Field Study of Performance and Cost of a Composite Pavement Consisting of Prestressed Concrete Panels Interconnected and Covered With Asphaltic Concrete

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This report describes the design, construction, and field testing of a new concept in highway pavement design—a composite of favorable features of both rigid and flexible pavements consisting of prefabricated prestressed concrete structural components covered with a leveling course of asphaltic concrete. The prestressed structural panels are placed on the prepared roadbed and interconnected with special steel connectors and grout keys. The panels produce the structural effects of a spread footing, yet possess a high degree of flexibility and resistance to permanent cracking. The asphalt leveling course furnishes a flexible and waterproof surface with excellent riding characteristics. Design details, construction costs, and field tests for an evaluation of structural performance are included and discussed in view of the short period of the field performance study.

•AFTER receiving favorable structural performance from the laboratory investigation of composite pavement, the South Dakota Department of Highways approved a small-scale field study of this type of pavement. The field study was designed to furnish additional information regarding costs, construction problems, and structural performance of the composite pavement under field conditions. The primary factors investigated in the study of structural performance were load-carrying capacity and expansion-contraction characteristics.

LOCATION AND DESIGN OF FIELD TEST SECTION

The location of a field study of this new type of pavement on a mainline highway was not recommended because it was in its early stages of development. The site selected was the driveway to the South Dakota Highway Maintenance building east of Brookings, where it was possible to subject the composite pavement to actual traffic and typical weathering conditions for the area.

The longitudinal panel arrangement was selected for this investigation in view of its promising riding characteristics. The length of the test section was limited to 96 ft by the high construction costs anticipated for this new concept in pavement construction. Figure 1 shows a plan and elevation view of the composite pavement as designed for the field study. The individual panels were designed with the following dimensions: 6 ft wide, 24 ft long, and $4\frac{1}{2}$ in. thick. The panels were interconnected with grout keys and tongue-and-fork connectors developed during the latter part of the laboratory in-

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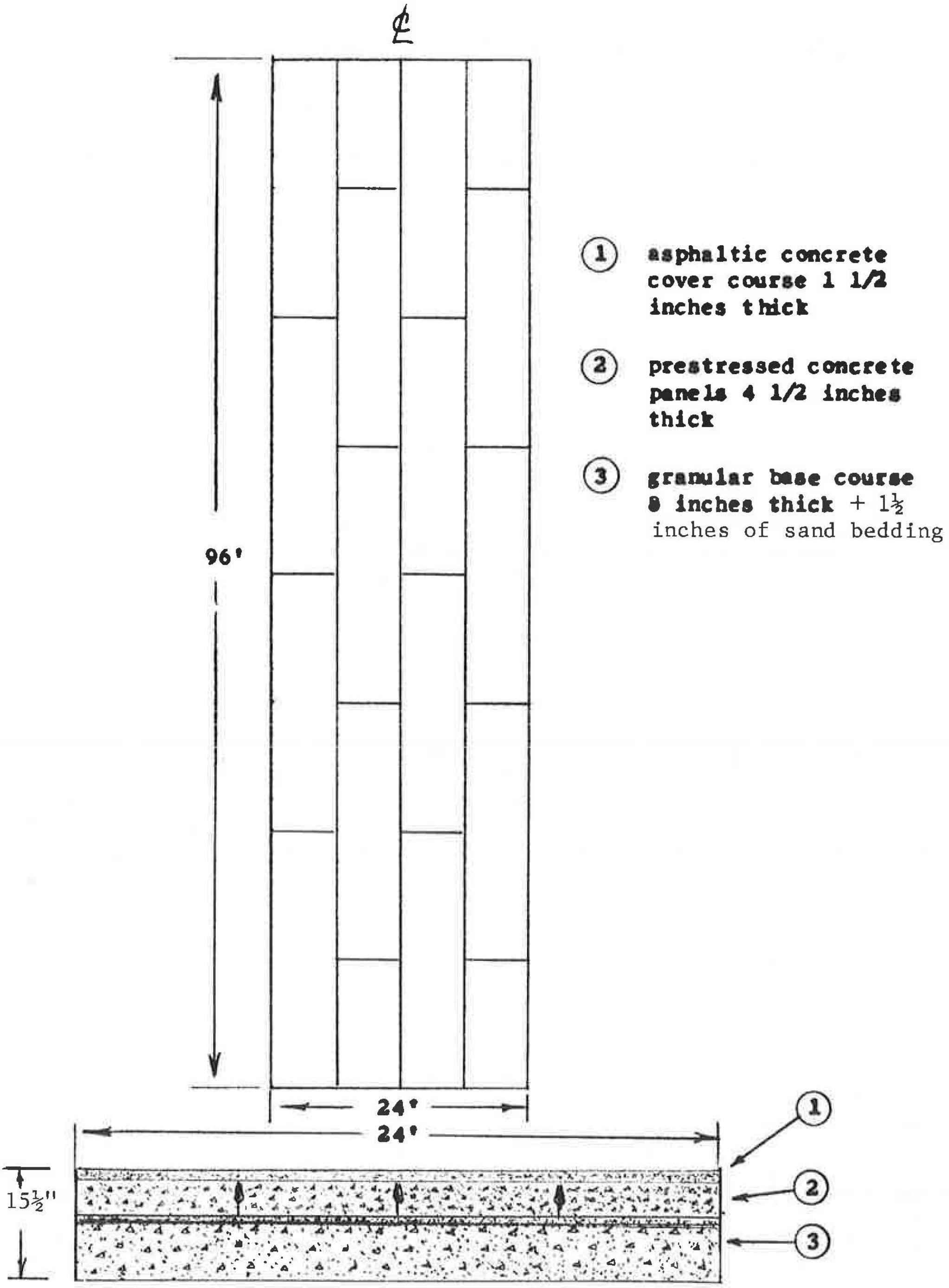

Figure 1. Panel arrangement and composite pavement construction.

vestigation. Figure 2 shows a half section of an interior panel with connectors and grout keys. Figure 3 shows the details for the tongue-and-fork connectors. The panels were designed for a longitudinal prestress of 350 psi. Nine 7-strand tendons of ⅜-in. diameter were used to develop the 350-psi uniform prestress in the longitudinal direction.

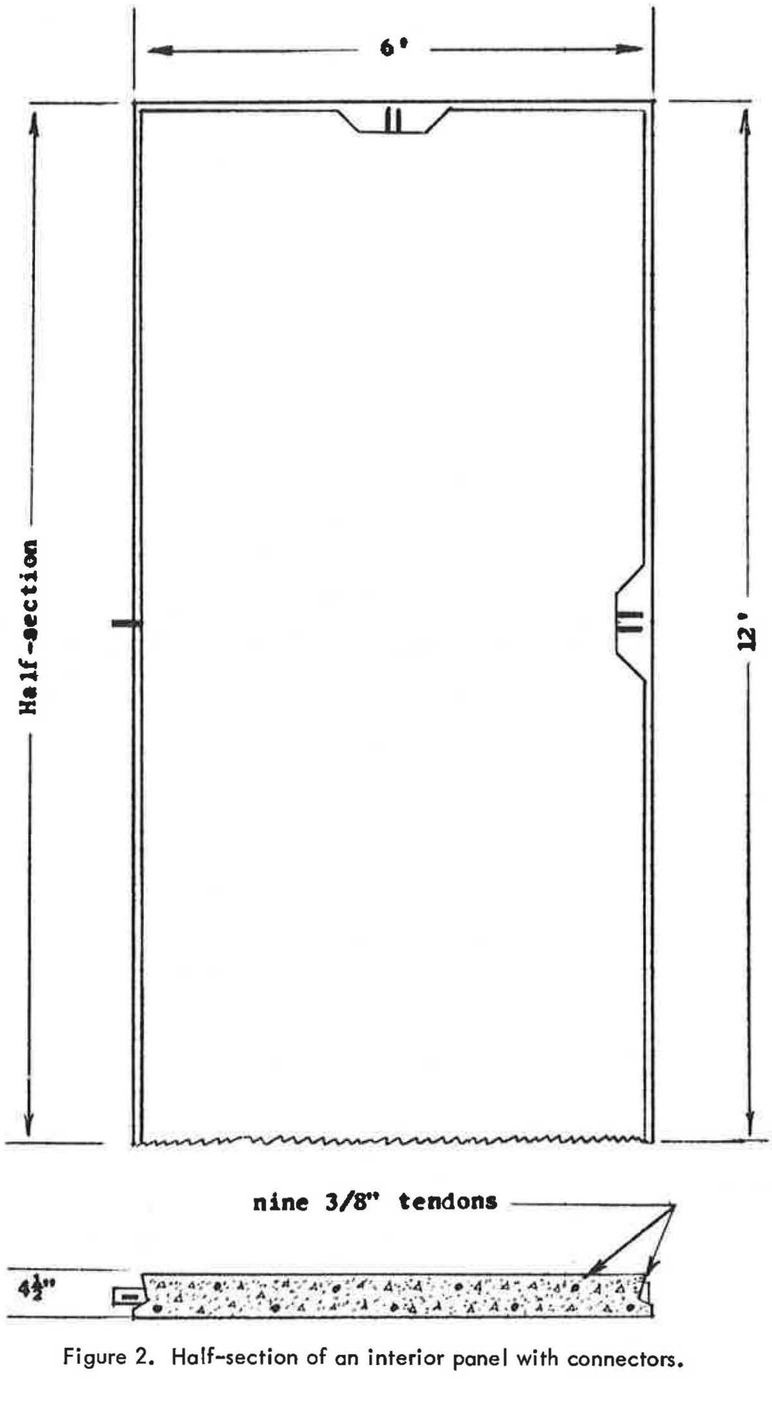

Figure 2. Half-section of an interior panel with connectors.

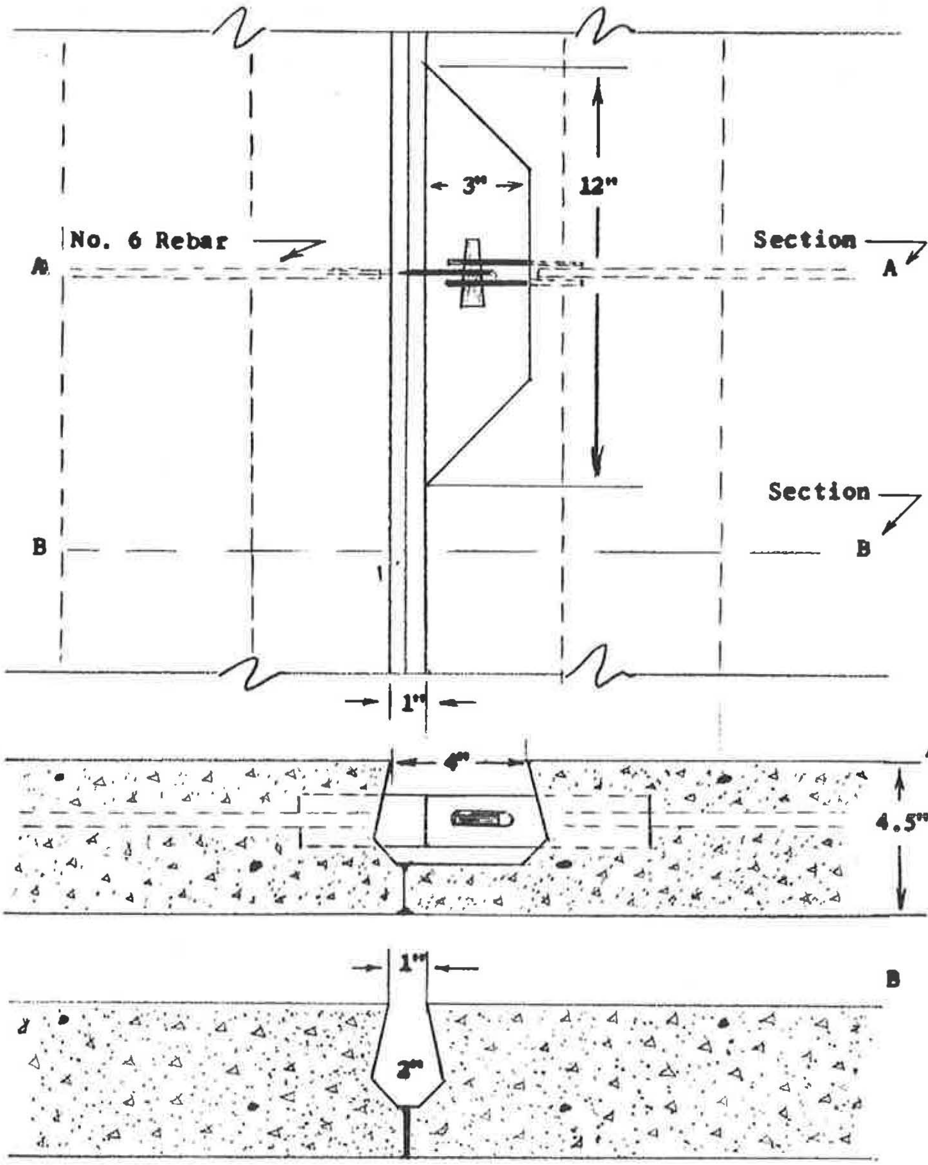

Figure 3. Details for tongue-and-fork connection and grout key.

CONSTRUCTION AND CONSTRUCTION COSTS

The test section was prepared for placement of the panels by the South Dakota Department of Highways. The work items consisted of shaping and compacting the subgrade, constructing an 8-in. granular base course, and placing the sand bedding course. The subgrade material consisted of silty clay and black topsoil with a maximum dry density of 112.0 pcf. Compaction of 99 percent of standard Proctor was obtained from one field density test. The base course material was predominately fine grained; 74 percent passed the No. 4 sieve and 3 percent passed the No. 200 sieve. A vibratory compactor was used to compact the base course. The sand used for the bedding course met ASTM specification C 33-63 for fine aggregate for portland cement concrete. In order to exercise strict control over the grading of the sand, it was necessary to fine-grade

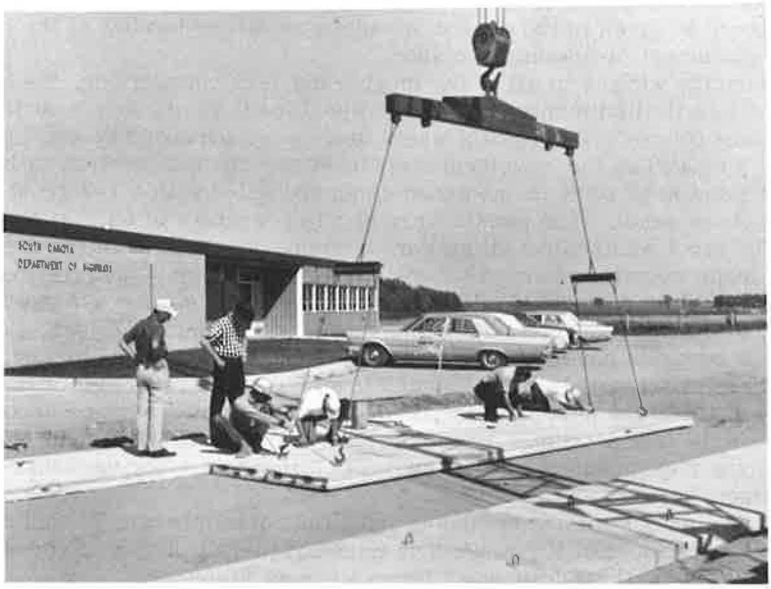

Figure 4. Field placement of prestressed panels.

the sand bedding course by hand with the use of screed strips and "blue tops." The sand bedding course was prepared the same day that the panels were laid.

The prestressed panels were produced and laid by Gage Brothers Concrete Products Co. of Sioux Falls. Figure 4 shows the placement of the prestressed panels during September 1966. No major difficulty was encountered during the laying operation. The construction tolerances in the panel dimensions did not affect the positioning of the panels in this 96-ft test section. Observations were made regarding the need for further simplification of the tongue-and-fork connection. The limited tolerance in the vertical alignment of the slots in the tongue-and-fork connections made it difficult to insert the wedge, as shown in Figure 5. The tolerance was further restricted by the section of concrete below the fork. In a few cases, this section of concrete served as

Figure 5. Inserting the wedge in a tongue-and-fork connection.

a bearing area for the tongue from the adjacent panel. It was decided that further consideration should be given to the design of panel connectors in view of the high material cost and the placement problems described.

After driving the wedges in all of the tongue-and-fork connections, the test section was subjected to a limited number of impact wheel loads in order to seat the panels in the sand bedding course. The impact wheel loads were produced by placing timbers (2 by 4's and 4 by 4's) on the pavement and traversing the test section with a front-end loader. The grout keys were then washed clean and filled with a 1-2 grout (1 part of cement, 2 parts of sand). The panels were at a temperature of 68 F at the time of grouting. The grout was sealed with a curing compound about 2 hours after placement. The pick-up loops were then burned off with an electric welder, and the test section was closed to traffic for a period of 7 days to let the grout cure. A 7-day (field-cured) test cylinder of the grout developed a compressive strength of 4775 psi.

The asphalt concrete cover course was applied to the surface by blading and rolling about 2 weeks after the panels were grouted together. The reference markers (bolts) were then installed in the pavement for the measurement of expansion and contraction of the panels in the test section. A temperature well was installed near the edge of the pavement for the measurement of differences in temperature for various depths in the pavement structure.

Unit construction costs were computed from the actual charges submitted by the South Dakota Department of Highways and Gage Brothers Concrete Products Company. Construction costs for the major work items were as follows:

Item	Unit Cost	Total Cost
Compacted 8-in. granular base course	\$ 0.39/S.Y.	\$ 101
Sand bedding course 1½-in. thick	\$ 0.30/S.Y.	78
Prestressed concrete panels	\$11.33/S.Y.	2900
Transportation of panels and panel placement	L.S.	350
Grouting panels	\$ 0.13/lin. ft.	50
Bituminous cover course 1½-in. thick	\$ 0.86/S.Y.	220
Total	\$14.45/S.Y.	\$3699

STUDY OF STRUCTURAL PERFORMANCE

The field study of the structural performance of the composite pavement consisted of the following measurements and observations:

1. Measurements of contraction and expansion of the panels due to changes in temperature.
2. Benkelman beam measurements of pavement deflections under dynamic wheel loads.
3. Measurement of plate load vs pavement deflection according to ASTM Standard Test D1196-64.
4. Visual observation of pavement performance under traffic and actual weathering conditions.

Measurements of Temperature Contractions and Expansions

Permanent reference markers were set in the pavement for the measurement of contraction and expansion resulting from changes in temperature. The reference markers were established by grouting bolts in holes drilled into the prestressed panels. The bolt heads were drilled and tapped for ¼-in. Allen screws. When measurements

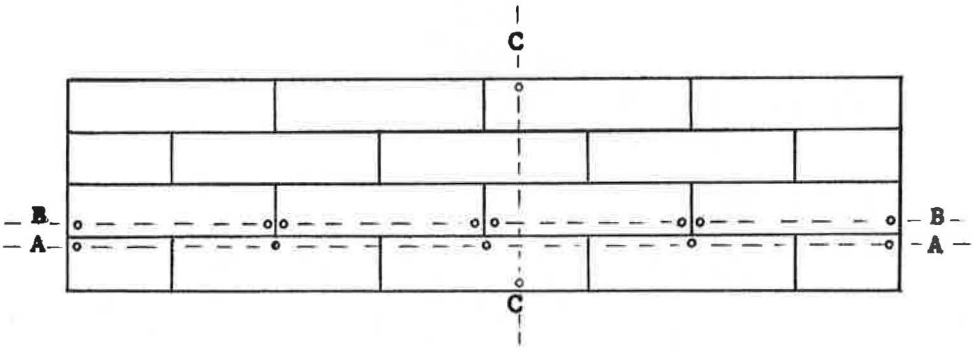

Figure 6. Location of reference markers in the test section.

were made, the Allen screws were removed and replaced with short studs for reference "stops." Figure 6 shows the arrangement of permanent reference markers in the test section. Measurements were made of the contractions and expansions in the entire length of the test section, as well as the contractions and expansions reflected at transverse panel joints.

The changes in the length and width of the test section were measured with a 100-ft steel tape equipped with one sliding stop and one fixed stop. The tape was used to measure changes in the lengths of lines A, B, and C in Figure 6. Table 1 shows the lengths of these three lines for various changes in air temperature.

These measurements show an average contraction of 0.019 ft in the length of the test section due to a 78-deg change in temperature. However, the transverse contraction obtained from measurements along line C was found to be 0.010 ft for the same change in temperature. These data indicate that the transverse panel joints accommodated approximately 50 percent of the longitudinal contraction.

The contractions at transverse panel joints were measured with an extensometer (Fig. 7). When the air temperature was decreased 78 deg, a contraction of 0.005 in. was measured at the transverse panel joint at the center of the test section. Measurements indicate that the two transverse panel joints 24 ft from the end of the test section accommodated contractions of 0.003 in. and 0.004 in. The primary forces resisting contraction consist of the resistance offered by the panel connector, friction along the joint, and subgrade friction. The accumulation of stress resulting from expansion will be dictated in a large measure by the level of end restraint developed between individual panels.

The maximum changes in length of a 24-ft panel are as follows: expansion = 0.086 in. for a 60 deg change in temperature, contraction = 0.144 in. for a 100 deg change. The joints between 24-ft panels may be designed to accommodate expansion (0.086 in.). Therefore, the composite pavement could be constructed as a continuous pavement as far as expansion is concerned. However, the magnitude of contraction precludes construction as a continuous pavement. The distance between contraction joints is

TABLE 1

PAVEMENT DIMENSIONS VS CHANGES IN TEMPERATURE

Change in Air Temp. (deg F)	Line A (ft)	Line B (ft)	Line C (ft)
0	94.940	94.925	23.150
-22	94.941	94.925	23.149
-13	94.941	94.922	23.149
-42	94.934	94.923	23.148
-49	94.930	94.910	23.143
-29	94.926	94.904	23.145
-20	94.938	94.919	23.147
-78	94.922	94.905	23.140
-49	94.925	94.910	23.144
-46	94.924	94.911	23.143
-53	94.924	94.907	23.142
-19	94.937	94.919	23.146
- 8	94.936	94.921	23.149
+ 1	94.936	94.921	23.149

Figure 7. Extensometer used to measure contractions and expansions at panel joints.

dictated by subgrade friction and the tensile strength in the critical cross-sectional area in pavement. In the following expression the tensile force in the pavement is equal to the force of subgrade friction developed in one-half of the distance between joints:

(Area of concrete) (prestress + tensile stress) = (Normal force) (Coefficient of friction)

The area of concrete, A_c, is critical at one-half the distance between contraction joints (L/2). The critical area consists of the two panels adjacent to the two transverse panel joints. The level of prestress, f_p, in the panels was equal to 350 psi. The tensile strength, f_t, in the concrete is assumed to be about 500 psi. A coefficient of subgrade friction of 0.5 is used since the smooth face of the panel is laid on the ground. A weight of 156 pcf is used for the weight of the pavement, W_c, (4½ in. prestressed concrete + 1½ in. of asphalt). These data are used to determine the length between contraction joints according to the following formula:

$$A_c\ (f_p + f_t) = W_c\ (C_f)\ (L/2)$$

$$2 \times 6 \times 12 \times 4.5\ (350 + 500) = 6/12 \times 24 \times 156 \times 0.5 \times L/2$$

$$648\ (850) = 468\ L$$

$$L = 1175 \text{ ft}$$

It may be possible to increase this length, L, after analyzing the effects of reversed contraction forces in adjacent longitudinal panels (longitudinal panel arrangement).

Relative elevations of the 15 reference markers (bolts) were determined during the fall and spring with an engineer's level. These elevations failed to reveal any significant changes in the vertical alignment of the panel assembly.

Benkelman Beam Deflections

Benkelman beam equipment was used for the study of load-deflection characteristics of the composite pavement. The pavement was loaded with a 9000-lb wheel load and 85-psi tire pressure. Measurements of pavement deflection were obtained during the fall of 1966 and the spring of 1967. Pavement deflections were measured at panel joints and panel interiors along the two wheelpaths. Locations of the Benkelman beam test stations are shown in Figure 8. Pavement deflections measured at these stations

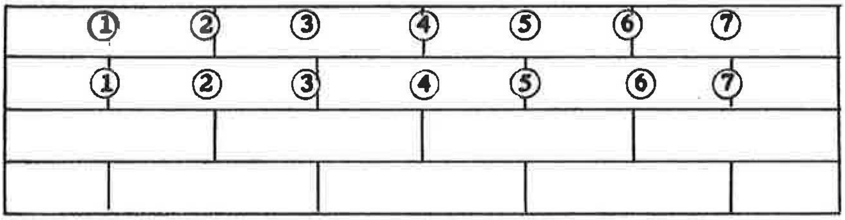

Figure 8. Location of Benkelman beam test stations.

TABLE 2

BENKELMAN BEAM DEFLECTIONS
(Thousandths of an inch)

Test Station No.	Beam Deflections—Fall 1966		Beam Deflections—Spring 1967	
	Panel Interior	Panel Joint	Panel Interior	Panel Joint
1	24	40	24	22
2	26	38	16	28
3	32	48	20	26
4	32	52	18	26
5	28	38	24	30
6	26	38	18	30
7	32	22	20	26

Figure 9. Field equipment for Benkelman beam deflections.

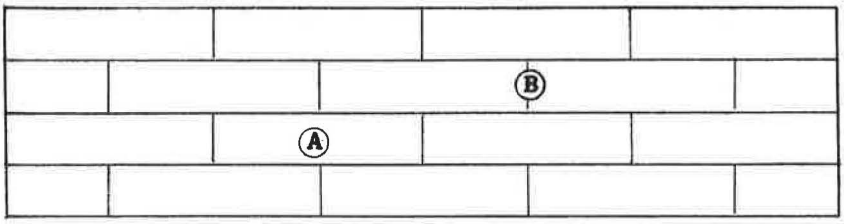

Figure 10. Location of plate bearing tests.

are given in Table 2. Figure 9 shows the equipment used to measure pavement deflections.

The test data show an increase in pavement firmness during the winter months (October 1966-April 1967). Part of this increase in pavement firmness is attributed to the densification of the sand bedding course under traffic.

Plate Bearing Tests

A further study of the load-deflection characteristics of the pavement was made from plate bearing tests. The Physical Research Division of the Department of Highways made the tests according to ASTM Standard Method D 1196-64. The plate bearing tests were made at two locations during the fall of 1966 and spring of 1967 (Fig. 10). The center of one of the prestressed panels was selected for one of the test locations (A) and the other was located at a transverse panel joint (B). These two locations were tested with 15- and 18-in. plates. Figure 11 shows the equipment used for the plate bearing tests. Table 3 gives the plate load test data obtained.

Measurements were made during the spring to determine the radius of influence for the 18-in. plate load. The following deflections were obtained from a 46, 000-lb plate load: 0.038 in., 4 ft from the plate; 0.012 in., 8 ft from the plate; and 0.003 in., 10 ft from the plate. These deflections indicate that the 46,000-lb plate load was distributed over an area approximately 24 ft in diameter. This deflection pattern reflects favorable structural performance.

Figure 11. Field equipment for plate bearing tests.

TABLE 3

PLATE LOAD TEST DATA

Location	15-in. Plate		18-in. Plate	
	Plate Pressure (psi)	Deflection (in.)	Plate Pressure (psi)	Deflection (in.)
		October 1966		
A	93	0.053	70	0.049
	158	0.103	118	0.090
	196	0.143	162	0.135
	239	0.187	194	0.180
	0	0.073	0	0.041
B	109	0.064	43	0.048
	141	0.096	80	0.098
	182	0.151	116	0.145
	229	0.205	154	0.200
	0	0.074	0	0.039
		April 1967		
A	76	0.048	47	0.038
	149	0.092	94	0.080
	218	0.140	137	0.127
	280	0.202	181	0.183
	0	0.027	0	0.028
B	44	0.037	25	0.040
	90	0.083	55	0.083
	137	0.122	84	0.128
	155	0.165	125	0.192
	194	0.214	0	0.038
	0	0.050		

The plate bearing data in Table 3 show that the pavement deflections measured at the panel joint during the spring were larger than the corresponding deflections measured during the fall. However, at the panel interior the deflections obtained from the 15-in. plate test were larger in the fall than the corresponding deflections measured during the spring. It is believed that the deflections measured at the panel joint during the fall reflected the effects of bonding between the grout key and the panels. This bonding effect was unquestionably destroyed by the first series of plate load tests. The increase in pavement firmness at the panel interior may be attributed to a densification of the base material.

VISUAL OBSERVATIONS OF PAVEMENT PERFORMANCE

The limited visual observations of pavement performance are considered significant even though the field test conditions were not severe. The test conditions were established by collecting traffic and weather control data.

A traffic counter was used during the fall of 1966 for a measure of the traffic carried by the test section. The average daily traffic was 25 vehicles per day for the period surveyed. A major part of the traffic consisted of vehicles weighing less than 4000 lb. However, the South Dakota Department of Highways hauled approximately 120 truckloads of cold mix across the test section during the last two weeks in November. The truck loads ranged between 22,000 and 26,000 lb (gross weight).

The weather control data consist of maximum and minimum temperatures and averages of the maximums and minimums for the period from September 1966 through April 1967. These temperatures are shown in Table 4.

The composite pavement demonstrated favorable structural performance during the observation period. There were no indications of joint failure or changes in the vertical alignment in the test section. Reflection cracks corresponding to panel joints did appear in the asphalt surface about one month after the surface was applied. These cracks were attributed to the "hinge action" of the pavement at the panel joints. Very small cracks developed along the transverse grout keys due to contraction of the panels at lower temperatures. These cracks provide contraction joints for the pavement with-

TABLE 4
TEMPERATURE CONTROL DATA FOR BROOKINGS[a]

Period	Minimum	Maximum	Average Minimum	Average Maximum
Sept. 1966	30	86	46	71
Oct. 1966	17	84	32	60
Nov. 1966	-11	58	15	40
Dec. 1966	-24	43	6	26
Jan. 1967	-21	46	4	26
Feb. 1967	-23	48	-4	20
March 1967	-10	20	20	44
April 1967	19	78	32	54

[a]U.S. Weather Bureau figures.

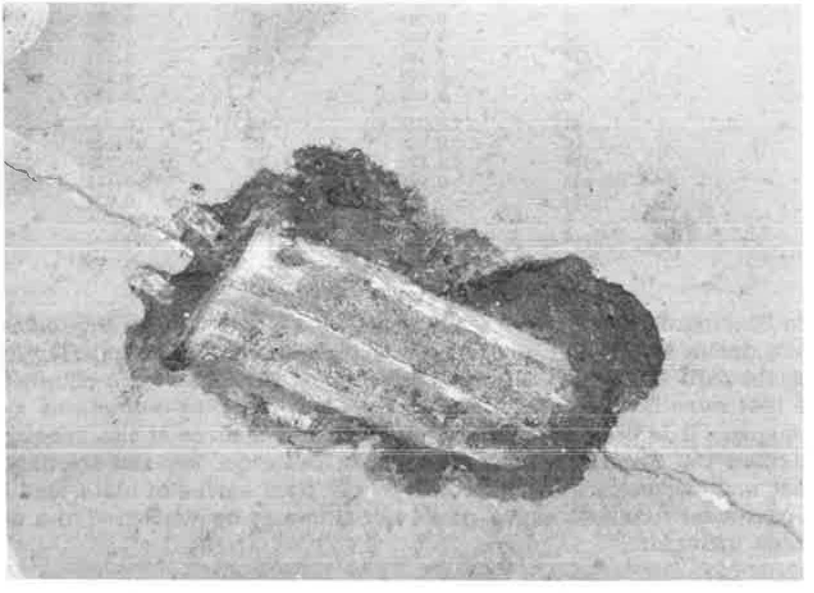

Figure 12. Tension cracks in the grout key and reflection cracks in the asphalt surface.

out affecting the riding characteristics of the asphalt surface. Figure 12 shows a crack along the grout key and the reflection crack in the asphalt surface. There was evidence of the grout spalling along the contraction crack. This was attributed to the hinge action between the panels.

There was some indication of pavement pumping during the time the pavement was subjected to heavy truckloads. This evidence appeared at the lower end of the test section. Some of the sand was pumped through the crack that developed at the end of the test section. It is believed that this condition was caused primarily by impact wheel loads applied to the ends of the resilient panels.

DISCUSSION

Field placement of 4-ton prestressed concrete panels for highway construction did not reveal any significant placement or construction problems. The placement and fine grading of the sand bedding course by hand was a time-consuming operation. This problem may be eliminated with the use of mechanical equipment normally available

for a large-scale operation. The bedding course should consist of material that is not susceptible to pumping action.

Field measurements indicate that the longitudinal panel arrangement facilitates a distribution of the pavement contraction throughout the pavement. The staggered pattern of 6-ft transverse joints coupled with longitudinal friction joints precludes a significant build-up of contraction stresses. Calculations indicate the feasibility of constructing sections of this type of pavement 1175 ft long without any special provisions for contraction. However, due consideration should be given to the maximum and minimum field temperatures anticipated and the temperature of the panels at the time of placement in order to provide panel spacings that are balanced for contraction and expansion.

An increase in pavement firmness was observed after the first winter. Part of this increase was attributed to a densification of the base material and sand bedding course under traffic. There was no indication of a significant change in the supporting capacity of the pavement due to pumping.

The primary purpose of the measurement of plate loadings and corresponding deflections was to evaluate the wheel load distributions. Test data show that the wheel load was distributed over the width of the 24-ft pavement. The flexible but spread footing effect, developed through the use of prestressed concrete panels, is recognized as one of the favorable characteristics of this type of pavement.

The observations of the structural performance of this type of pavement during the first year of service were favorable. The interconnected panels demonstrated a continuous slab effect. The reflection cracking of the asphalt at the transverse panel joints is not considered a serious problem.

This type of pavement holds definite promise for the increasing demand for a construction method that may be used under unfavorable weather conditions and without causing a major disruption in the normal flow of traffic. It offers even greater promise for airports in view of the increasing demand for methods that may be used to reinforce existing airport pavements, taxiways, and aprons without disrupting the normal airport operation.

ACKNOWLEDGMENTS

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