listed as dowel reinforced. The "dowel" term noted on the signs refers to the centerline tie bars.

PRECONSTRUCTION TESTING

In the spring of 1951 soil borings were taken and load bearing tests were performed by the plate bearing method to determine the suitability of the existing roadbed as a base for the pavement. Bearing values under a 12" diameter plate at yield point ranged from 58.5 psi (403 kPa) to 9 psi (62 kPa), with 30 psi (207 kPa) considered adequate. Based on this criteria, load bearing tests showed 4,100' (1,250 m) of unstable base and the soil borings indicated some areas in which there was a high water table and a subgrade which consisted mainly of clay loam (U.S. Bureau of Public Roads subgrade group No. A-6).

BASE DRAINAGE

In the areas identified as being unstable, vertical sand drains were constructed to provide for moisture movement. These drains were 6' (1.8 m) deep, 7" (17.8 cm) diameter holes filled with clean sand and a solution of calcium chloride and water compacted with a mechanical vibrator. They were located on 5' (1.5 m) centers in five parallel lines in a checkerboard pattern. There were 4,064 drains constructed in the following locations:

From Station[a]	3+50	to	11+25
	26+00		31+00
	47+00		53+00
	62+00		65+50
	87+00		99+50
	99+50		105+60

[a]Note: The project is stationed east to west.

Soon after the project was paved, the county engineer questioned the effectiveness of these drains since no horizontal interconnecting blanket nor outlets through the earth shoulders were provided. The first winter after construction produced severe frost action and resulted in minor heaving of two areas where there had been vertical sand drain treatment.

GRADE PREPARATION

The original intent was to use the existing gravel surfaced roadway with very little preparation except for uniform distribution of the loose aggregate on the surface. A profile grade tolerance of 0.15 of a foot (4.6 cm) was established (the allowable variation between the finish grade and the existing grade). This tolerance presented a challenge to the contractor since the roadbed had been constructed 12 years earlier.

DESIGN AND CONSTRUCTION

The four-mile (6.4 km) project was divided into 10 sections of various lengths, shown in Table 2. The pavement thicknesses were arbitrarily selected to range from 4-1/2" to 6" (11.4 cm to 15.2 cm) and were not based on the plate bearing results or the PCA design formula. Substantial engineering judgement is used with the modulus of subgrade reaction for Iowa pavement thickness design yet today. The concrete proportions were specified as Iowa State Highway Commission Mix No. 4A:

	Absolute Volume	Batch Quantities lbs (kg)
Cement Minimum	0.096419	510 (231)
Water Approximate	0.161201	272 (123)
Aggregates:		
Fine Approx. (Sp.Gr.=2.66)	0.371190[a]	1664 (755)
Coarse Approx. (Sp.Gr.=2.69)	0.371190	1682 (763)

[a]Aggregate absolute volumes and batch quantities were adjusted for the air entrained concrete.

The cement was type I from Penn Dixie in Des Moines, Iowa, and the sand and gravel aggregates were produced by Ferguson Diehl Company of Jefferson, Iowa. The air entraining agent used in section No. 10 was a commercially available liquid product (Darex) added at the mixer. Air entrainment was not a common practice in 1951.

Paving operations began in September 1951. The 20' (6.1 m) wide pavement was built using the conventional equipment of that time. The concrete was dry-batched at a plant located in Farlin. The dry-batched concrete was mixed on site and deposited on subgrade paper between the fixed forms.

These forms were 8" (20.3 cm) high, and since the pavement thicknesses specified were less than 8" (20.3 cm), the outer 6" (15.2 cm) of the base on each side was sloped to the bottom of the form yielding a thickened edge of slab. Figure 1 shows a typical cross-section of the pavement.

All of the "non-reinforced" pavement designs have 4' (1.2 m) long #4 (1.27 cm dia.) deformed steel re-bars placed on 4' (1.2 m) centers across the centerline as tie bars. Two of the four 4-1/2" (11.4 cm) thick sections were also reinforced with welded wire mesh. The layouts for the non-reinforced and reinforced pavements are given in Figures 2 and 3 respectively.

The joints in the slab were formed by placing pre-molded bituminous parting strips in the fresh concrete. A longitudinal joint was formed along the center of the slab. Other joints included days-work joints and contraction joints at the ends of the mats of reinforcement (29' 7" (9.02 m) spacing) in the 4-1/2" (11.4 cm) mesh reinforced sections.

TESTING AND EVALUATION

A. Concrete Strength

Both beam (6" x 6" x 33" or 15.2 cm x 15.2 cm x 83.8 cm) and cylinder (6" x 12" or 15.2 cm x 30.5 cm) test specimens were made during construction. Cores were drilled at 260 days and 28 years. A summary of concrete strengths is given in Table 3.

B. Crack Surveys

Crack surveys have been conducted 14 times since construction, being more frequent in the first two years. The last three were 6, 14 and 28 years after construction. The length of individual sections is divided by the total transverse cracks plus transverse joints to yield an average slab length. A summary is given in Table 4. At one month, the average slab length of pavement without contraction joints ranged from 81' (24.7 m) to 192' (58.5 m). The five-year range is from 17' (5.2 m) to 33' (10.1 m) and the 28-year range is from 13' (4.0 m) to 22' (6.7 m)(on the jointed slab).

A summary of the longitudinal cracking is given in Table 5. Very little longitudinal cracking occurred during the first year but it increased steadily thereafter. There are some variations that are somewhat different than expected, both between repeated sections and averages of sections with different thicknesses. These differences may be due to the variations in stability of the grade.

C. Riding Quality

A test of the longitudinal profile was not made until 1955 when the sections were tested with a Bureau of Public Roads (BPR) type roughometer. Testing with the BPR roughometer was conducted in 1955, 1979 and 1981. The results are summarized in Table 6.

MAINTENANCE

Maintenance of this pavement has been minimal, with little more than crack sealing for most of its life. A crack sealing effort in 1980 deposited enough sealant material on the surface to result in a significant decrease in riding quality. In recent years, full depth patches have been placed to restore some small broken and distorted areas.

A Greene County cost accounting program provides information to obtain a cost per mile (kilometer) for both portland cement concrete pavement and gravel surfaced roadways. The maintenance costs per mile (kilometer) for paved and gravel surface roadways are $1,034 ($642) and $1,365 ($848), respectively. A higher level of service (signing, mowing, winter maintenance) is provided on paved roads than for gravel roads. If signing, mowing and winter maintenance are not included, the basic maintenance costs for paved and gravel roadways are $483 ($300) and $1,108 ($688) respectively.

AGGREGATE DEMAND

Calculation shows that it will take many years for a paved road to result in a reduction of aggregate usage. The construction of this roadway required 2,450 tons per mile (1,381,061 kg/m) for 4-1/2" (11.4 cm) thick and 3,270 tons per mile (1,843,294 kg/m) for 6" (15.2 cm) thick pavement.

Typical Greene County gravel road construction uses 700 tons per mile (394,589 kg/m) the first year, 600 tons per mile (338,219 kg/m) the second year and 45 tons per mile (25,366 kg/m) per year thereafter. With these figures, it would be 27.6 years for a gravel roadway to use 2,450 tons per mile (1,381,061 kg/m) and 45.8 years to use 3,270 tons per mile (1,843,294 kg/m).

A paved road must yield a greater than normal life to result in a true reduction of aggregate demand. The paving aggregate, however, is not lost and provides an excellent base for future overlays.

PERFORMANCE

The volume of traffic over this project has been fairly constant over the years. The average daily traffic from 1957 to 1981 was about 260 vehicles per day. Traffic volumes for the 24-year period are given in Table 7. A grain elevator in Farlin increased the amount of truck traffic during harvest season during its operation from 1951 through 1976. A gravel pit operation one-half mile (0.8 km) east of Farlin also produced heavier loads on the road (1951-1977).

The 6" (15.2 cm) diameter cylinders of non-air entrained concrete averaged over 5,600 psi (38.61 MPa) when tested at the age of twenty-eight days. The 28-day modulus of rupture of the beams was 800 psi (5.52 MPa). The concrete is of excellent quality 28 years after construction with compressive strength averaging 7,920 psi (54.61 MPa).

The high pressure air content was determined on 28-year-old cores with the non-air entrained concrete averaging 3.2% and the air entrained section averaging 6.6%.

Typical surface appearance of the pavement is shown in Figure 4 (4-1/2" or 11.4 cm non-reinforced) and Figure 5 (6" or 15.2 cm non-reinforced). Even though transverse joints were not sawed, the random cracking in the 6" (15.2 cm) pavement produced a relatively uniform spacing with an orientation nearly perpendicular to the centerline. Most of the transverse cracking occurred early in the life of the pavement. In the thinner sections, little additional cracking developed after the first two years. Transverse cracks continued to develop in the 6" (15.2 cm) pavement through 28 years, but at a declining rate.

The 4-1/2" (11.4 cm) mesh reinforced sections with contraction joints exhibit the longest average slab length (22' or 6.7 m) after 28 years. The non-reinforced pavements have slab lengths that range from 13' (4.0 m) to 18' (5.5 m). The average slab length for the non-reinforced pavement varies directly with the thickness. The 4-1/2" (11.4 cm) pavement has the shortest slab length (13' or 4.0 m), while the 6" pavement has slab lengths of 18' (5.5 m). These lengths are just less than the current Iowa DOT design of 20'. It is unfortunate that jointed non-reinforced pavement was not included for comparison.

The longitudinal cracking generally varies inversely with thickness but there are irregularities. These irregularities may be attributed to variations in the grade from inadequate support or grade settlement. The 4-1/2" (11.4 cm) thick pavement, both reinforced and non-reinforced, developed the most longitudinal cracking, but the 81' per station or m/hm average for the mesh reinforced design results from widely differing data from the two sections of 19' per station or m/hm and 144' per station or m/hm. This, and the fact that the 5' 1/2" (14.0 cm) section exhibits the least longitudinal cracking, would indicate that the longitudinal cracking was dependent on the base. There was no obvious correlation between sand drain locations and subgrade with longitudinal cracking. The cracking at 1/4 point has not contributed to any substantial degree in a loss of service, though it may result in increased maintenance.

The profile variation at 30 years of age ranging from 129" per mile (204 cm/km) to 158" per mile (249 cm/km) is rough for a primary or interstate route, but is quite adequate for a secondary route. The data exhibits a substantial increase in roughness from 1979 to 1981. Visual observations indicate an extensive sealing effort during this period (1980) that deposited enough material on the surface to adversely affect the riding quality. It is expected that the material on the surface will be worn and bladed (winter maintenance) away and a longitudinal profile comparable to 1979 will result. The 4-1/2" (11.4 cm) mesh reinforced section exhibits the smoothest profile. No joint heaving or slab warping is apparent.

COSTS

The cost of each section is listed in Table 8. It is believed that these prices were greater than normal costs of pavement at the time of construction because of the extra work involved due to the research and short sections.

CONCLUSIONS

The conclusions drawn from this research are:

1. All design thickness, from 4-1/2" (11.4 cm) to 6" (15.2 cm), provided quite adequate service for a low volume secondary roadway with minimal maintenance for 30 years.

2. The 4-1/2" (11.4 cm) thick pavement has resulted in a slight reduction of aggregate usage when compared to requirements for an unpaved gravel roadway, but the 6" (15.2 cm) pavement results in a substantial increase in aggregate usage.

3. The 4-1/2" (11.4 cm) thick mesh reinforced section has provided the best overall performance.

4. Slab lengths of the non-reinforced sections without contraction joints vary directly with thickness and are all just less than the current design length of 20' (6.1 m).

5. The amount of longitudinal cracking varies inversely with the thickness of pavement.

6. The cost of maintaining a paved road is less than for a gravel roadway. If only basic maintenance is provided, the cost for a paved road may be less than half that for a gravel surfaced roadway.

ACKNOWLEDGEMENT

This research resulted from the efforts and ideas of C. Arthur Elliott, former Greene County Engineer. The authors wish to express appreciation to Greene County Engineer Ron Betterton and long time Greene County employee Warren Raver for their assistance in preparation of this report.

Richard Smith and Clarence DeYoung of the Iowa Department of Transportation provided valuable assistance in the evaluation of the research and input to this report.

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Table 1. Miles (kilometers) of Iowa highway by surface type - 1981.

Surface Type	Primary	Secondary	Municipal	Total
Portland Cement Paved	4,557	4,536	3,305	12,463
	(7,334)	(7,300)	(5,320)	(20,057)
Asphalt Concrete Paved	5,465	8,936	5,879	20,379
	(8,795)	(14,380)	(9,462)	(32,797)
Bituminous Treated	88	1,514	1,058	2,694
	(141)	(2,436)	(1,702)	(4,335)
Gravel	15	68,942	1,701	70,767
	(24)	(110,951)	(2,738)	(113,888)
Not Surfaced (dirt)	0	5,825	127	5,954
	(0)	(9,374)	(204)	(9,582)

Table 2. Design and construction summary.

Section No.	Location From Station[a]	to Station	Thickness inches	(centimeters)	Reinforcement	Contraction Joint Spacing feet (meters)
1	0+10	18+00	5	(12.7)	None	c
2	18+00	27+00	4½	(11.4)	Mesh	29.58 (9.02)
3	27+00	35+00	4½	(11.4)	None	c
4	35+00	53+00	5½	(14.0)	None	c
5	53+00	71+00	5	(12.7)	None	c
6	71+00	80+00	4½	(11.4)	Mesh	29.58 (9.02)
7	80+00	89+00	4½	(11.4)	None	c
8	89+00	106+00	5½	(14.0)	None	c
9	106+00	159+00	6	(15.2)	None	c
10	159+00	211+15	6AE[b]	(15.2)	None	c

[a] Project is stationed east to west

[b] AE = Air Entrained

[c] No contraction joints

Table 3. Concrete strengths.

Section Number	Thickness inches	(cm)	Air Content by High Pressure Test %	Modulus of Rupture 28-day beams psi	(MPa)	Compressive Cylinders 28 days psi	(MPa)	Compressive Cores 260 days psi	(MPa)	Compressive Cores 28 years psi	(MPa)
1, 5	5	(12.7)	3.5	800	(5.52)	5370	(37.02)	6060	(41.78)	8090	(55.78)
2, 6	4½	(11.4)	2.6	780	(5.38)	5520	(38.06)	6210	(42.82)	8070	(55.64)
3, 7	4½	(11.4)	3.2	790	(5.45)	5850	(40.33)	6220	(42.89)	8100	(55.85)
4, 8	5½	(14.0)	3.4	800	(5.52)	5490	(37.85)	6240	(43.02)	7500	(51.71)
9	6	(15.2)	3.5	810	(5.58)	5870	(40.47)	6580	(45.37)	7820	(53.92)
	Average		3.2	800	(5.52)	5620	(38.75)	6260	(43.16)	7920	(54.61)
10	6AE[a]	(15.2)	6.6	770	(5.31)	5290	(36.47)	6080	(41.92)	7540	(51.99)

[a] Air entrained

Table 4. Transverse crack summary

$$\text{Slab Length} = \frac{(\text{Length of Section})}{(\text{No. Transverse Cracks} + \text{No. Joints})}$$

Sections	Thickness in. (cm)	Average Slab Length in Feet (Meters) 1 month	1 year	2 years	5 years	14 years	28 years
1, 5	5 (12.7)	92 (28)	26 (08)	19 (06)	17 (06)	15 (5)	15 (5)
2, 6	4½ (11.4)	30 (09)	29 (09)	28 (09)	26 (08)	22 (7)	22 (7)
3, 7	4½ (11.4)	81 (25)	29 (09)	21 (06)	18 (05)	15 (5)	13 (4)
4, 8	5½ (14.0)	192 (58)	33 (10)	25 (08)	22 (07)	19 (6)	17 (5)
9	6 (15.2)	123 (37)	56 (17)	39 (12)	33 (10)	26 (8)	18 (5)
10	6AE (15.2)	177 (54)	59 (18)	36 (11)	27 (08)	21 (6)	18 (5)

Table 5. Longitudinal crack summary

Sections	Thickness in. (cm)	Average Longitudinal Cracking, Feet per Station or meter per hectometer: 1 month	1 year	2 years	5 years	14 years	28 years
1, 5	5 (12.7)	0	2	11	14	47	67
2, 6	4½ (11.4)	0	0	11	12	46	81
3, 7	4½ (11.4)	0	2	7	12	36	80
4, 8	5½ (14.0)	0	5	6	8	13	25
9	6 (15.2)	0	3	7	8	20	N.A.
10	6AE (15.2)	0	2	5	11	42	N.A.

N.A. - Not Available

Table 6. Profile variation, BPR type roughometer.

Section Number	Thickness inches	(cm)	Inches per Mile (centimeters per kilometer) 1955	1979	1981
1, 5	5	(12.7)	112 (177)	129 (204)	158 (249)
2, 6	4½ mesh	(11.4)	107 (169)	110 (174)	129 (204)
3, 7	4½	(11.4)	107 (169)	132 (208)	156 (246)
4, 8	5½	(14.0)	109 (172)	123 (194)	143 (226)
9	6	(15.2)	110 (174)	127 (200)	144 (227)
10	6AE[a]	(15.2)	105 (166)	121 (191)	131 (207)

Longitudinal Profile Value[b] (LPV)

(from BPR roughometer values)

Section	1955	1979	1981
1, 5	3.5	3.3	3.0
2, 6	3.6	3.5	3.3
3, 7	3.6	3.2	3.0
4, 8	3.5	3.3	3.1
9	3.5	3.3	3.1
10	3.6	3.4	3.2

a - air entrained.

b - longitudinal profile value (obtained by correlation with the CHLOE profilometer and use of AASHO Road Test PSI formula) = present serviceability index (PSI) without deduction for cracking and patching.

Table 7. Average traffic - vehicles per day.

	Mile Number				
	East			West	
Year	1	2	3	4	Average
1957	250	241	241	265	249
1962	299	294	249	262	276
1967	353	329	271	295	312
1972	236	286	218	188	232
1976	315	272	238	258	271
1981	292	248	195	167	226
Average	291	278	235	239	261

Table 8. Pavement costs - 1955 bid prices.

Section Number	Thickness (in.)	(cm)	Cost per sq. yd.	Cost per sq. m
1, 5	5	(12.7)	$ 3.15	$ 3.77
2, 6	4½ mesh	(11.4)	3.42	4.09
3, 7	4½	(11.4)	3.04	3.64
4, 8	5½	(14.0)	3.26	3.90
9	6	(15.2)	3.38	4.04
10	6AE	(15.2)	3.38	4.04

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FIGURE 1 - CROSS SECTION OF PAVEMENT

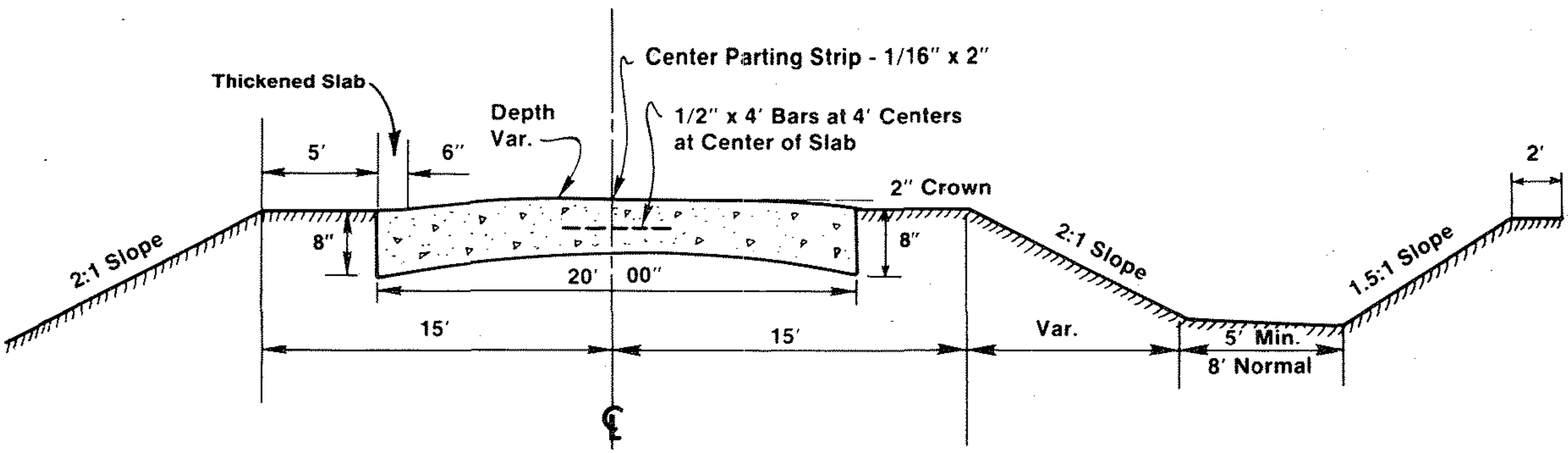

FIGURE 2 - LAYOUT FOR PAVEMENT

Non-reinforced Pavement

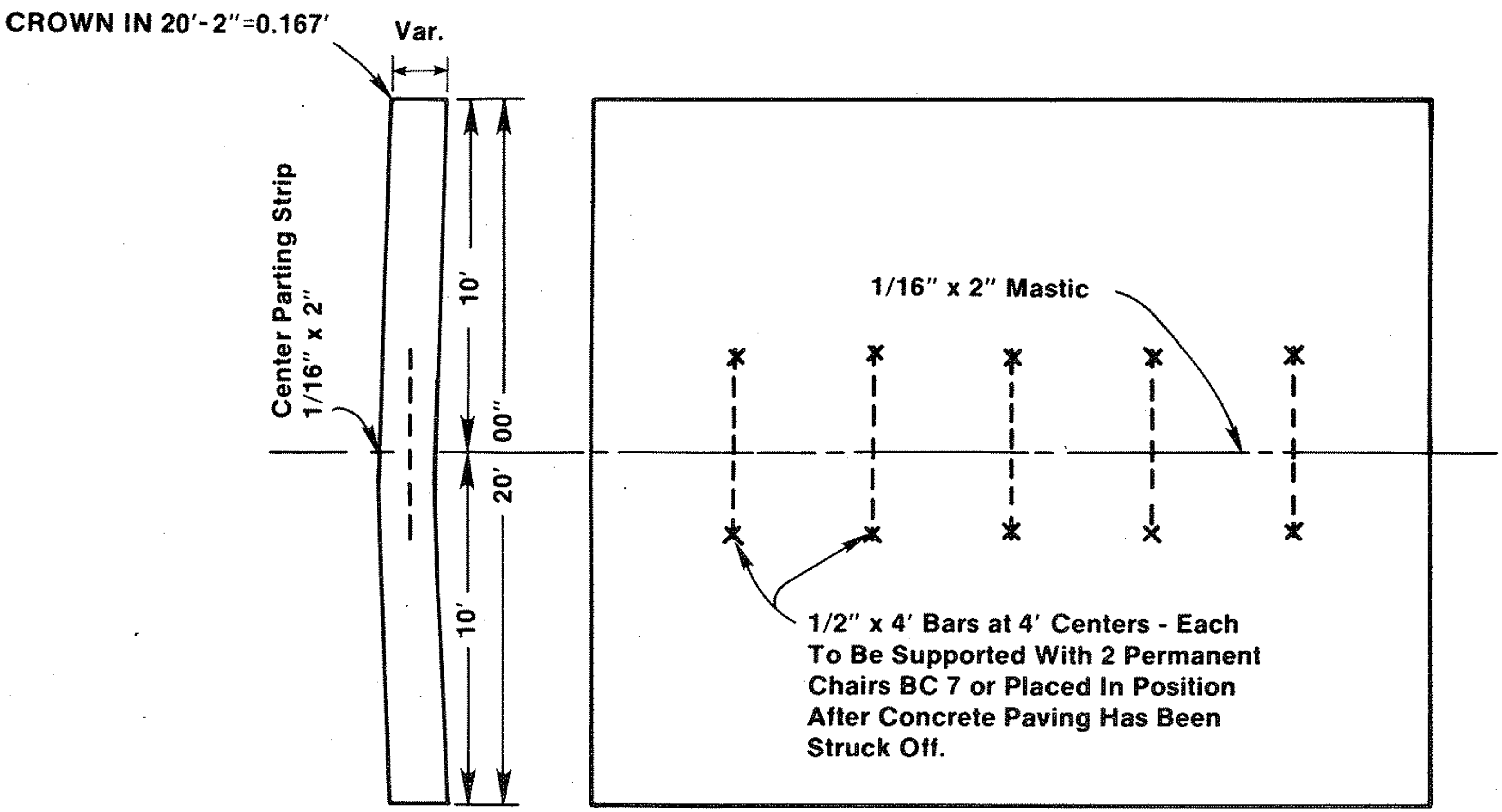

FIGURE 3 - LAYOUT FOR PAVEMENT

4½ Inch Mesh Reinforced Pavement

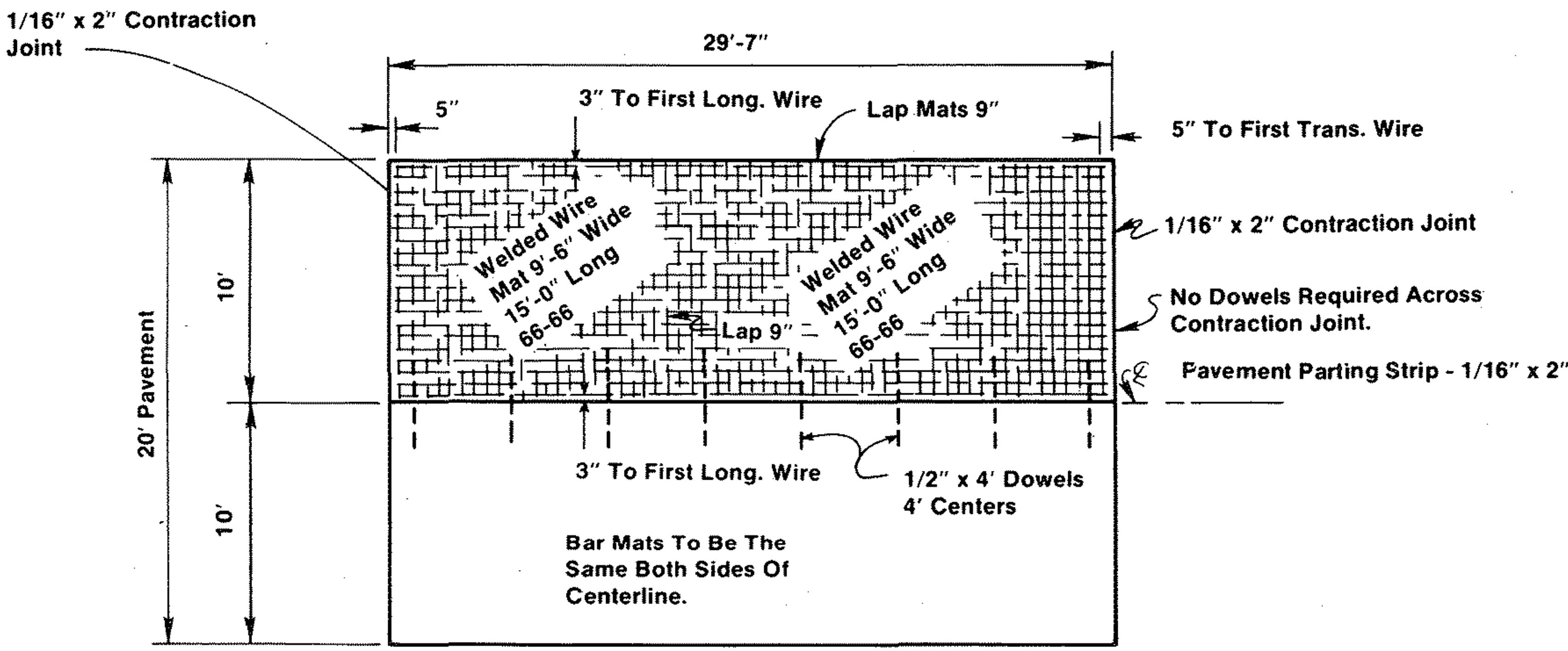

FIGURE 4 - TYPICAL PAVEMENT CONDITION OF THE 4-1/2"
NON-REINFORCED SLAB IN SECTION 3

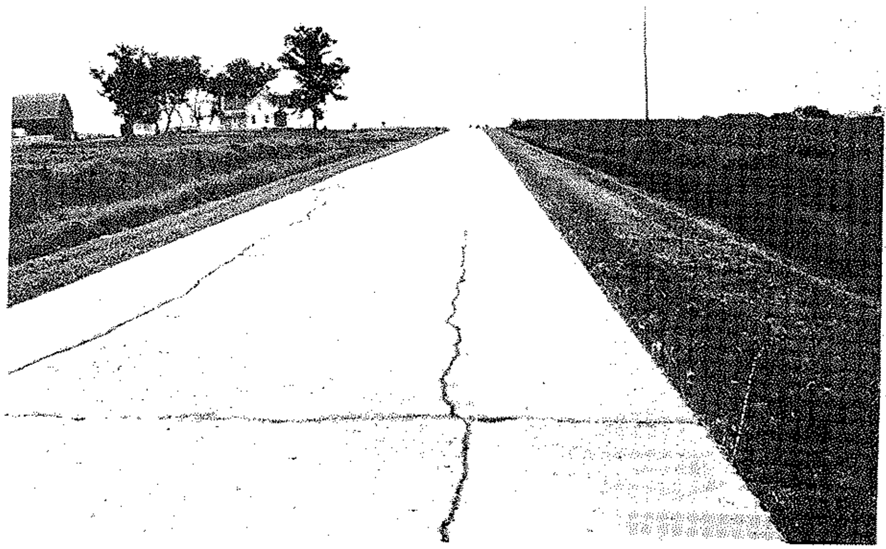

FIGURE 5 - TYPICAL PAVEMENT CONDITION OF THE 6"

NON-REINFORCED SLAB IN SECTION 9