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Performance of Various Thicknesses of PCC Pavement

JOHN I. HELMERS AND VERNON J. MARKS

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 United States), which was paved in 1904. It 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 4-mile (6.4-km) demonstration project to evaluate thicknesses that ranged from 4.5 to 6 in (11.4-15.2 cm). The project, which consisted 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 nonreinforced except for centerline tie bars, and no contraction joints were used. Mesh reinforcing and contraction joints spaced at 29 ft 7 in (9.02 m) intervals were used in two 4.5-in (11.4-cm) thick sections. The only air-entrained section was nonreinforced. The pavement performed well over its 30-year life of carrying a light volume of traffic and did not require major maintenance. Cracking was substantial; average slab length varied directly with thickness. The 4.5-in-thick nonair entrained, mesh-reinforced pavement with contraction joints has performed the best.

Iowa's portland cement concrete (pcc) paving began in 1904 with one-half block in the town of LeMars (second oldest pavement in the United States). This two-lift pavement was 6.5 in (16.5 cm) thick, and the top 1.5 in (3.8 cm) had a greater cement factor than the bottom 5 in (12.7 cm). The joints were formed at 6-ft (1.83-m) intervals skewed 45° from each side, which created a diamond pattern. The texture was obtained by scoring the surface in 4-in (10.2-cm) squares. This pavement performed well for 70 years without resurfacing and demonstrates the potential of pcc pavement. Many miles of pcc pavement were constructed in the late 1920s and early 1930s during a campaign to get Iowa out of the mud.

Iowa is a state of 56 290 miles^2 (145 791 km^2), and only eight urban areas have a population greater than 50 000. It has 112 257 miles of roadway (180 660 km), the surface types of which are given in Table 1. In 1951, excluding municipal roads, there were 8248 miles (13 274 km) of hard surfacing, 58 598 miles (94 304 km) of gravel, and 35 523 miles (57 169 km) that had 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 Iowa Highway research project HR-9.

Substantial research has been conducted into structural requirements. Studies of flexural fatigue as a function of design thickness were completed in the 1920s. This research was used in the development of the 1933 Portland Cement Association (PCA) design curve for pavement. The Iowa Department of Transportation is currently using the 1966 PCA design procedure.

Table 1. Miles of Iowa highway by surface type, 1981.

	Iowa Highway by Surface Type (miles)			
Surface Type	Primary	Secondary	Municipal	Total
Portland cement paved	4557	4 536	3305	12 463
Asphalt concrete paved	5465	8 936	5879	20 379
Bituminous treated	88	1 514	1058	2 694
Gravel	15	68 942	1701	70 767
Not surfaced, dirt	0	5 825	127	5 954

The objective of the research project was to determine to what thickness pcc pavement could be reduced, with corresponding cost reduction, and still provide 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 4 miles (6.4 km) long on County Road E-33 from IA-4 to Farlin.

Signs that show 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 nonconformity of the signs' text and the terms used in this report is that the nonreinforced 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-in diameter plate at yield point ranged from 58.5 to 9 $lb \cdot f/in^2$ (403-62 kPa); 30 $lb \cdot f/in^2$ (207 kPa) is considered adequate. Based on this criteria, load-bearing tests showed 4100 ft (1250 m) of unstable base, and the soil borings indicated some areas in which there was a high water table and a subgrade that consisted mainly of clay loam (U.S. Bureau of Public Roads subgrade group 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 ft (1.8 m) deep, 7-in (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-ft (1.5-m) centers in five parallel lines in a checkerboard pattern. There were 4064 drains constructed in the following locations (note that the project is stationed east to west):

From station 3+50 to 11+25,
From station 26+00 to 31+00,
From station 47+00 to 53+00,
From station 62+00 to 65+50,
From station 87+00 to 99+50, and
From station 99+50 to 105+60.

Soon after the project was paved, the county engineer questioned the effectiveness of these drains because no horizontal interconnecting blanket or 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.

Table 2. Design and construction summary.

Section No.	Location[a] From Station	To Station	Thickness (in)	Reinforcement	Contraction Joint Spacing (ft)
1	0+10	18+00	5	None	-[c]
2	18+00	27+00	4.5	Mesh	29.58
3	27+00	35+00	4.5	None	-[c]
4	35+00	53+00	5.5	None	-[c]
5	53+00	71+00	5	None	-[c]
6	71+00	80+00	4.5	Mesh	29.58
7	80+00	89+00	4.5	None	-[c]
8	89+00	106+00	5.5	None	-[c]
9	106+00	159+00	6	None	-[c]
10	159+00	211+15	6[b]	None	-[c]

[a]Project is stationed east to west. [b]Air entrained. [c]No contraction joints.

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 ft (4.6 cm) was established (the allowable variation between the finish grade and the existing grade). This tolerance presented a challenge to the contractor because the roadbed had been constructed 12 years earlier.

DESIGN AND CONSTRUCTION

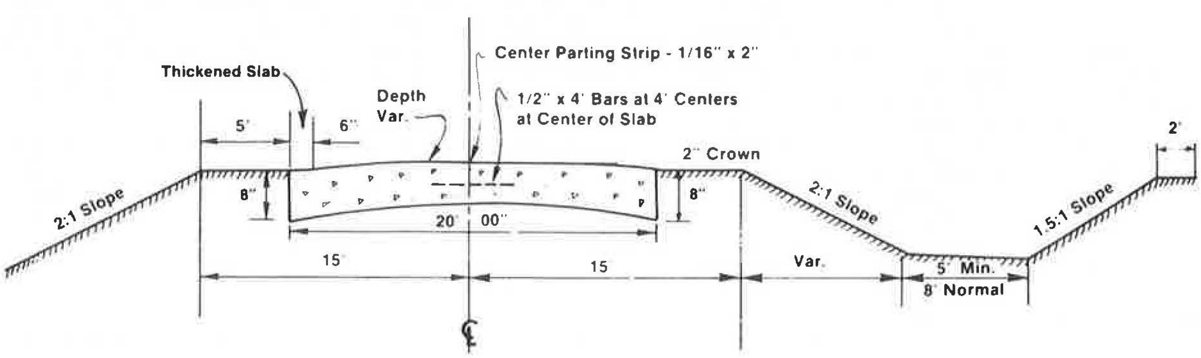
The 4-mile (6.4-km) project was divided into 10 sections of various lengths, given in Table 2. The pavement thicknesses were arbitrarily selected to range from 4.5 to 6 in (11.4-15.2 cm) and were not based on the plate-bearing results or the PCA design formula. Substantial engineering judgment is used with the modulus of subgrade reaction for Iowa pavement thickness design yet today. The concrete proportions were specified as Iowa State Highway Commission Mix 4A. (Note: Aggregate absolute volumes and batch quantities were adjusted for the air-entrained concrete.)

Item	Absolute Volume	Batch Quantities (lb)
Cement, min	0.096 419	510
Water, approx.	0.161 201	272
Aggregates		
Fine, approx. (Sp.Gr. = 2.66)	0.371 190	1664
Coarse approx. (Sp.Gr. = 2.69)	0.371 190	1682

The cement was type 1 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 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-ft (6.1-m) wide pavement was built by 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 in (20.3 cm) high, and since the pavement thicknesses specified were less than 8 in, the outer 6 in (15.2 cm) of the base on each side was sloped to the bottom of the form to yield a thickened edge of slab. Figure 1 shows a typical cross section of the pavement.

Figure 1. Cross section of pavement.



All of the nonreinforced pavement designs have 4-ft (1.2-m) long no. 4 (1.27-cm diameter) deformed steel rebars placed on 4-ft centers across the centerline as tie bars. Two of the four 4.5-in (11.4-cm) thick sections were also reinforced with welded wire mesh. The layouts for the nonreinforced and reinforced pavements are given in Figures 2 and 3, respectively.

The joints in the slab were formed by placing premolded 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-ft 7-in (9.02-m) spacing] in the 4.5-in mesh-reinforced sections.

TESTING AND EVALUATION

Both beam [6x6x33 in (15.2x15.2x83.8 cm)] and cylinder [6x12 in (15.2x30.5 cm)] test specimens were made to test concrete strength during construction. Cores were drilled at 260 days and 28 years. A summary of concrete strengths is given in Table 3.

Crack surveys have been conducted 14 times since construction, more frequently 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 to 192 ft (24.7-58.5 m). The 5-year range is from 17 to 33 ft (5.2-10.1 m) and the 28-year range is from 13 to 22 ft (4.0-6.7 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. Some variations are somewhat different than expected, both between repeated sections and averages of sections that have different thicknesses. These differences may be due to the variations in stability of the grade.

A test of the longitudinal profile was not made until 1955, when the sections were tested with a Bureau of Public Roads (BPR) 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; little more than crack sealing has been done for most of its life. A crack-sealing effort in 1980 deposited enough sealant material on the surface to

Figure 2. Layout for nonreinforced pavement.

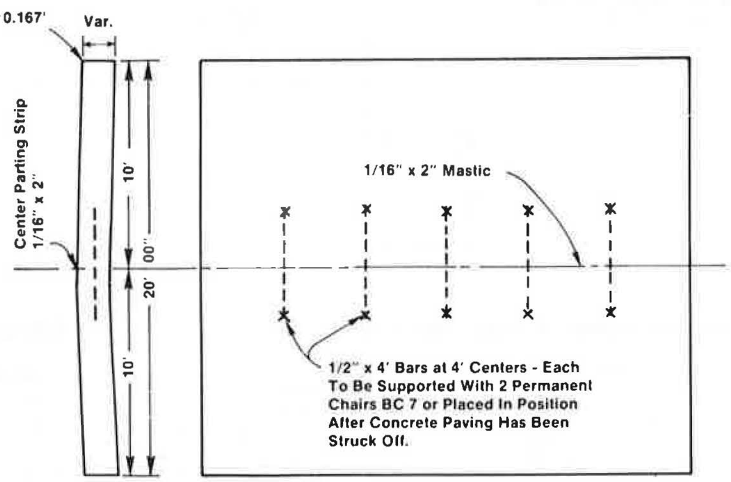


Figure 3. Layout for 4.5-in mesh-reinforced pavement.

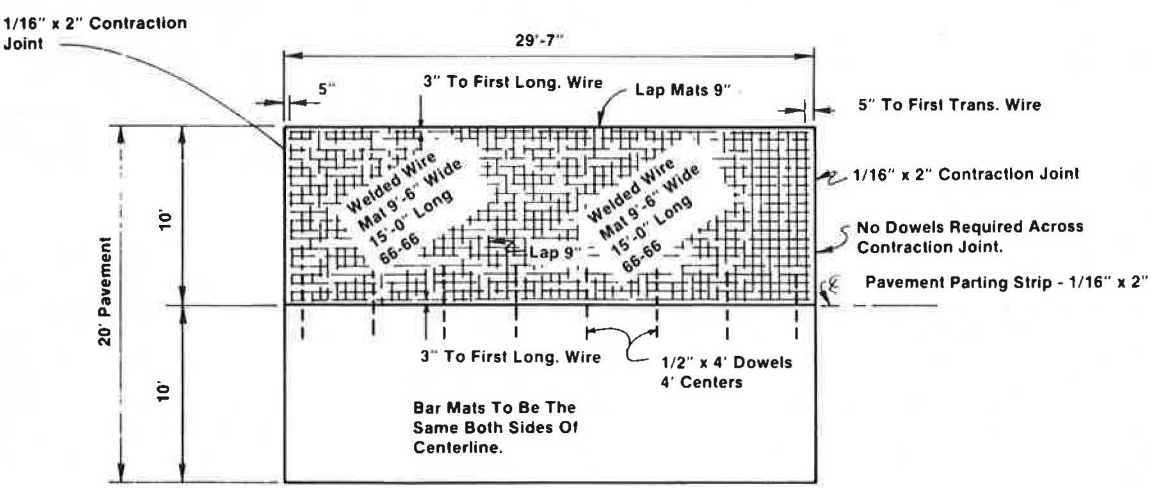


Table 3. Concrete strengths.

Section No.	Thickness (in)	Air Content by High-Pressure Test (%)	Modulus of Rupture, 28-Day Beams (lb·f/in²)	Compressive Cylinders, 28 Days (lb·f/in²)	Compressive Cores, 260 Days (lb·f/in²)	Compressive Cores, 28 Years (lb·f/in²)
1, 5	5	3.5	800	5370	6060	8090
2, 6	4.5	2.6	780	5520	6210	8070
3, 7	4.5	3.2	790	5850	6220	8100
4, 8	5.5	3.4	800	5490	6240	7500
9	6	3.5	810	5870	6580	7820
Avg		3.2	800	5620	6260	7920
10	6[a]	6.6	770	5290	6080	7540

[a]Air entrained.

Table 4. Transverse crack summary.

Section No.	Thickness (in)	Average Slab Length (ft)					
		1 Month	1 Year	2 Years	5 Years	14 Years	28 Years
1, 5	5	92	26	19	17	15	15
2, 6	4.5	30	29	28	26	22	22
3, 7	4.5	81	29	21	18	15	13
4, 8	5.5	192	33	25	22	19	17
9	6	123	56	39	33	26	18
10	6[a]	177	59	36	27	21	18

Note: Slab length = length of section/(no. of transverse cracks + no. of joints).
[a]Air entrained.

Table 5. Longitudinal crack summary.

Section No.	Thickness (in)	Avg Longitudinal Cracking (ft/station)					
		1 Month	1 Year	2 Years	5 Years	14 Years	28 Years
1, 5	5	0	2	11	14	47	67
2, 6	4.5	0	0	11	12	46	81
3, 7	4.5	0	2	7	12	36	80
4, 8	5.5	0	5	6	8	13	25
9	6	0	3	7	8	20	NA
10	6[a]	0	2	5	11	42	NA

[a]Air entrained.

Table 6. Profile variation, BPR-type roughometer.

Section No.	Thickness (in)	Profile Variation (in/mile)			Longitudinal Profile Value[b]		
		1955	1979	1981	1955	1979	1981
1, 5	5	112	129	158	3.5	3.3	3.0
2, 6	4.5 mesh	107	110	129	3.6	3.5	3.3
3, 7	4.5	107	132	156	3.6	3.2	3.0
4, 8	5.5	109	123	143	3.5	3.3	3.1
9	6	110	127	144	3.5	3.3	3.1
10	6[a]	105	121	131	3.6	3.4	3.2

[a]Air entrained.
[b]Longitudinal profile value is obtained by correlation with the CHLOE profilometer and use of AASHO road test present serviceability index (PSI) formula. It is the PSI without deduction for cracking and patching.

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 the cost per mile for both pcc pavement and gravel-surfaced roadways. The maintenance costs per mile for paved and gravel-surface roadways are $1034 and $1365, respectively. A higher level of service (signing, mowing, and 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 and $1108, respectively.

Aggregate Demand

Calculation shows that it will take many years for a paved road to result in a reduction of aggregate use. The construction of this roadway required 2450 tons/mile (1 381 061 kg/m) for 4.5-in (11.4-cm) thick and 3270 tons/mile (1 843 294 kg/m) for 6-in (15.2-cm) thick pavement.

Typical Greene County gravel road construction uses 700 tons/mile (394 589 kg/m) the first year, 600 tons/mile (338 219 kg/m) the second year, and 45 tons/mile (25 366 kg/m) each year thereafter. With these figures, it would take 27.6 years for a gravel roadway to use 2450 tons/mile (1 381 061 kg/m) and 45.8 years to use 3270 tons/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/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 0.5 mile (0.8 km) east of Farlin also produced heavier loads on the road (1951-1977).

Table 7. Average traffic.

	Avg Traffic by Mile Number (vehicles/day)				
Year	East 1	2	3	West 4	Avg
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
Avg	291	278	235	239	261

The 6-in (15.2-cm) diameter cylinders of non-air-entrained concrete averaged more than 5600 lb•f/in² (38.61 MPa) when tested at the age of 28 days. The 28-day modulus of rupture of the beams was 800 lb•f/in² (5.52 MPa). The concrete is of excellent quality 28 years after construction; compressive strength averages 7920 lb•f/in² (54.61 MPa).

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

Typical surface appearance of the pavement is shown in Figure 4 [4.5-in (11.4-cm) nonreinforced] and Figure 5 [6-in (15.2-cm) nonreinforced]. Even though transverse joints were not sawed, the random cracking in the 6-in pavement produced a relatively uniform spacing and 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-in pavement through 28 years but at a declining rate.

The 4.5-in (11.4-cm) mesh-reinforced sections with contraction joints exhibit the longest average slab length [22 ft (6.7 m)] after 28 years. The nonreinforced pavements have slab lengths that range from 13 to 18 ft (4.0-5.5 m). The average slab length for the nonreinforced pavement varies directly with the thickness. The 4.5-in pavement has the shortest slab length [13 ft (4.0 m)]; the 6-in pavement has slab lengths of 18 ft. These lengths are just less than the current Iowa Department of Transportation design of 20 ft. Unfortunately, jointed nonreinforced 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 4.5-in thick pavement, both reinforced and nonreinforced, developed the most longitudinal cracking, but the 81 ft/station average for the mesh-reinforced design results from widely differing data from the two sections of 19 ft/station and 144 ft/station. This, and that the 5 ft 0.5 in (14.0 cm) section exhibits the least longitudinal cracking, would indicate that the longitudinal cracking was dependent on the base. No correlation was obvious between sand-drain locations and subgrade with longitudinal cracking. The cracking at 0.25 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 ranged from 129 in/mile (204 cm/km) to 158 in/mile (249 cm/km). This is rough for a primary or Interstate route, but is quite adequate for a secondary route. The data exhibit a substantial increase in roughness

Figure 4. Typical pavement condition of 4.5-in nonreinforced slab in section 3.

Figure 5. Typical pavement condition of 6-in nonreinforced slab in section 9.

Table 8. Pavement costs in 1955 bid prices.

Section No.	Thickness (in)	Cost per Yard² ($)
1, 5	5	3.15
2, 6	4.5 mesh	3.42
3, 7	4.5	3.04
4, 8	5.5	3.26
9	6	3.38
10	6[a]	3.38

[a]Air entrained.

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. The material on the surface can be expected to be worn and bladed (winter maintenance) away and a longitudinal profile comparable to 1979 will result. The 4.5-in 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. 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 as follows:

1. All design thickness, from 4.5 to 6 in (11.4-15.2 cm), provided quite adequate service for a low-volume secondary roadway with minimal maintenance for 30 years.
2. The 4.5-in (11.4-cm) thick pavement has resulted in a slight reduction of aggregate use when compared with requirements for an unpaved gravel roadway, but the 6-in (15.2-cm) pavement results in a substantial increase in aggregate use.
3. The 4.5-in thick mesh-reinforced section has provided the best overall performance.
4. Slab lengths of the nonreinforced sections without contraction joints vary directly with thickness and are all just less than the current design length of 20 ft (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 that 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.

ACKNOWLEDGMENT

This research resulted from the efforts and ideas of C. Arthur Elliott, former Greene County engineer. We 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. This report does not constitute a standard, specification, or regulation.

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Pavement Evaluation and Upgrading of Low-Cost Roads

JACOB GREENSTEIN

Design, construction, and performance experience on nonsurfaced gravel low-cost roads show that, even when proper design and construction procedures are followed, unexpected early failure often occurs. These modes of failure generally occur after the wet season and are normally attributed to the development of unexpected, very high moisture content in the subgrade. This moisture buildup in localized subgrade areas cannot be predicted and is frequently attributed to changes in topography, drainage, and environmental factors that take place during and after construction. This paper presents a new methodology to minimize unexpected pavement failure and to upgrade the underdesigned road sections. The methodology is based on the subgrade strain criterion. The strain characteristics developed on top of the subgrade are calculated for a given dynamic loading and therefore permit the determination of the location of these high-moisture and low-strength sections of the pavement. The proposed methodology also permits the calculation of the amount of roadway reinforcement required to achieve uniform roadway strain characteristics. The uniform strain should obviously result in a uniform life expectancy of the roadway. The automated instrumentation for making this strain inventory is now being used in Thailand, several countries in Latin America, and elsewhere. It has proven to be simple, economical, and practical.

Figure 1. Failure of unsurfaced road.

Many unsurfaced roads constructed in accordance with the best design technology have failed well before their predicted life expectancy. Such an unexpected failure is shown in Figure 1. Normally, these failures are attributed to the development of very high moisture content in the subgrade, moisture substantially greater than the in situ moisture content found in the natural subgrade prior to construction. This moisture buildup in localized subgrade areas cannot be predicted; it is frequently attributed to changes in topography, drainage, and environmental factors that develop during and after construction. It is rarely assumed that all of the natural subgrade would become saturated because this would lead to conservative, low-strength values for the natural subgrade that would generate thick and costly pavement.

In conventional design methods for unsurfaced roads, the stability of the pavement is ensured through material quality requirements for the subbase or the base materials. By contrast, only the subgrade strain criterion is represented qualitatively in the determination of pavement thickness. In other words, under given traffic and environmental loadings, the subgrade strain developed at the top of the subgrade must be identical along the road. The magnitude of the subgrade strain is affected strongly by environmental factors, which corresponds to the conclusions of numerous field studies: The principal failure cause, particularly in areas of high rainfall, is due to underground springs that pump moisture from a high-water table, which causes saturation of the subgrade due to flooding of side ditches during the rainy season.

The equipment and methodology have now become available for determining the strain characteris-