Report No. FHWA/RD-86/042

DOWEL PLACEMENT TOLERANCES

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May 1986
Interim Report

Prepared for:
Federal Highway Administration
Office of Engineering and Highway Operations
Research and Development

Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101

Technical Report Documentation Page

1. Report No. FHWA/RD-86/042

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Dowel Placement Tolerances

5. Report Date
May 1986

6. Performing Organization Code

8. Performing Organization Report No.

7. Author(s)
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10. Work Unit No. (TRAIS)
34B1-302 (35J2-032)

11. Contract or Grant No.
DTFH-61-80-C-00052

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations R & D
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered
Interim Report
May 1985

14. Sponsoring Agency Code

15. Supplementary Notes
Contracting Officer's Technical Representative: Roger M. Larson (HNR-20)

16. Abstract

This report presents results of an investigation conducted to develop placement tolerances for dowels at concrete pavement joints. 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 pull-out tests on sections of concrete slabs incorporating a joint and dowels with different levels of misalignment. Test results are presented in this report.

Test results indicate that pull-out loads were relatively low for dowel misalignment levels of less than 1 inch per 18-inch length of dowel bars and a maximum joint opening of 0.25 inch. Because of the limited amount of laboratory data, no recommendations are made to establish new acceptable levels of dowel misalignment.

17. Key Words
Concrete pavements, dowel bars, dowel misalignment, joints, load transfer devices, pavement design

18. Distribution Statement
No restriction. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	36	

Form DOT F 1700.7 (8-72)

NOTICE

PREFACE

This report was prepared as a part of a contract between the Federal Highway Administration and the Construction Technology Laboratories, a Division of the Portland Cement Association. The contract objective is to develop improved joint systems and load transfer devices for jointed concrete pavements and to evaluate load transfer restoration techniques and undersealing practices.

The following reports have been prepared as part of the contract:

1. Analysis of Jointed Concrete Pavements, February 1984
2. Improved Rigid Pavement Joints, February 1984
3. Dowel Placement Tolerances, May 1986
4. Evaluation of Load Transfer Restoration Techniques and Undersealing Practices, May 1986

The first report presents details of a computer program for analysis of jointed concrete pavements. The program, denoted as JSLAB, can analyze concrete pavement sections consisting of a large number of jointed slabs. Joints may be modeled as doweled, aggregate interlock, or keyed. The computer program is available from the Federal Highway Administration.

The second report contains results of a study conducted to develop improvements to concrete pavement joints. Improvements in design identified to produce better joint performance include use of tied-concrete shoulders, widened lanes, and use of fewer non-uniformly spaced dowel bars. No new load transfer devices were developed as part of this study.

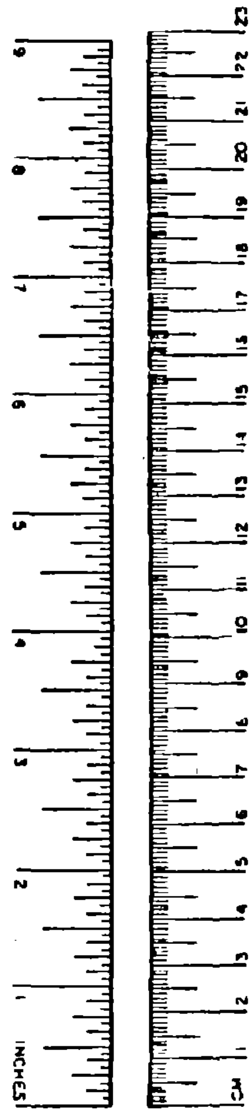
The third report presents results of an investigation conducted to obtain data to develop placement tolerances for dowels at concrete pavement joints. Pull-out tests were conducted in the laboratory on sections of concrete slabs incorporating a joint and dowels with different levels of misalignment. Test results indicate that pull-out loads were relatively low for dowel misalignment levels of less than 1 in. per 18 in. length of dowels bars and a maximum joint opening of 0.25 in. However, because of the limited amount of laboratory data, no recommendations were made to establish new acceptable levels of dowel misalignment.

The fourth report presents results of an investigation conducted to evaluate the performance of "retrofit" load transfer devices installed at a test site on I-75 in Georgia. This report also presents a summary and recommendations on practices of undersealing of concrete pavements.

METRIC CONVERSION FACTORS

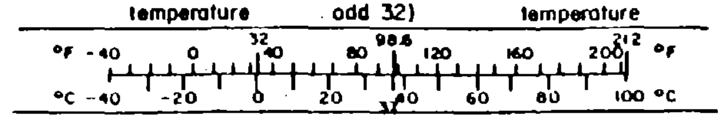
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

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. A summary of state practices on dowel usage for the year 1982 is given in Appendix A.

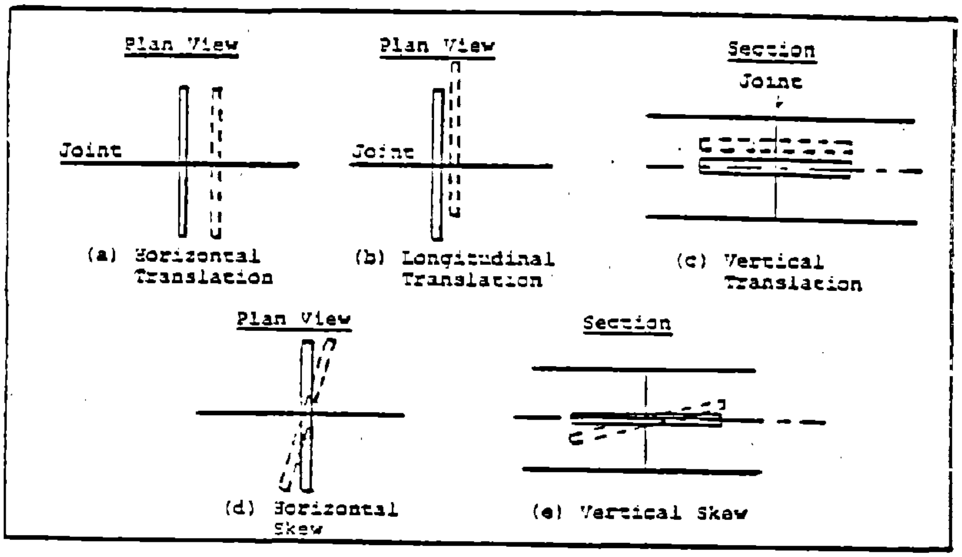
Current practice for load transfer devices at joints has evolved over a period of time. Some of the systems used have included the I-beam, Starlug, two-component devices, and round steel dowel bars. Today, round steel dowel bars are the most widely used. Current recommended practice for doweled joints 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 parallel as practical 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 Fig. 1.

Prior to December 1980, FHWA specified limits on dowel placement.(1)* However, the current FHWA Technical Advisory No. 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, alignment error of 1/4 in. per 18 in. length of dowel has been considered acceptable. However, many state highway agencies do specify different permissible levels of misalignment. For example, the Illinois Department of Transportation specifies in the "Standard Specifications for Road and Bridge Construction," dated October 1979, that any deviation from correct alignment greater than 1/8 in. in 12 in. shall be corrected before any concrete is placed. Georgia Department of Transportation specifies an allowable tolerance of 3/8 in. per foot in both the horizontal and vertical directions.

*Numbers in raised parentheses refer to references at the end of the text.



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

Fig. 1 Effects of Dowel Misalignment

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 very slow process to determine levels of misalignment once the pavement is constructed. Attempts have been made to measure levels of misalignment 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 temperatures 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. Use analytical methods to perform stress analysis of the joint system incorporating dowels with different levels of misalignment
2. Conduct laboratory tests to determine the effect of dowel misalignment
3. Select placement tolerance criteria based on study results

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 assembly, 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 paver may displace individual dowels or the basket assembly
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
5. Field inspection during construction

For basket assemblies, basket rigidity and proper fastening of the basket assembly to the subbase is very 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.[10] However, degree of compliance with allowable dowel placement tolerances has been reported as being not satisfactory for any of these procedures.[10]

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 Fig. 1, excessive restraint to slab movement may result in transverse and corner cracking and spalling at the concrete face around the dowel. Example calculations of restraint that need 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 have been limited because of lack of practical methods for evaluating alignment of dowels in-place.

An early field study conducted in Indiana by Smith and Benham found a large number of misaligned dowels.[3] 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

TABLE 1 CALCULATED RESTRAINT TO CAUSE MIDSLAB CRACKING IN A 10-IN. THICK SLAB

Age (Days)	Tensile Strength, psi	Compressive Strength, psi	Concrete Modulus, million psi	Allowable Strain, millionth	Restraint to Cause Cracking, lb per foot width
1	87	700	1.5	58	10,400
3	184	1800	2.3	80	22,100
7	258	2750	2.9	89	31,000
28	333	3800	3.4	97	40,000
365	425	5250	4.2	102	51,000

<u>Notes</u>:

1. Before midslab cracking occurs, spalling may take place around load transfer device.
2. Tensile stress in the form of curling restraint stress and load stress also exist. Therefore, even a reduced level of restraint can contribute significantly to crack formation.
3. Age, strength, and modulus relationships are general and are used for illustration only.

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 3000 lb per dowel.

In another study, conducted by Segner, Jr. and Cobb at the University of Alabama, slab sections 5 ft wide, 5-1/2 ft long, and 10 in. thick were used.(4) 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 4000 lb and for a 1-in. horizontal misalignment of a dowel the load was about 2000 lb. Spalling was produced for a vertical misalignment of 1 in. or for horizontal misalignment of 3 in. at a joint opening of about 0.9 in.

Theoretical effects of misalignment have been studied by Friberg(5) and Weaver and Clark.(6) 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:(5)

$$\alpha i = \left[\frac{P}{2EI} \quad \frac{(1+Ba)^2}{B^3} + \frac{a^3}{6}\right]$$

where: α = misalignment of the dowel in the direction of slab movement, radians

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 $= \sqrt[4]{\frac{GD}{4EI}}$

G = modulus of dowel concrete reaction

D = dowel diameter

Using 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 using the equation are given in Table 2 for a one percent dowel misalignment and different levels of slab end movements. However, this analysis considers only dowel bearing effects and does not consider 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.

Recent investigations have concentrated on comparing misalignment levels and performance of joints having machine implanted dowels and pre-set basket assemblies.[7,8,9] These studies have been conducted because of concern about dowel placement accuracy using machine implanters. In the Pennsylvania study,[7] 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 tolerances. 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 were made at several sites in Alabama to compare joints with mechanically implanted and conventionally placed dowels.[8] 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,[9] misalignment levels were determined at several sites by uncovering dowels in freshly placed plastic concrete and by core drilling in hardened concrete. Based on findings, it was recommended that horizontal and vertical skew tolerances be 1/2 in., vertical tolerance be $\pm$ 1 in., and the longitudinal tolerance be $\pm$ 1-1/2 in.

TABLE 2 DOWEL SHEAR INDUCED DUE TO MISALIGNMENT OF 1 PERCENT (Ref. 5)

Dowel Diameter in.	Final Joint Width (a_j) in.	Dowel Shear Induced, lb	
		i=0.25 in.	i=0.50 in.
1.00	0.25 0.50	815 695	1630 1390
1.25	0.25 0.50	1235 1090	2465 2175

<u>Notes</u>: (1) "i" is the change in joint width due to slab end movement.

TABLE 3 LEVELS OF MISALIGNMENT MEASURED IN THE FIELD (Ref. 7)

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

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

In a study conducted during 1982 by the Georgia Department of Transportation, dowel bar placement was investigated at five highway projects.[10] 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 non-compliance 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.[10] In addition, it was reported that during construction of the five projects all joints had started "working" within few days of construction. However, because of the non-compliance problem with implanted dowels, the study recommended that implanting of dowels should 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 MODELLING

Analytical modelling 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
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 modelling the slip between the dowel and concrete. Recently, the finite element method has been used to model slippage at joints in rock masses. However, this area of modelling is still under development.

Initial modelling of a misaligned dowel was conducted 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 modelled

TABLE 4 PROJECT DESCRIPTION (REF. 10)

Project	Project Number	Location	Age	Dowel Placement Method
A	I-16-1(38)115 Ct 3 Bulloch County	SR 73 to SR 67 10.285 miles	5 yrs.	Implanter
B	I-20-1(23)00 Ct 4 Carroll-Haralson	Alabama Line to US 27 11.585 miles	3 yrs.	Implanter
C	I-85-1(33)12 Ct 3 Troup County	SR 219 to Hines Rd. 8.538 miles	3 yrs.	Implanter
D	I-20-1(27)11 Ct 4 Carroll County	US 27 to SR 61 11.874 miles	3 yrs.	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 miles	3 mos.	Baskets

TABLE 5 PERCENT OF DOWELS OUT OF SPECIFICATION TOLERANCE (REF. 10)

Project	Dowel Installation	Depth(1)	Vertical Rotation(1)	Horizontal Rotation		Longitudinal Alignment	
				(1)	(2)	(1)	(2)
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

(1)Core measurements; (2)Metal detector measurements.

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

using "soft" elements at the interface between the dowel and concrete. After work started using the SAP4 program, another finite element computer program was made available. This computer program, denoted BMINES, 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 modelling the three-dimensional nature of the problem.

Summary of Analytical Modeling

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

The effect of dowel misalignment was then investigated in the laboratory. The laboratory testing program and text 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 pull-out 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 pull-out direction remained perpendicular to the joint during the test. Pull-out loads measured during these tests were relatively low. Because of a concern that the low measured loads could be due to possible 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 procedure, a pair of two misaligned dowels was used.

Test with a Single Misaligned Dowel

The test setup is shown in Fig. 2. The test frame was constructed using channel-shaped steel members. One section of the test specimen was held firmly to the rigid frame. The other section of the test specimen was pulled using a hydraulic jack. Dowel misaligned 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 Fig. 3(a). 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 using load cells installed between the rollers and the test frame. During the test, joint opening was monitored using a pair of displacement sensors mounted on the slab surface, as shown in Fig. 3(b). A data acquisition system was used to record joint opening and load cell data.

Pull-out load was applied gradually and uniformly to obtain a joint opening of 0.25 in. in about 1 minute.

A total of sixteen specimens were tested using the described test procedure. Specimen details and test results are given in Table 6. Typical relationship

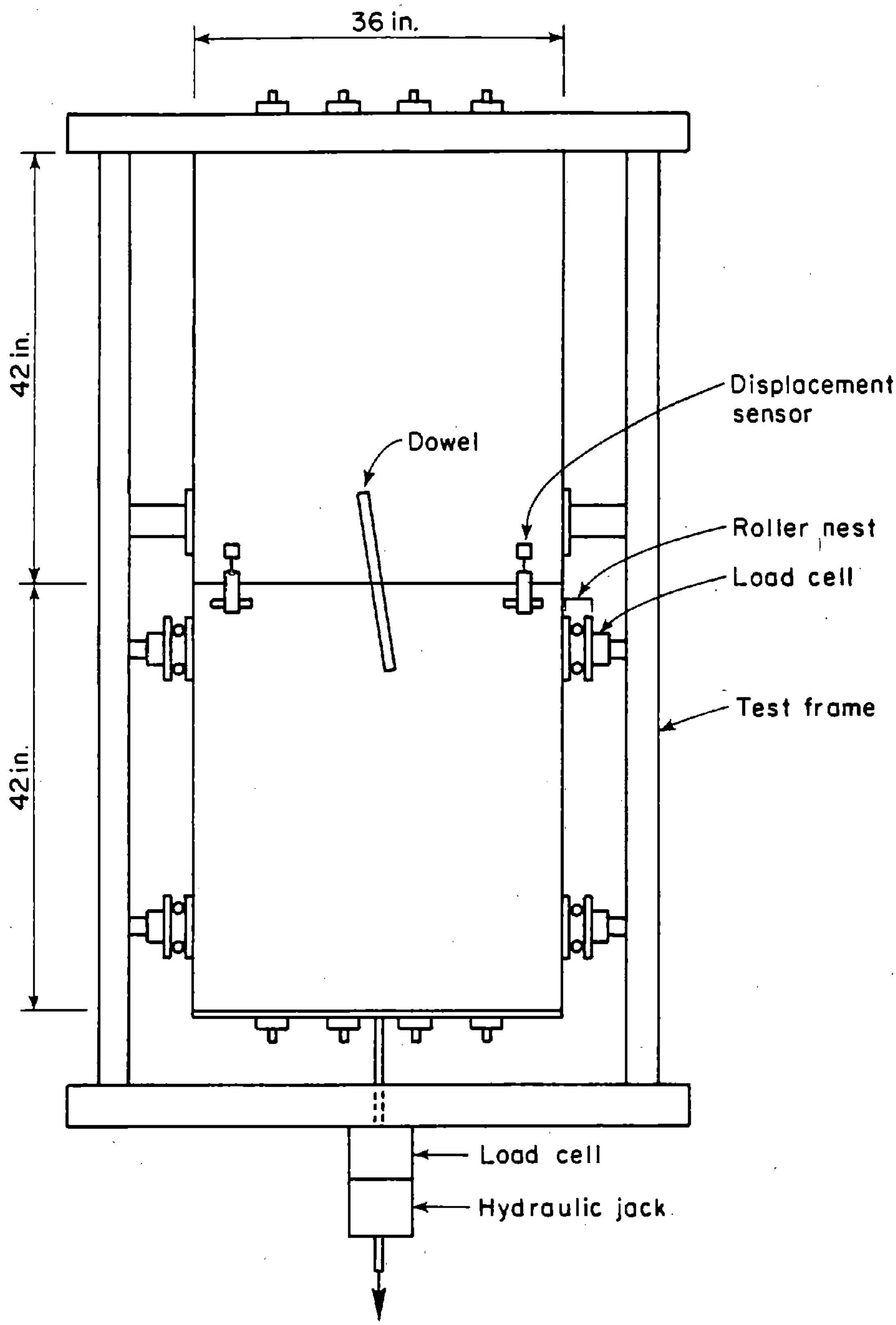
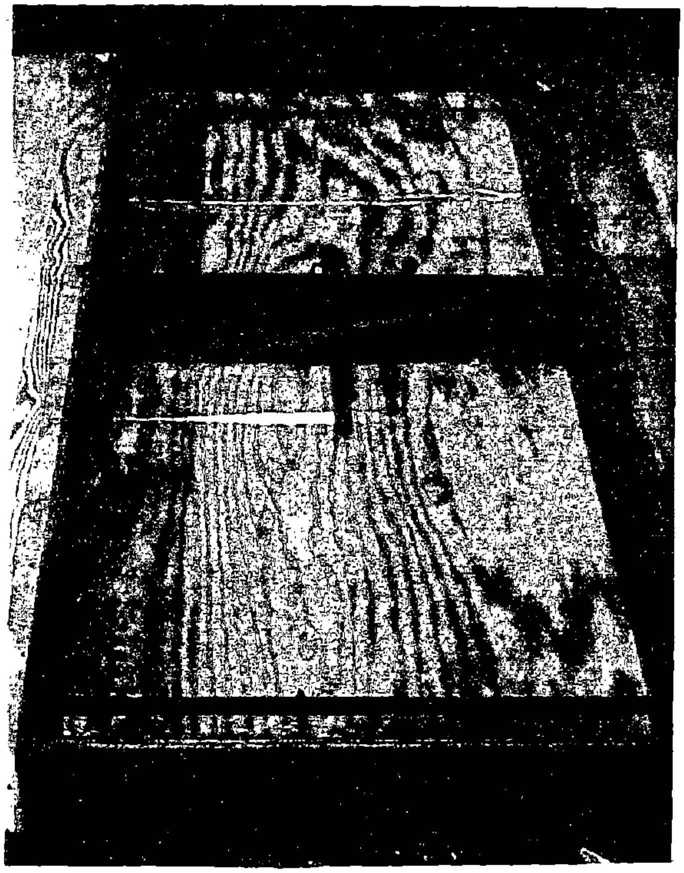
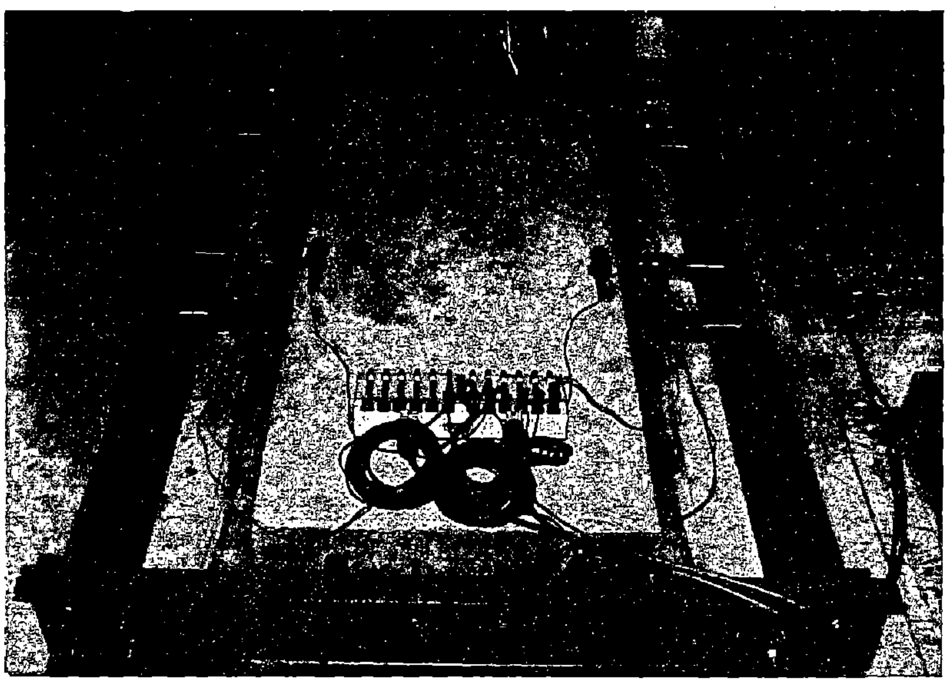


Fig. 2 Setup for the Single-Dowel Test



(a) Form



(b) Specimen Ready for Testing

Fig. 3 View of Test Setup (Single Dowel Test)

TABLE 6 TEST DETAILS AND RESULTS

Test Series	Misalignment, in.	Maximum Pull-Out Load, lb			
		1 day Test	3 day Test	7 day Test	28 day Test
A	0 Hori.	1030	840	1020	1640
B	1/4 Hori.	890	670	980	2000
C	1/2 Hori.	1160	1270	1410	1890
D	1 Hori.	1460	1280	1020	NA

Notes: 1) NA - Not available
2) Slab thickness = 8 in.
3) Maximum joint opening = 0.25 in.
4) Concrete compressive strengths were as follows:

Test Series	Age,days	Compressive Strength, psi
A, C	1	1960
	3	2990
	7	3810
	28	5100
B, D	1	1490
	3	2970
	7	4040
	28	5420

Maximum aggregate size = 1 in.

between the pull-out load and joint opening are shown in Fig. 4. It is seen that a large portion of the pull-out 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 pull-out load.

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

Test results do not show significant differences in the pull-out load for the different levels of misalignment. There was a 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.

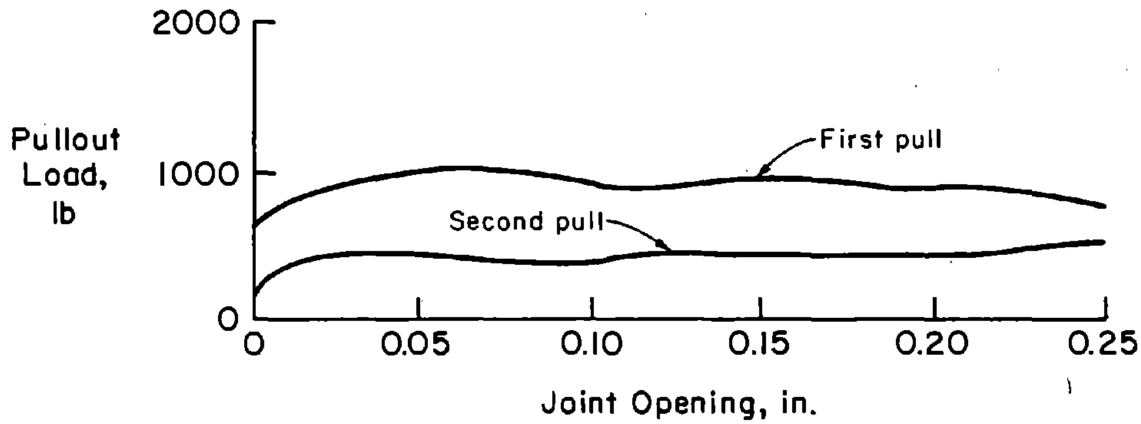
A new test procedure was then developed for the pull-out test. This procedure, using a pair of misaligned dowels, is discussed next.

Test with a Pair of Misaligned Dowels

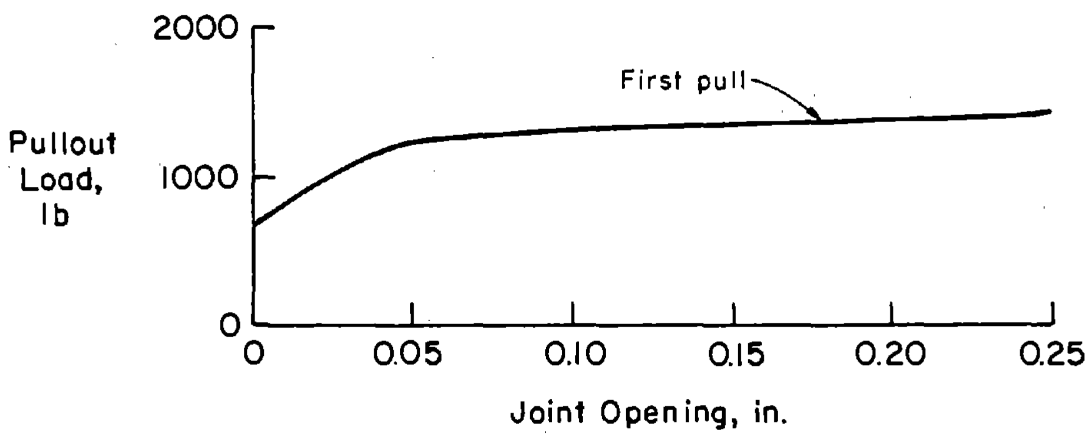
The test setup for a pair of misaligned dowels is shown in Fig. 5. The test frame was the same as used for the single dowel tests. However, use of the rollers along the sides of the specimen was discontinued and the specimen length was shortened to 4 ft. For this procedure also, one slab section was 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 was used to form the joint. A form ready for casting is shown in Fig. 6. 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 using a displacement sensor mounted on the slab surface. An X-Y plotter was used to record the pull-out 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 minute.



(a) Dowel Properly Aligned - Tested at 1 Day



(b) Dowel with Horizontal Misalignment of 1 in. - Tested at 1 Day

Fig. 4 Relationship Between Pull-Out Load and Joint Opening

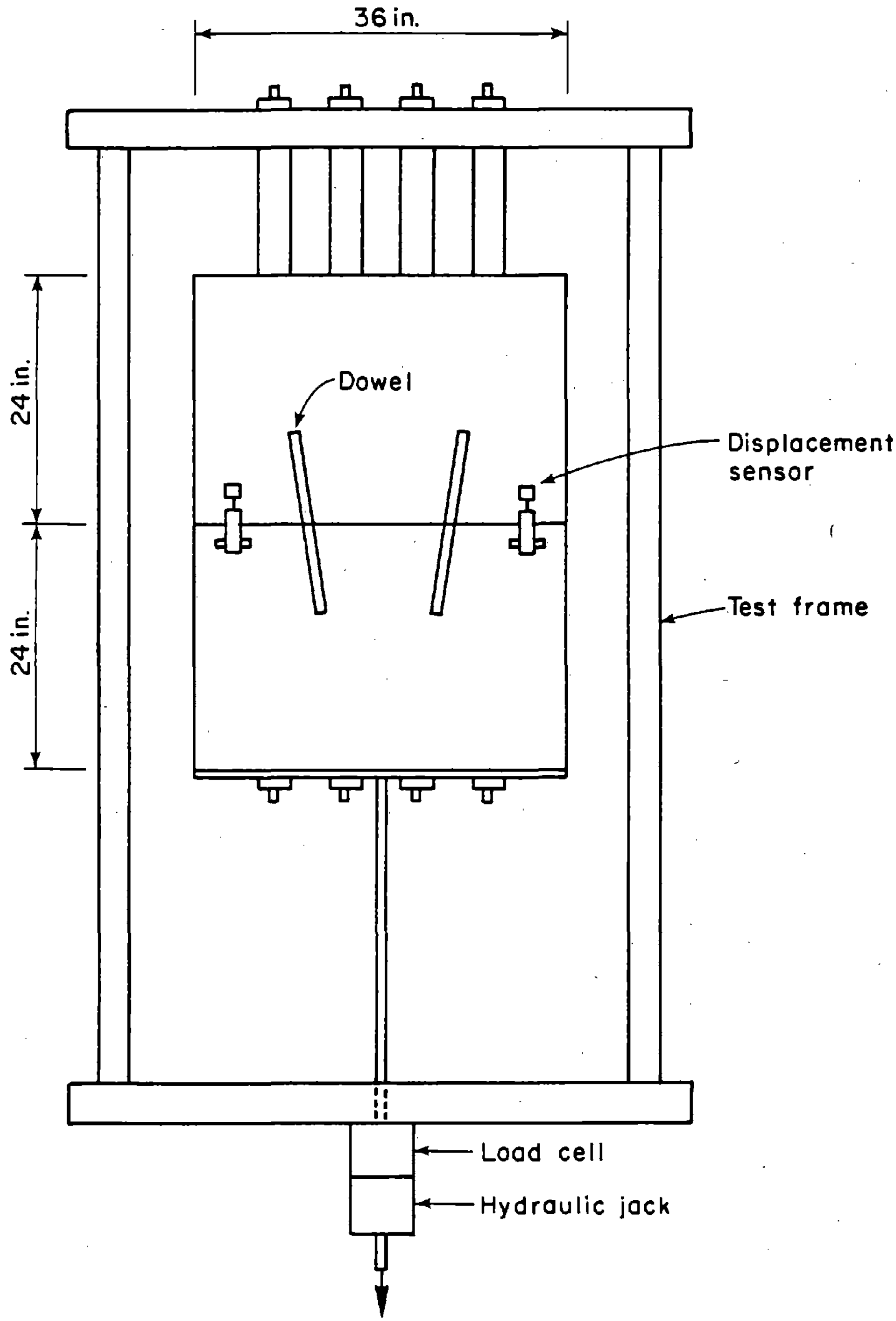


Fig. 5 Setup for the Two-Dowel Test

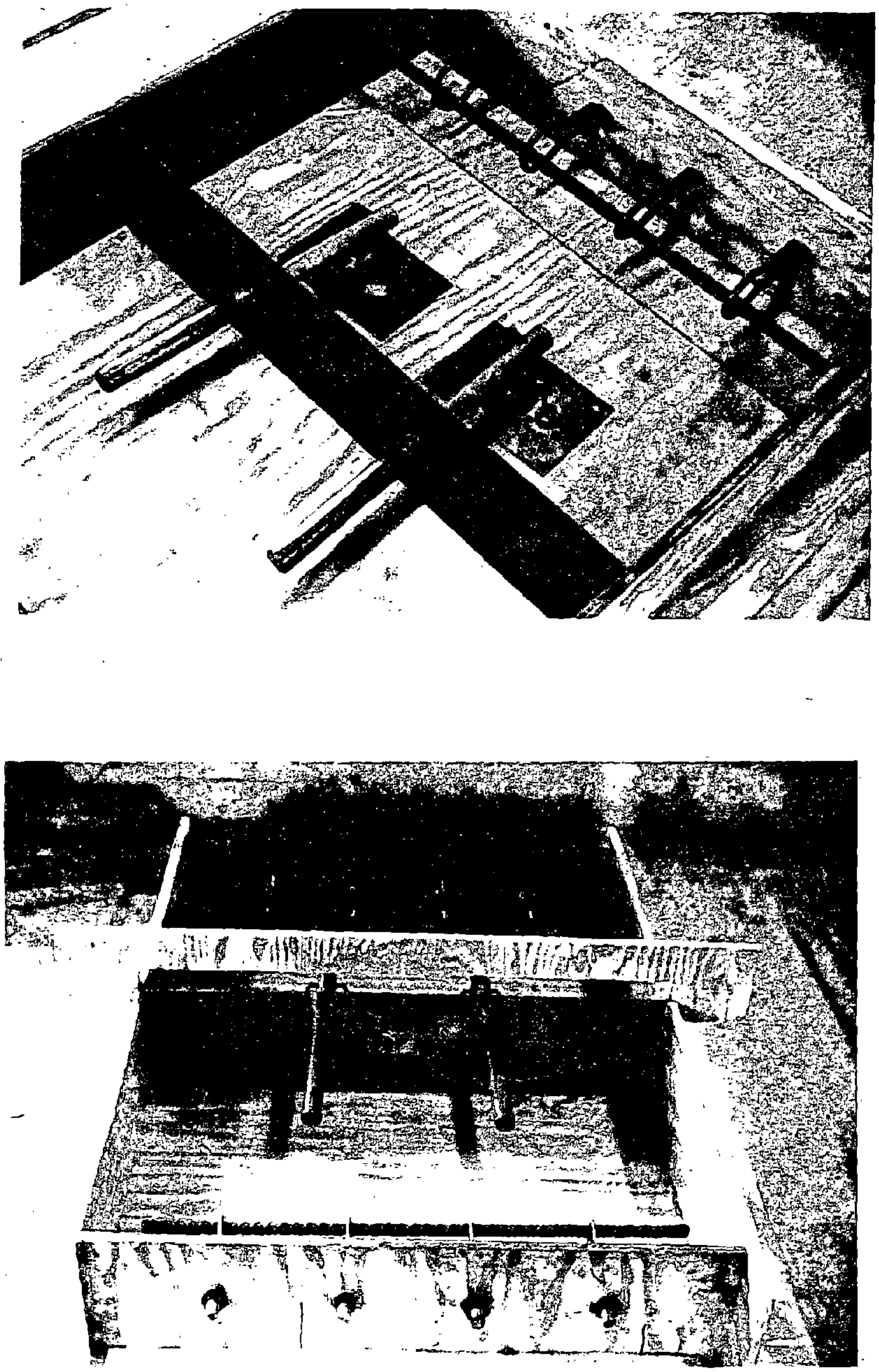


Fig. 6 Views of Test Setup (Two-Dowel Test)

A total of thirty three specimens were tested. Twenty four of the specimens had a slab thickness of 8 in. and the remaining nine specimens 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.

It is seen from Table 7 that although there is an increase in the pull-out load with increased level of dowel misalignment, the absolute magnitudes of the pull-out load are still relatively low for dowel misalignment levels below 1 in. As seen from Table 8, the magnitude of the pull-out 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 pull out 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 noted 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 results of tests conducted using a single misaligned dowel per specimen. The similarities in the results of tests using the two different procedures confirm the reliability of the low levels of the pull-out loads measured for dowel misalignment of 1 in. or less.

Discussion of Test Results

Laboratory test results indicate that pull-out loads are relatively low for dowel misalignment levels of less than 1 in. per 18 in. length of dowel bars 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 opening 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[(3)] and by Segner, Jr. and Cobb[(4)] 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 pull-out load required to open a joint 1/2 in. did not exceed 3000 lb per misaligned dowel. Segner, Jr. and Cobb's laboratory work indicated that a pull-out load of about 2000 lb was needed to open a joint 1/2 in. when a dowel

TABLE 7 TEST DETAILS AND RESULTS
(Using 2 Dowels per Specimen)

Test Series	Misalignment, in. (Total per dowel)	Maximum Pull-Out Load/Dowel, lb		
		1 day Test	3 day Test	7 day Test
E	0 Hori.	600	700	850
F	1/4 Hori.	650	750	NA
G	1/2 Hori.	800	900	1100
H	1 Hori.	900	1250	1250
I	0 Vert.	600	800	850
J	1/4 Vert.	750	1250	1350
K	1/2 Vert.	1150	1300	1750
L	1 Vert.	1400	1600	1750

Notes: 1) Slab thickness = 8 in.
2) Maximum joint opening = 0.25 in.
3) Concrete compressive strengths were as follows:

Test Series	Age, days	Compressive Strength, psi
E,F,G,H	1	1640
	3	2640
	7	3530
	28	4940
I,J,K,L	1	1460
	3	2640
	7	3740
	28	5140

TABLE 8 TEST DETAILS AND RESULTS
(Using 2 Dowels per Specimen)

Test Series	Misalignment, in. (Total per dowel)	7-day Maximum Pull-Out Load/Dowel, lb
M	0	750
N	1/2 Hori.	2250
O	1 Hori.	2000
P	2 Hori.	4000
Q	4 Hori.	5500
R	1/2 Vert.	1666
S	1 Vert.	2000
T	2 Vert.	(R)
U	4 Vert.	(R)

Notes:
1) Slab thickness = 10 in.
2) Maximum joint opening = 0.25 in. except for Test Series Q for which maximum joint opening was 0.20 in.
3) R = rejected due to excessive twisting of the test panels
4) Concrete compressive strengths were as follows:

Age, days	Compressive Strength, psi
8	4070
28	5050

had a horizontal misalignment of 1 in. per 16 in. length of the dowels and that pull-out load was about 4000 lb for a vertical dowel misalignment of 1 in.

Vertical and horizontal misalignment levels of 1/4 in. per 18 in. length of a dowel bar have been considered acceptable in the past by many state highway agencies. There was relatively low difference in measured pull-out loads between specimens incorporating a 1/4 in. misalignment and specimens incorporating a 1/2 in. misalignment.

However, because of the limited number of tests that were conducted and because the tests did not consider the effects of multiple misaligned dowels at a joint, it is recommended that the tolerances of 1/4 in. per 18 in. length of dowel bars specified currently by many state agencies be continued for use at future construction projects.

It is also 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 are required to determine if revisions to the current dowel misalignment specifications are needed.

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 using finite element computer programs SAP4 and BMINES. Because of the complexity of modelling 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 pull-out 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 due to the limited amount of laboratory test data and lack of sufficient data on field performance of jointed concrete pavements with misaligned dowels.

ACKNOWLEDGMENTS

Work was conducted by the Construction Technology Laboratories under direction of W. G. Corley, Director, Engineering Development and B. E. Colley, Director, Transportation Development Department. Paul Teng, Richard McComb, and W. George Ring of Federal Highway Administration provided technical coordination. Their cooperation and suggestions are gratefully acknowledged.

The opinions and findings expressed or implied in the paper are those of the author. They are not necessarily those of the Federal Highway Administration.

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APPENDIX A

SUMMARY OF STATE PRACTICES

ON DOWEL USAGE

Source: "A Chartered Summary of Concrete Highway Pavement Practices in the United States - 1982," Publication IS201, Portland Cement Association, 1982.

State	Longitudinal Joints											Transverse Joints	
	Construction Joints			Centerline					Tiebars			Contraction Joints Spacing, ft	
				Type			Dimensions		Diam.	Length	Spacing		
	Keyed	Butt	Tied	Sawed	Formed	Insert	Width, in.	Depth, in.	in.	in.	in.	PC	PD
Ala.	-	✓	✓	✓	-	✓ (1)	3/8	D/3	5/8	30	30	20	20
Ariz.		✓	✓	✓		✓	1/8 initial 1/2 seal	D/4 initial 1 seal	1/2	24	30	13-15-17	-
Ark.	✓	-	✓	✓	-	-	1/8-3/8	D/4	1/2	48 RD 30 CRC	30	-	15
Calif.	-	✓	-	✓	-	-	≤ 0.02	D/4	-	-	-	12-15-13-14	-
Colo.	✓	-	✓	✓	-	✓	1/4	D/4 + 1/2	1/2-5/8	24	30	12-18-19-13	-
Conn.	✓	✓	✓	✓	✓	✓	1/4	D/3	1/2-5/8 RD 1 - CRC	30 36	30 18	-	-
Del.	-	✓	✓	✓	-	-	1/4 1/8	D/4 + 1/4 2-1/2	5/8 1/2	48 30	40 24	-	-
D.C.	✓	-	✓	✓	✓	-	1/8, 1/4	D/5, D/4	1/2	30	30-60	15 (2)	20 (2)
Fla.	✓	-	✓	✓	✓	-	1/8	D/4	1/2	24	30	15	15-18
Ga.	-	-	✓	✓	-	-	1/4	D/4	1/2	30	30	-	20
Hawaii	-	-	-	-	-	✓	NR	2	5/8	30	30	13-19-18-12	-
Idaho	-	✓	✓	(3)	-	✓	3/8, 0.01	D/4 & 1/2	1/2	30	30	13-16-17-14	-
Ill.	✓	-	✓	✓	-	NP	1/8 min.	D/3	1/2, 5/8	30	30	-	-
Ind.	✓	-	✓	✓	✓	-	1/8-3/8	D/3	5/8	36	36	20 13-19-18-12	
Iowa	✓	-	✓	✓	-	-	1/8	D/4	1/2	36	30	20 (4)	20 (4)
Kan.	✓	-	✓	✓	-	✓	1/4 RD 3/8 PC	2-1/2	1/2	24	30	15	-
Ky.	✓	-	✓	✓	-	NP	1/8-1/4	D/4 + 1/4	1/2	30	30	-	12-13-17-18
La.		✓	✓		✓	✓	7/16	3	1/2	24	24	-	20
Maine	-	✓	✓	✓	-	-	1/4	D/4 + 1/2	5/8	30	30	-	20
Md.	✓	-	✓	-	-	-	1/4	D/4 + 1/2	5/8	30	36-9 in. 30-10 in.	-	-
Mich.	-	✓	✓	✓	-	-	1/8 initial 1/4 final	3 initial 1 final	5/8	24	(5)	-	-
Minn.	(6)	(6)	(6)	✓	-	-	1/8	(7)	(8)	(8)	30	15.5 eff.	15.5 eff.
Miss.	(9)	(10)	✓	-	-	✓	0.008	D/3	1/2	30	36	-	-
Mo.	✓	-	✓	✓	-	-	1/8	D/4	5/8	30	30	-	30
Mont.	✓	-	-	✓	-	✓	1/4-3/8	2	1/2	36	30	13-19-18-12	-
Neb.	✓	-	✓	✓	-	-	1/8	D/4	5/8	30	48	12-13-18-19	-
Nev.		✓	✓	✓			1/4	2	1/2	22	30	9-10-14-13 (proposed)	-
N.J.	✓	-	✓	✓	✓	-	(11)	(11)	(12)	(12)	(12)	-	-
N.M.	-	-	✓	✓	-	-	1/2	D/3	1/2	30	30	Variable	-
N.Y.	✓	-	✓	✓	✓	-	(13)	(13)	5/8	15	40	-	20
N.C.	-	✓	✓	Opt.	-	Opt.	1/4	D/4 + 1/4	5/8	30	30	13-15-17	18-19-23-25
N.D.	✓	✓	✓	✓	-	✓	1/8-1/4	D/4 + 1/4	5/8	30	48	14-18	-
Ohio	-	-	✓	✓	✓	-	1/8	D/3	5/8	30	30	17	20
Okla.	✓	-	✓	✓	-	✓	3/8	D/4	1/2	30	30	15	-
Ore.	-	-	✓	✓	-	-	1/4	2	5/8	30	36	-	-
Pa.	✓	-	✓	✓	-	-	3/16	D/3	(14)	30	30	15	20 (15)
S.C.	-	✓	✓	✓	-	✓	3/16, 0.02	D/4 + 1/2	1/2	30	30	-	19-25-24-18
S.D.	✓	-	✓	✓	-	-	1/8	D/4	5/8	30	48	15	-
Tenn.	✓	-	✓	(16)	-	(16)	1/4, 0.01	D/4	1/2	24	30	-	(17)
Texas	-	✓	✓	✓	-	✓	1/4-3/8	D/4	1/2	30	24-30	-	15
Utah	✓	-	✓	✓	-	-	1/4	D/3	5/8	30	30	13-18-17-12	-
Va.	-	✓	✓	✓	-	✓	1/8, 0.01	D/3, 2-1/2	5/8	30	40	20	-
Wash.	-	✓	(18)	✓	-	✓	1/8-1/4	D/4 + 1/2	1/2	24	36	10-14-13-9	-
W. Va.	✓	-	✓	✓	-	NP	1/4	D/3	5/8 (19)	30	30	-	-
Wis.	-	✓	✓	✓	-	-	1/8-1/4	1-1/2, 2, 2-1/2	1/2	24	24, 30, 36	13-19-18-12	-
Wyo.	✓		✓	✓		✓	3/8	D/3	1/2	24	30	14-16-13-12	

Transverse Joints

State	Contraction Joints: Spacing, ft. RO	Type: Skewed	Type: Sawed	Type: Formed	Type: Insert	Dimensions: Width, in.	Dimensions: Depth, in.	Dowels: Diam, in.	Dowels: Length, in.	Dowels: Spacing, in.	Construction Joints: Keyed	Construction Joints: Butt	Construction Joints: Tied	Construction Joints: Doweled
Ala.	-	-	✓	-	-	3/8	0/3	0/8	18	12	-	✓	-	✓
Ariz.	-	✓	✓	-	-	1/8	2	-	-	-		✓		✓
Ark.	45	-	✓	-	-	3/8-1/2 PO 5/8-3/4 RO	0/3	1	18	15	-	✓	(1)	-
Calif.	-	✓	✓	-	✓	0.013-0.02	0/4	-	-	-	✓		✓	
Colo.	-	✓	✓	-	✓	1/4	0/4 + 1/2	-	-	-	✓	-	✓	-
Conn.	40	-	✓	-	-	3/8	0/3	0/8 1-1/2 I-Bm	16 18	12 12	✓	✓	(1)	✓
Del.	45	-	✓	-	-	5/8	0/4 + 1/4	1-1/4	18	12	-	✓	-	✓
D.C.	40	-	✓	✓	-	1/4-3/8	0/5 - 0/4	(2)	(2)	12	(3)	(3)	(3)	-
Fla.	-	✓	✓	-	-	1/4	0/4	1-1/4	18	12	✓	-	-	✓
Ga.	-	-	✓	-	-	3/8-1/2	0/3.6	0/8	18	12	-	✓	(1)	✓
Hawaii	-	✓	✓	-	-	1/4	2-1/2	-	-	-	-	✓	-	✓
Idaho	-	✓	✓	-	(4)	3/8, 0.02	0/4	-	-	-	✓	-	✓	-
Ill.	50	-	✓	-	-	5/8	2-1/4	1-1/4	18	12	-	✓	(1)	-
Ind.	40	✓	✓	✓	-	(5)	0/4	1-1/4	18	12	-	-	(1)	-
Iowa	-	✓	✓	-	-	1/8	0/4	1-1/4	18	12	-	✓	(1)	✓
Kansas	30	✓	✓	-	✓	3/8	2-1/4 RO 2-1/2 PC	1-1/4	18	12	-	-	✓	-
Ky.	25, 50	✓	✓	NP	NP	3/8	2	0/8	18	12	✓	-	✓	-
La.		E		✓	✓	7/16	3 ± 1/4	1-1/8	18	12		✓		✓
Maine	-	-	✓	-	-	1/8 initial 1/2 final	0/4 init. 1/2 final	0/8 rnd. 1 x 1-1/2 I-Bm	16	12	-	✓	-	✓
Md.	40	-	✓	-	-	3/16	0/4	1-1/4	18	12	✓	-	(1)	✓
Mich.	41	-	✓	-	-	1/2	2-1/2	1-1/4	18	12	-	-	(1)	✓
Minn.	27	✓	✓	-	-	1/8 plus reservoir	0/4 1-5/8 min.	1 for 8, 9 1-1/4 for 10	15	12	✓	-	✓	-
Miss.	-	-	-	-	-	-	-	-	-	-	-	✓	(1)	-
Mo.	61.5	-	✓	-	-	3/8	0/4	1-1/4 RO 1 PO	18	12	✓	-	✓	-
Mont.	-	✓	✓	-	-	1/4-3/8	0/4	1	18	12	✓	-	-	✓
Neb.	46.5	✓	✓	-	-	(6)	(6)	1 for 8 1-1/4 for 9, 10	18	12	-	✓	(1)	✓
Nev.	-	✓	✓	-	-	3/8	0/4	-	-	-	✓	-	✓	-
N.J.	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N.M.	-	✓	✓	-	-	1/4	0/4	1	18	18	✓	✓	-	-
N.Y.	63	-	✓	-	-	(7)	(7)	1 rnd. 1 x 1-1/2 I-Bm	18	12	-	✓	-	-
N.C.	-	-	✓	-	-	3/8	0/4 + 1/4	1-1/4	18	12	-	✓	-	✓
N.D.	-	-	✓	✓	✓	7/32 - 1/4	0/4	1-1/4	18	12	✓	✓	(1)	-
Ohio	40	✓	✓	-	-	1/4	0/5	1-1/4	18	12	-	✓	-	✓
Okla.	-	-	✓	-	-	3/8	0/4	1-1/4	18	12	-	✓	(1)	✓
Ore.	-	-	-	-	-	-	-	-	-	-	-	✓	(1)	-
Pa.	40	-	✓	-	-	(8)	0/4	1-1/4 - 10 - 1-1/2 - 11 +	18	12	-	✓	(1)	✓
S.C.	-	-	✓	-	-	1/8 initial 3/8-1/2 final	0/4	1-1/4	18	12	-	✓	-	✓
S.D.	-	✓	✓	-	-	3/8	0/4	-	-	-	-	-	✓	-
Tenn.	-	✓	(9)	-	(9)	3/8	0/4	1-1/4	15	12	-	✓	-	✓
Texas	30	-	✓	✓	✓	3/8	0/4	1-1/4	18-22	12	-	✓	(1)	✓
Utah	-	✓	✓	-	-	3/8	0/3	-	-	-	-	✓	✓	-
Va.	40	-	✓	✓	-	5/8	0/4 + 1/4	1-1/4	18	12	-	✓	(1)	✓
Wash.	-	✓	✓	-	-	1/8-1/4	2-1/4	-	-	-	-	✓	-	✓
W. Va.	40	-	✓	-	-	(10)	(10)	1-1/4	18	12	-	✓	-	✓
Wis.	40	✓	✓	-	-	1/4, 3/8	0/4	1, 1-1/4	18	12	-	✓	✓	-
Wyo.		✓	✓			3/8	0/4	-	-	-	✓		✓	

ABBREVIATIONS

CRC	- Continuously reinforced concrete pavement
D	- Slab thickness
Longit.	- Longitudinal
NP	- Not permitted
Opt.	- Optional
PC	- Plain concrete pavement
PCC	- Portland cement concrete
PD	- Plain concrete pavement with dowels
RD	- Mesh-dowel pavement

Notation for Page 28

(1) 20-mil-plastic strip.

(2) PCC base.

(3) Transverse must be plastic strip if longitudinal is sawed.

(4) Skewed joints at 15-ft spacing used in some PC and PD projects--not a standard practice at this time.

(5) Varies with number of lanes tied.

(6) Keyed if tied, butt if not tied, only two lanes tied.

(7) 2-1/4-in.-deep for 7- to 7-1/2-in. thick pavement; 1/4 in. deeper for each additional inch of thickness.

(8) 1/2x30-in. tiebars for less than 8-in. pavement; 5/8x30 in. for 8 to 9 in.; 5/8x36 in. for 10-in. thickness.

(9) With conventional forms.

(10) With slipform construction.

(11) Sawed: 1/8 to 1/4 in. wide by 2-3/4 in. deep, formed: 1/4 in. wide by 7/8 in. deep.

(12) Sawed: 5/8x36 at 48 in. formed: 11/16 to 3/4 in. x 16 at 60 in.

(13) Poured sealant: 3/8x7/8 in.; compression seal: 5/16 or 3/8 by depth of sealant plus 1/4 in.

(14) 1/2 for 6- to 9-in. depth, 5/8 for 10- to 13-in. depth.

(15) On ramps and some primary routes.

(16) Sawed at 25-ft spacing for crshd. stone CA; plastic inserts at 18-ft spacing for grav. CA.

(17) With limestone CA 19-25-18; with grav. CA 13-18-17-12.

(18) Tiebars not required on AT base.

(19) Standard hook bolts or J-bars are optional to tiebars.

Notation for Page 29

(1) Add extra longitudinal steel for CRC.

(2) 1-1/8-in. by 16-in. dowels for IS; 1 in. by 14 in. for primary highways; 1-1/4 in. by 18 in. for PC base pavement.

(3) Emergency only.

(4) Transverse must be plastic strip if longitudinal is sawed.

(5) 1/4- to 3/8-in. width for top 1-in. depth; 1/8 in. min. for remaining joint depth.

(6) D/4 with 3/8-in.-wide by 1/2-in.-deep reservoir for PC; D/4 with 9/16- by 1-7/8-in. widened top for 13/16-in. compression seal.

(7) Poured sealant 3/8 by 1-1/4 in.; compression seal 5/8 by 2 in.

(8) Varies: 1/2 to 3/4 in. with sawed joints at 40-ft spacing with compression seals; 1/2 in. for 20-ft PD design and poured sealant.

(9) Sawed at 25-ft spacing for crshd. stone CA: plastic inserts at 18-ft spacing for gravel CA.

(10) Initial sawcut 1/4 by D/4, final sealant reservoir 5/8 wide by 5/8 to D/4 deep, depending on sealant type.