Dowel Placement Tolerances for Concrete Pavements

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ABSTRACT

The results of an investigation conducted to develop placement tolerances for dowels at concrete pavement joints are presented. A theoretical analysis of dowel misalignment was attempted. The purpose of the analysis was to compute restraint stresses induced in the concrete pavement for different levels of dowel misalignment. However, because of the complexity of correctly incorporating the three-dimensional nature of dowel misalignment, the theoretical analysis was not completed. The effect of dowel misalignment was then investigated in the laboratory by conducting pullout tests on sections of concrete slabs incorporating a joint and dowels with different levels of misalignment. Test results are presented that indicate that pullout loads were relatively low for dowel misalignment levels of less than 1 in. per 18-in. length of dowel bar and a maximum joint opening of 0.25 in.

Joints are provided in concrete pavements to control transverse and longitudinal cracking that results from restrained deformations caused by moisture and temperature variations in the slab. Because joints create a discontinuity in the pavement, use of joints may reduce load-carrying capacity of the pavement at the joint. To ensure adequate load transfer, load-transfer devices are used at joints by many highway agencies.

Current practice for load-transfer devices at joints has evolved over a period of time. Some of the systems used have included the I-beam, Starlug, two-component devices, and round steel dowel bars. Today, round steel dowel bars are the most widely used. Current recommended practice for doweled joints is for dowel diameters to be one-eighth of slab thickness, dowel spacing to be 12 in., and dowel length to be 18 in.

Dowel bars require care in placement to minimize detrimental effects of misalignment. It is generally specified that dowels be placed as much as is practical parallel to the longitudinal axis and the horizontal plane of the pavement. Generally, limits on permissible tolerances are specified individually by state highway agencies. The different categories of dowel misalignment and their possible effects on pavement behavior are illustrated in Figure 1.

Before December 1980, FHWA specified limits on dowel placement (1). However, the current FHWA Technical Advisory T5140.18 of December 15, 1980, on rigid pavement joints does not specify limits on misalignment but cautions that "close tolerances for dowel placement are extremely important for proper functioning of the slab and for long-term performance" (2). This advisory also states that "care must be exercised in both specifying dowel placement tolerance and in evaluating the adequacy of construction placement" (2).

In the past, an alignment error of 1/4 in. per 18-in. length of dowel has been considered acceptable. However, many state highway agencies specify different permissible levels of misalignment. For example, the Illinois Department of Transportation specifies in their Standard Specifications for Road and Bridge Construction, dated October 1979, that

any deviation from correct alignment greater than 1/8 in. in 12 in. should be corrected before any concrete is placed. The Georgia Department of Transportation specifies an allowable tolerance of 3/8 in. per foot in both the horizontal and vertical directions.

No clear consensus exists as to the level of practical limits on dowel placement tolerances. When limits are specified, contractors often state that they are neither practical nor realistic. In addition, it is a slow process to determine levels of misalignment once the pavement has been constructed. Attempts have been made to measure levels of misalignment by using radar devices or by using a pachometer and taking partial-depth or full-depth cores near the ends of the dowel.

The primary reason for placing limits on dowel placement tolerance is to minimize problems associated with locked joints. Pavement slabs should be free to expand and contract with changes in slab temperature and moisture. Resistance to movement is provided by subbase friction and locked joints. For slabs up to 40 ft, resistance due to subbase friction is not as significant.

The magnitude of restraint due to locked joints depends on the degree of dowel misalignment, number of misaligned dowels, and dowel corrosion. Locked joints may result in transverse cracking, corner breaks, and spalling at the concrete face around the dowel. Once a spall occurs around a dowel, load-transfer effectiveness of the dowel may decrease.

STUDY OBJECTIVES

The investigation reported in this paper was undertaken to study the effects of dowel misalignment on pavement performance. Specific objectives were as follows:

1. To use analytical methods to perform stress analysis of the joint system incorporating dowels with different levels of misalignment,
2. To conduct laboratory tests to determine the effect of dowel misalignment, and
3. To select placement tolerance criteria based on study results.

FIGURE 1 Effects of dowel misalignment.
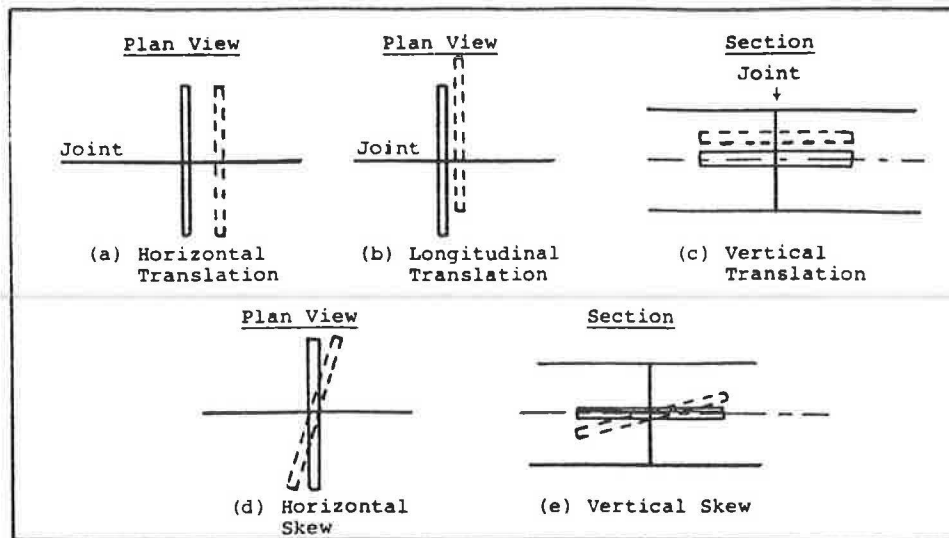
Type of Misalignment	Effect on		
	Spalling	Cracking	Load Transfer
a	—	—	(Yes)*
b	—	—	(Yes)*
c	Yes	—	(Yes)*
d	Yes	Yes	Yes
e	Yes	Yes	Yes

*Effect will depend on amount of translation

FACTORS AFFECTING DOWEL MISALIGNMENT

The following factors affect level of dowel misalignment when basket assemblies are used:

1. Basket rigidity,
2. Quality control during basket fabrication,
3. Care during basket transportation and placement,
4. Fastening of basket to subbase,
5. Location of saw cut over basket,
6. Paving operation (the large roll of concrete ahead of the paver may displace individual dowels or the basket assembly), and
7. Field inspection during construction.

The following factors affect level of dowel misalignment when dowels are implanted:

1. Implanting machine operation,
2. Strike-off after dowel placement,
3. Consolidation (vibration) after dowel placement,
4. Location of saw cut over implanted dowels, and
5. Field inspection during construction.

For basket assemblies, basket rigidity and proper fastening of the basket assembly to the subbase are critical. Even a small movement or rotation of the basket assembly during the paving operation is sufficient to cause noncompliance of dowel placement.

For implanted dowels, different paving sequences have been used to achieve proper placement of dowel bars. Some paving sequences used strike-off and concrete consolidation (internal vibration) operations following dowel placement. In other paving operations, concrete consolidation after dowel placement was not used (3). However, degree of compliance with allowable dowel placement tolerances has been reported as unsatisfactory for all these procedures (3).

The amount of misalignment that can be tolerated greatly depends on joint spacing and climate. Greater misalignment can be tolerated if the need for joint movement (opening) is not large. The magnitude of restraint due to locked joints depends on the degree of load-transfer device misalignment as well as dowel corrosion. As indicated in Figure 1, excessive restraint to slab movement may result in transverse and corner cracking and spalling at the concrete face around the dowel. Sample calculations of restraint that needs to be developed to cause midslab cracking are presented in Table 1.

BACKGROUND

Only a few investigations have been conducted to study levels and effects of dowel misalignment. The number of field investigations has been limited because of lack of practical methods for evaluating alignment of dowels in place.

TABLE 1 Calculated Restraint to Cause Midslab Cracking in 10-in.-Thick Slab

Age (days)	Tensile Strength (psi)	Compressive Strength (psi)	Concrete Modulus (psi 000,000s)	Allowable Strain (millionths)	Restraint to Cause Cracking (lb/ft width)
1	87	700	1.5	58	10,400
3	184	1,800	2.3	80	22,100
7	258	2,750	2.9	89	31,000
28	333	3,800	3.4	97	40,000
365	425	5,250	4.2	102	51,000

Note: (a) Before midslab cracking occurs, spalling may take place around load-transfer device. (b) Tensile stress in the form of curling restraint stress and load stress also exists. Therefore, even a reduced level of restraint can contribute significantly to crack formation. (c) Age, strength, and modulus relationships are general and are used for illustration only.

An early field study conducted in Indiana by Smith and Benham found a large number of misaligned dowels (4). As a supplement to the field work, laboratory tests were conducted using small slab sections incorporating a joint and dowels spaced at 12-in. centers. In these tests, 3/4-in.-diameter dowels were placed at different levels of misalignment and loading was applied at 28 days to open the joint. Results indicated that for a 6-in.-thick slab section, an alignment error in excess of 1 in. caused spalling when joints were opened 3/4 in. For a 5-in.-thick slab section, an alignment error of 1/4 in. caused slight spalling. Test results also showed that if the joint was not opened more than 1/2 in., alignment errors up to 1 1/2 in. could be tolerated without spalling. Generally, the load required to open a contraction joint 1/2 in. did not exceed 3,000 lb per dowel.

In another study, conducted by Segner and Cobb at the University of Alabama, slab sections 5 ft wide, 5 1/2 ft long, and 10 in. thick were used (5). Dowels used were 1 1/4 in. in diameter and 16 in. long. Testing was done at 2 and 7 days. Load required to open a joint 1/2 in. for a 1-in. vertical misalignment of a dowel was about 4,000 lb, and for a 1-in. horizontal misalignment of a dowel the load was about 2,000 lb. Spalling was produced for a vertical misalignment of 1 in. or for a horizontal misalignment of 3 in. at a joint opening of about 0.9 in.

Theoretical effects of misalignment have been studied by Friberg (6) and Weaver and Clark (7). Friberg assumed that in a misaligned dowel, the dowel deflection must equal the transverse component of the movement in a parallel displacement of the slab. The relationship between the deflection of the dowel and dowel misalignment was then determined by Friberg as follows (6):

$$\alpha i = \{ (P/2EI) [(1 + Ba)^2/B^3] + (a^3/6) \} \qquad (1)$$

where

  α = misalignment of the dowel in the direction of slab movement (rad),
  i = total slab end movement,
  a = total joint width,
  P = dowel shear developed due to misalignment,
  E = modulus of elasticity of dowel steel,
  I = moment of inertia of dowel section,
  B = relative stiffness of dowel and concrete = $(GD/4EI)^{1/4}$,
  G = modulus of dowel concrete reaction, and
  D = dowel diameter.

With this equation, dowel shear developed due to misalignment can be calculated. The calculated shear values can then be used to compute concrete bearing stresses under dowels. Shear loads calculated by

using the equation are given in Table 2 for a 1 percent dowel misalignment and different levels of slab end movements. However, this analysis considers only dowel bearing effects and not the effects of dowel slippage or the resistance to dowel movement of the concrete surrounding the dowel. The analysis does not provide information on development of tensile stress in the pavement slab as a result of dowel misalignment.

TABLE 2 Dowel Shear Induced due to Misalignment of 1 Percent (6)

Dowel Diameter (in.)	Final Joint Width (a_i) (in.)	Dowel Shear Induced (lb)	
		i = 0.25 in.	i = 0.50 in.
1.00	0.25	815	1,630
	0.50	695	1,390
1.25	0.25	1,235	2,465
	0.50	1,090	2,175

Note: i = change in joint width due to slab end movement.

Recent investigations have concentrated on comparing misalignment levels and performance of joints having machine-implanted dowels and preset basket assemblies (8-10). These studies have been conducted because of concern about dowel placement accuracy when machine implanters are used. In the Pennsylvania study (8), horizontal, vertical, and longitudinal misalignments were measured at implanted and conventionally placed dowel bar joints. Two bars each from five joints were chosen for each placement type. A pachometer was used to locate the dowels and 4-in.-diameter cores were drilled to the top of the bars at each end of the bar. The average values of misalignment are given in Table 3. Sixty percent of the implanted dowels and 40 percent of conventionally placed dowels were outside specified limits of tolerance. The Pennsylvania Department of Transportation specifies an allowable tolerance of 1/4 in. per 18-in. length of dowel bar in both the horizontal and vertical directions.

In an investigation conducted for the American Concrete Pavement Association, visual surveys and misalignment determinations using a metal detector

TABLE 3 Levels of Misalignment Measured in the Field (8)

Placement Method	Project	Vertical Skew (in.)	Horizontal Skew (in.)	Vertical Translation (in.)	Horizontal Translation (in.)
Basket	2E	5/8	1/4	0	1-3/8
	2E	1/8	0	3/8	1
	6E	7/16	0	1/32	1
	6E	1/16	0	5/16	1-1/4
	9E	1/16	0	7/16	1
	9E	1/16	1/8	7/16	15-16
	15E	3/8	1/4	1/16	5/8
	15E	1/16	1/4	1-1/4	3/8
	17E	1/8	3/8	11/16	11/16
	17E	0	0	11/16	1/8
Implanted	1	1/16	1/4	11/16	7/8
	1	1/16	1/4	3/4	7/8
	2	1/16	3/16	7/16	5/16
	2	3/16	0	3/4	1/4
	9	3/16	3/8	5/8	5/16
	9	1/8	3/8	5/8	7/16
	19	1/16	3/4	15/16	3/8
	19	1/16	1/4	3/4	3/8
	28	1/16	1/4	1-3/16	1/8
	28	1/8	0	1	0

Note: Specified tolerances for these projects were a skew of 1/4 in. per 18 in. length of dowel bar in both the vertical and horizontal directions and a vertical or horizontal translation of ±1 in.

were made at several sites in Alabama to compare joints with mechanically implanted and conventionally placed dowels (9). Projects studied were constructed between 1958 and 1969. A statistical analysis was conducted to identify trends. It was found that there was no significant difference between implanted and preset dowel joints with respect to joint-related distress. However, no statistically valid conclusions could be drawn from the misalignment data.

In a Tennessee investigation (10), misalignment levels were determined at several sites by uncovering dowels in freshly placed plastic concrete and by core drilling in hardened concrete. On the basis of the findings, it was recommended that horizontal and vertical skew tolerances be 1/2 in., vertical tolerance be ±1 in., and longitudinal tolerance be ±1 1/2 in.

In a study conducted during 1982 by the Georgia Department of Transportation, dowel bar placement was investigated at five highway projects (3). Three projects had implanted dowels and two projects had used dowel basket assemblies. Project details are given in Table 4. Dowel placement was determined by coring and use of a metal detector. In addition, distress at joint locations was observed. A total of 261 joints were evaluated in detail and another 400 to 500 joints were examined for signs of distress.

A summary of Georgia's field evaluation is given in Table 5. It is clear from Table 5 that there is substantial noncompliance with the specification requirement for the projects with the implanted dowels. However, no dowel-related distress was found in any of the joints that were examined (3). In addition, it was reported that during construction of the five projects, all joints had started "working" within a few days of construction. However, because of the noncompliance problem with implanted dowels, the study recommended that implanting of dowels not be allowed. The study also recommended that improvements be made in methods and equipment for implanting dowels and that studies be conducted to determine permissible levels of dowel misalignment.

ANALYTICAL MODELING

Analytical modeling was used to perform stress analysis of joint systems incorporating dowels with different levels of misalignment. The following items were considered in the analysis:

1. Slippage between dowel and concrete,
2. Simulation of temperature drop in the concrete slab, and
3. Dowel misalignment levels.

An analysis was conducted to simulate slab end movement due to temperature change within the slab. Restraint to slab end movement would be induced by the misaligned dowels. One of the difficulties in an analysis of a doweled system is the complexity of modeling the slip between the dowel and the concrete. Recently, the finite-element method has been used to model slippage at joints in rock masses. However, this type of modeling is still under development.

Initial modeling of a misaligned dowel was conducted by using computer program SAP4 (11). Program SAP4 is a general-purpose finite-element computer program developed at the University of California at Berkeley. Program SAP4 cannot model slip behavior directly. Therefore, slip behavior was modeled by using "soft" elements at the interface between the dowel and the concrete. After work started with the SAP4 program, another finite-element computer program was made available, denoted BMINES, which was developed by Agbabian Associates for the U.S. Bureau of Mines (12). Program BMINES is a static, two- or three-dimensional, nonlinear, finite-element computer program for analysis of structural and geological systems. It has the capability to consider slippage at cracks and joints.

Analysis was conducted only for the case of a single dowel with skew misalignment. Analysis of a full-width joint incorporating several misaligned dowels is not practical because of the difficulty in modeling the three-dimensional nature of the problem.

On the basis of attempts to theoretically model dowel misalignment, it was concluded that it is not currently feasible to conduct a rational analysis of misaligned dowel bars. The modeling of slippage between the dowel and the concrete and the simulation of the three-dimensional dowel misalignment are considered too complex to be correctly incorporated in currently available analysis techniques.

The effect of dowel misalignment was then in-

TABLE 4 Georgia Department of Transportation Project Description (3)

Project	Project No.	Location	Age (years)	Dowel Placement Method
A	I-16-1(38)115 Ct 3, Bulloch County	SR-73 to SR-67, 10.285 mi	5	Implanter
B	I-20-1(23)00 Ct 4, Carroll-Haralson	Alabama Line to US-27, 11.585 mi	3	Implanter
C	I-85-1(33)12 Ct 3, Troup County	SR 219 to Hines Road, 8.538 mi	3	Implanter
D	I-20-1(27)11 Ct 4, Carroll County	US-27 to SR-61, 11.874 mi	3	Baskets
E	GS 7-ACS-13-1(42), GS 9-ACF-13-1(44), Hall County (SR 365)	SR-23 to SR-52, 8.111 mi	1/4	Baskets

TABLE 5 Percent of Dowels out of Specification Tolerance (3)

Project	Dowel Installation	Depth[a] (in.)	Vertical[a] Rotation (in.)	Horizontal Rotation (in.)		Longitudinal Alignment (in.)	
				Core Measurements	Metal Detector Measurements	Core Measurements	Metal Detector Measurements
A	Implant	24	20	9	10	65	68
B	Implant	72	17	25	15	75	66
C	Implant	83	28	20	22	63	62
D	Basket	0	5	0	4	57	54
E	Basket	0	0	5	10	21	22

Note: The following tolerance levels were specified by Georgia Department of Transportation during construction of the listed projects: vertical tolerance ± 1 in., horizontal tolerance ± 1 in., rotation (horizontal plane) 1 1/8 in. per 18-in. length, rotation (vertical plane) 9/16 in. per 18-in. length.

[a]Core measurements.

vestigated in the laboratory. The laboratory testing program and test results are presented in the next section.

LABORATORY TEST PROGRAM

A laboratory test program was conducted to study the effect of dowel misalignment. Testing consisted of a pullout test of slab specimens incorporating a joint and dowels with different levels of misalignment. Initial tests were conducted with a single misaligned dowel per test specimen and use of rollers along the sides of the specimen to ensure that the pullout direction remained perpendicular to the joint during the test. Pullout loads measured during these tests were relatively low. Because of a concern that the low measured loads could be due to improper testing procedures, the test procedure was modified. In the modified test procedure, a pair of misaligned dowels was used. The two dowels were misaligned in opposite directions to cancel out side forces and thus eliminate any tendency for the slab sections to tilt while being pulled apart.

Test Parameters

The following test parameters were considered:

   • Slab section dimensions: 3 ft wide by 7 ft long;
   • Slab thickness: 8 and 10 in.;
   • Misalignment levels (per 18-in. length): 0, 1/4, 1/2, 1, 2, and 4 in.;
   • Misalignment category: horizontal and vertical;
   • Test age: 1, 3, 7, and 28 days;
   • Maximum joint opening: 0.25 in.

Test Procedure

As discussed previously, two different test procedures were used. In one procedure, a single misaligned dowel was used. In the other, a pair of misaligned dowels was used.

Test with a Single Misaligned Dowel

The test setup is shown in Figure 2. The test frame was constructed by using channel-shaped steel members. One section of the test specimen was held firmly to the rigid frame. The other section was pulled by using a hydraulic jack. Dowel misalignment was controlled by welding one end of the dowel to a chair with a base plate and nailing the base plate onto the form. A 1/8-in.-thick steel plate was used to form the joint. A form ready for casting is shown in Figure 3. Concrete was placed carefully around the dowel to ensure that the dowel misalignment remained true. Each specimen was cast over two layers of polyethylene sheets.

   Two pairs of rollers were used along the sides of the test specimen to ensure that the movement of the pulled slab section was perpendicular to the joint. The bearing force on the two pairs of rollers along the pulled section was monitored by using load cells installed between the rollers and the test frame. During the test, joint opening was monitored with a pair of displacement sensors mounted on the slab surface, as shown in Figure 4. A data-acquisition system was used to record joint-opening and load-cell data.

   Pullout load was applied gradually and uniformly to obtain a joint opening of 0.25 in. in about 1 min.
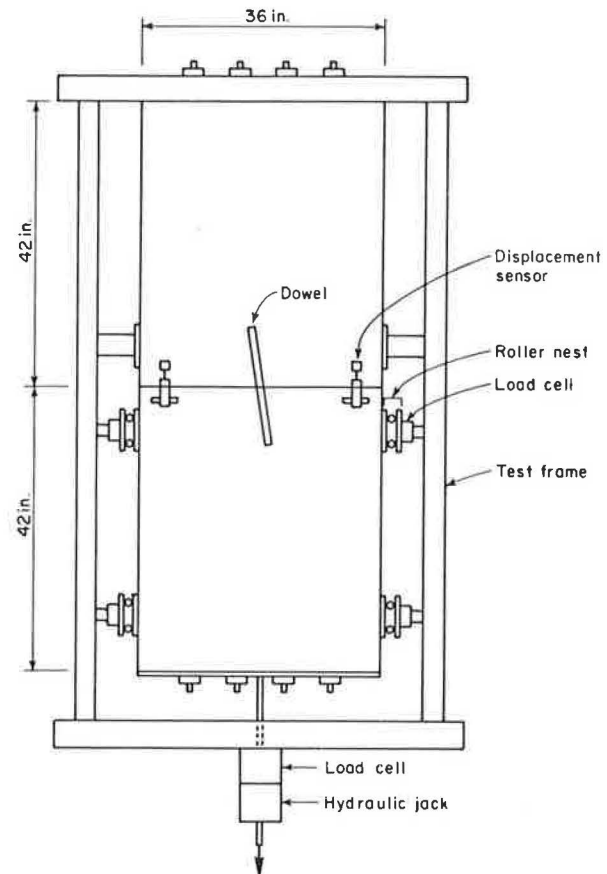

FIGURE 2   Setup for single-dowel test.

A total of 16 specimens were tested with the test procedure described. Specimen details and test results are given in Table 6. Concrete compressive strengths were as follows:

Test Series	Age (days)	Compressive Strength (psi)
A,C	1	1,960
	3	2,990
	7	3,810
	28	5,100
B,D	1	1,490
	3	2,970
	7	4,040
	28	5,420

Typical relationships between the pullout load and joint opening are shown in Figure 5. It is seen that a large portion of the pullout load is required to open the joint 0.01 in. After the joint has opened about 0.05 in., there is no further increase in the pullout load.

   For each test, the pullout test was performed three times. After each, the pulled slab was pushed back to close the joint and the pullout test repeated. The maximum pullout load was always obtained under the first test. For the second and third tests, the maximum pullout load obtained was less than half that obtained for the first test.

   Test results do not show significant differences in the pullout load for the different levels of misalignment. There was concern that this behavior may be due to the use of a single misaligned dowel and the possible pulling of the slab in a direction parallel to the misaligned dowel even though rollers were used along the slab sides.

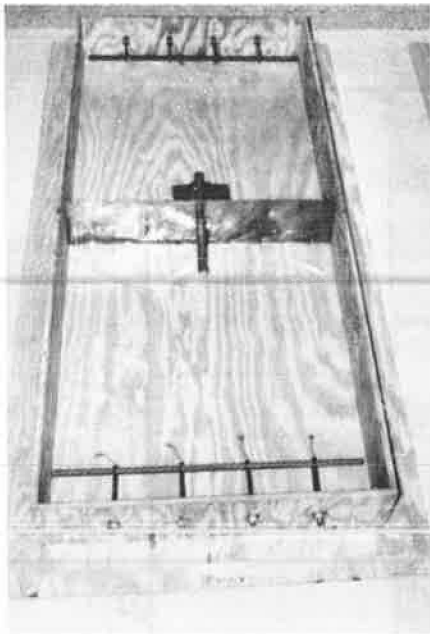   A new test procedure was then developed for the
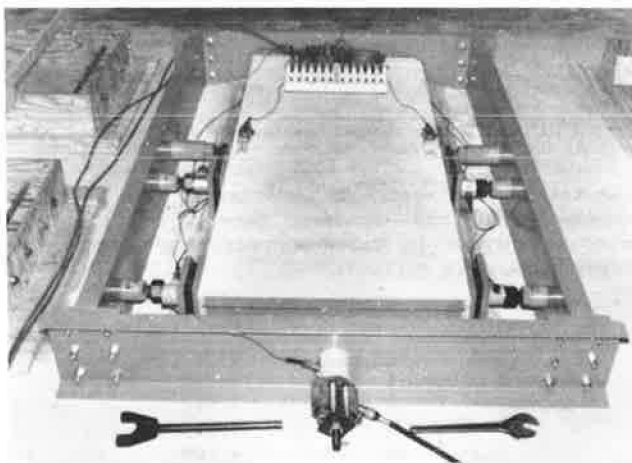
FIGURE 3 Single-dowel test: form ready for casting.

FIGURE 4 Single-dowel test: displacement sensors on slab surface.

TABLE 6 Test Details and Results

Test Series	Misalignment (in.)	Maximum Pullout Load (lb) by Test			
		1 Day	3 Days	7 Days	28 Days
A	0 horizontal	1,030	840	1,020	1,640
B	1/4 horizontal	890	670	980	2,000
C	1/2 horizontal	1,160	1,270	1,410	1,890
D	1 horizontal	1,460	1,280	1,020	NA

Note: NA = not available. Slab thickness = 8 in. Maximum joint opening = 0.25 in. Maximum aggregate size = 1 in.
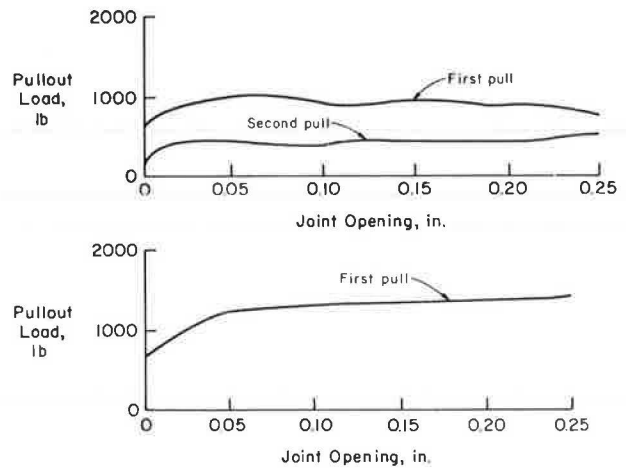

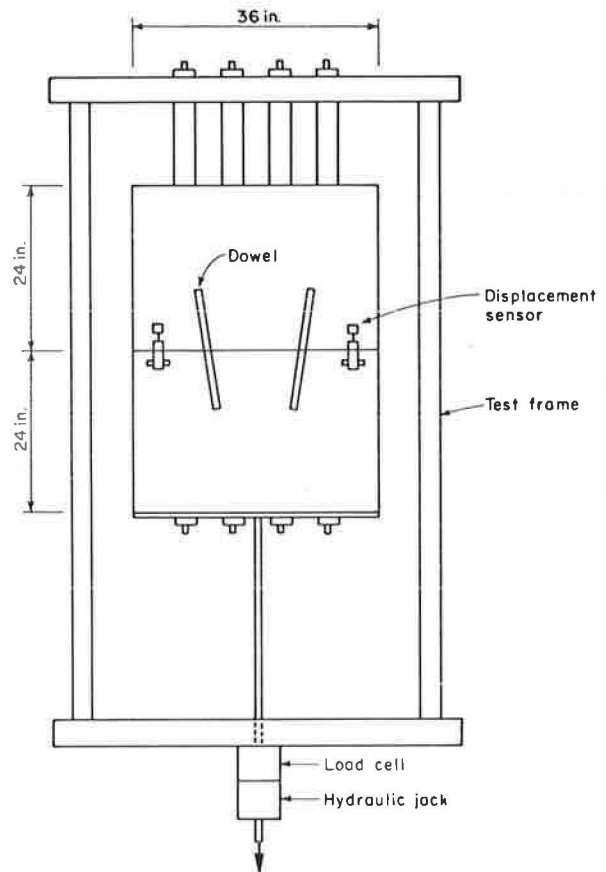FIGURE 5 Relationships between pullout load and joint opening.

FIGURE 6 Setup for two-dowel test.

pullout test. This procedure, using a pair of misaligned dowels, is discussed next.

Test with a Pair of Misaligned Dowels

The test setup for a pair of misaligned dowels is shown in Figure 6. The test frame was the same as that used for the single-dowel tests. However, use of the rollers along the sides of the specimen was discontinued and the specimen length was shortened to 4 ft. For this procedure also, one slab section was held firmly to the test frame while the other slab section was pulled.

For each test, each of the two dowels had the same level of misalignment. However, the dowels were misaligned in opposite directions to cancel out any tendency of the pulled-slab section to tilt horizontally or vertically. Dowel misalignment was controlled by use of chairs. A 1/8-in.-thick steel plate

FIGURE 7 Two-dowel test: form ready for casting.

was used to form the joint. A form ready for casting is shown in Figure 7. Concrete was placed carefully around the dowels to ensure that the dowel misalignment remained true. Each specimen was cast over two layers of polyethylene sheets.

Joint opening was monitored with a displacement sensor mounted on the slab surface. An X-Y plotter was used to record the pullout load measured by a load cell and the joint opening measured by the displacement sensor. Pullout load was gradually and uniformly applied to obtain a joint opening of 0.25 in. in about 1 min.

A total of 33 specimens were tested, 24 of which had a slab thickness of 8 in. and the remaining 9 had a slab thickness of 10 in. Specimen details and test results are given in Table 7 for the 8-in.-thick specimens and in Table 8 for the 10-in.-thick specimens. Concrete compressive strengths were as follows:

Specimen Thickness and Test Series	Age (days)	Compressive Strength (psi)
8 in.		
E,F,G,H	1	1,640
	3	2,640
	7	3,530
	28	4,940
I,J,K,L	1	1,460
	3	2,640
	7	3,740
	28	5,140
10 in.		
M-U	8	4,070
	28	5,050

It may be seen from Table 7 that although there is an increase in the pullout load with increased level of dowel misalignment, the absolute magnitudes of the pullout load are still relatively low for dowel misalignment levels below 1 in. As seen from Table 8, the magnitude of the pullout load increases greatly when the dowel misalignment exceeds 1 in. It should be noted that maximum joint opening did not exceed 0.25 in. and that the pullout load would have been greater for larger joint openings than that shown in Table 8 for dowel misalignment levels exceeding 1 in. It should also be noted that no spalling was seen around dowel bars at the joint face for specimens having dowels with misalignment levels of less than 1 in.

Results of tests conducted using two misaligned dowels per specimen verify the general reliability of the test results obtained with a single misaligned dowel per specimen. The similarities in the results

TABLE 7 Test Details and Results for 8-in.-Thick Slab

Test Series	Misalignment[a] (in.)	Maximum Pullout Load per Dowel (lb) by Test		
		1 Day	3 Days	7 Days
E	0 horizontal	600	700	850
F	1/4 horizontal	650	750	NA
G	1/2 horizontal	800	900	1,100
H	1 horizontal	900	1,250	1,250
I	0 vertical	600	800	850
J	1/4 vertical	750	1,250	1,350
K	1/2 vertical	1,150	1,300	1,750
L	1 vertical	1,400	1,600	1,750

Note: Two dowels were used per specimen. Maximum joint opening = 0.25 in.

[a]Total per dowel.

TABLE 8 Test Details and Results for 10-in.-Thick Slab

Test Series	Misalignment[a] (in.)	Maximum 7-Day Pullout Load per Dowel (lb)
M	0	750
N	1/2 horizontal	2,250
O	1 horizontal	2,000
P	2 horizontal	4,000
Q	4 horizontal	5,500
R	1/2 vertical	1,666
S	1 vertical	2,000
T	2 vertical	R
U	4 vertical	R

Note: Two dowels were used per specimen. Maximum joint opening = 0.25 in. except for Test Series Q, for which maximum joint opening was 0.20 in. R = rejected due to excessive twisting of the test panels.

[a]Total per dowel.

of tests using the two different procedures confirm the reliability of the low levels of the pullout loads measured for dowel misalignment of 1 in. or less.

Discussion of Test Results

Laboratory test results indicate that pullout loads are relatively low for dowel misalignment levels of less than 1 in. per 18-in. length of dowel bar and a maximum joint opening of 0.25 in. A maximum joint opening of 0.25 in. was selected for the laboratory tests because joint openings in the field do not exceed this value. Joint openings in the field due to daily and seasonal volume changes generally range from about 0.05 in. to about 0.20 in. for slab lengths ranging from about 15 ft to about 40 ft.

Test results agree generally with observations reported by Smith and Benham (4) and by Segner and Cobb (5) that were discussed previously in the section entitled Background. Smith and Benham's laboratory test indicated that if a joint was not opened more than 1/2 in., alignment errors up to 1 1/2 in. per 24-in. length of the bar could be tolerated without spalling and that pullout load required to open a joint 1/2 in. did not exceed 3,000 lb per misaligned dowel. Segner and Cobb's laboratory work indicated that a pullout load of about 2,000 lb was needed to open a joint 1/2 in. when a dowel had a horizontal misalignment of 1 in. per 16-in. length of dowel and that pullout load was about 4,000 lb for a vertical dowel misalignment of 1 in.

Vertical and horizontal misalignment levels of 1/4 in. per 18-in. length of dowel bar have been

considered acceptable in the past by many state highway agencies. There was relatively little difference in measured pullout loads between specimens incorporating a 1/4-in. misalignment and specimens incorporating a 1/2-in. misalignment.

Because of the limited number of tests that were conducted during the present study and because these tests did not consider the effects of multiple misaligned dowels at a joint, no recommendations are made to change levels of permissible misalignment currently specified by state highway agencies. However, data developed to date from various studies indicate that misalignment levels greater than those currently specified may be acceptable.

To ensure that a realistic specification is developed in the future, it is necessary that a practical, reliable, and cost-effective nondestructive test method be available to measure dowel misalignment in the field. Factors to be considered in developing an effective program of field evaluation of dowel-bar misalignment are given by Tayabji (13). These factors include consideration of the allowable number of misaligned dowels per joint and selection of a strategy to resolve the misalignment problem once it is identified.

SUMMARY

An investigation was conducted to develop limits on allowable levels of tolerances for dowel placement at concrete pavement joints. Theoretical analyses of the effect of dowel misalignment were conducted by using finite-element computer programs SAP4 and BMINES. Because of the complexity of modeling slippage between the dowel and the concrete and of simulating the three-dimensional nature of dowel misalignment, the theoretical analysis was not completed.

The effect of dowel misalignment was studied in the laboratory. Test results indicate that pullout loads for dowels with misalignment levels of 1 in. or less are relatively low.

However, no revisions to the currently accepted levels of dowel misalignment are recommended at this time because of the limited amount of laboratory test data and lack of sufficient data on field performance of jointed concrete pavements with misaligned dowels.

It is recommended that a concerted effort be made to document dowel misalignment in the field and to relate the levels of misalignment to performance at the joints. An adequate data base on field performance of jointed concrete pavements incorporating dowels with different levels of misalignment as well as data developed from laboratory tests can then be used to make revisions to the currently used specifications for dowel misalignment.

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