Improved Rigid Pavement Joints

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A computerized finite-element analysis procedure for jointed concrete pavement is presented. In this finite-element analysis procedure, joints can be modeled as doweled, aggregate interlock, or keyed. The procedure can be used to evaluate the effect of joints with nonuniformly spaced load-transfer devices. Examples are presented to illustrate capabilities of the analytic procedure. Maximum dowel shear is obtained when a tandem-axle load is positioned at a corner. Maximum dowel shear magnitude is about 2,700 lb for the outermost dowel for a 36,000-lb tandem-axle load. Analysis of joints with nonuniformly spaced dowels indicates that use of 6 dowels/joint/lane would provide response at the joint comparable to that provided by 12 uniformly spaced dowels. In addition to considerable cost savings, use of fewer dowels per joint can result in less restraint due to possible misaligned dowels and frozen dowels. Analysis results also show that tied concrete shoulders reduce pavement deflections, pavement stresses, and dowel shears. These reductions can be expected to improve pavement performance significantly by minimizing joint faulting, subbase and subgrade erosion, and corner breaks.

Joints are provided in concrete pavements to control transverse and longitudinal cracking that occurs due to restrained deformations caused by moisture and temperature variations in the slab. The use of joints reduces the load-carrying capacity of the pavement at the joint. Therefore, joint design must consider methods to maintain adequate structural integrity at the joint. A poor design often results in joint-related distress that affects pavement performance and ride.

Soon after the pavement is placed, drying shrinkage of the concrete begins. In addition, due to the heat of hydration, concrete generally sets at a temperature higher than ambient. Subsequent cooling results in a reduction in concrete volume. Early drying shrinkage and volume reduction of concrete are restrained by subgrade friction. If the restraint exceeds the concrete tensile strength, cracking occurs.

Subsequent concrete cracking may occur due to stresses caused by restrained curling and warping. These restraint stresses are a result of differences in temperature and moisture between the top and bottom of the slab. Curling refers to effects of temperature differential and warping refers to effects of moisture differential. In addition, traffic load stresses also affect the extent of cracking.

CURRENT PRACTICE

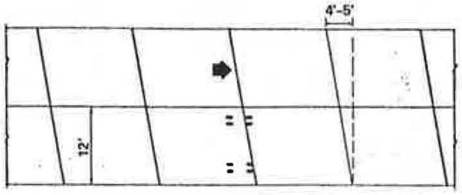
Over the years, two design approaches have been used for jointed concrete pavements. The first approach considers plain concrete pavements. Joint spacing is about 15 to 20 ft and no midslab cracking is expected to occur. In many instances, random joint spacing may be used. A representative random spacing pattern is 13, 19, 18, and 12 ft. Load-transfer devices may or may not be used at the joints.

The second approach considers jointed concrete pavements with distributed steel. Joint spacing in this case is generally about 27 to 60 ft. One or more cracks may be expected to occur in these slabs between joints. However, the distributed steel prevents the cracks from opening widely. For concrete pavements with distributed steel, load-transfer devices are always specified at joints. Figure 1 shows representative transverse contraction joint details. Contraction joints may be skewed counterclockwise about 4 to 5 ft in a width of 24 ft. Figure 2 shows longitudinal joint details.

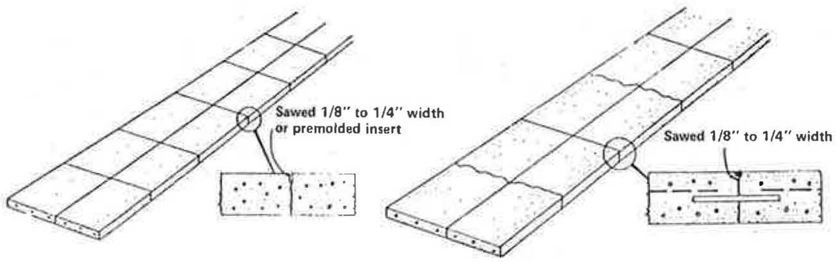
In the early days, expansion joints were often provided at regular intervals. Based on field experience and performance evaluations of experimental projects during the 1940s, expansion joints in concrete pavements are no longer specified except at fixed structures or intersections (1).

Current practice for load transfer at joints has evolved over a period of years. For transverse joints, aggregate interlock or dowel bars are generally used. For longitudinal joints, tie bars are used at centerline joints and a tied keyway is often used at the concrete shoulder joint. Aggregate interlock is generally depended on for load transfer at transverse joints in plain concrete pavements. Although many types of mechanical load-transfer systems have been tried, round steel dowel bars have proved to be the most widely used. Current practice for doweled joints requires dowel diameters to be one-eighth of slab thickness, dowel spacing to be 12 in., and dowel length to be 18 in. Coated dowels are used to provide resistance to corrosion. The

Figure 1. Transverse joints.



Skewed joints.



coating may be a zinc- or lead-based paint, epoxy, or plastic.

FHWA previously recommended dowel placement limits of ±1 in. on horizontal and vertical positioning and ±0.25 in./18-in. length on skew (2). The current FHWA technical advisory on rigid pavement joints (3) 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." This advisory also states that "care must be exercised in both specifying dowel placement tolerance and in evaluating the adequacy of construction placement."

FUNCTIONS OF JOINTS

As stated previously, joints are controlled crack locations that create areas of weakness if not designed properly. Proper transverse joint design for jointed concrete pavements requires provision of adequate load transfer, allowance for slab end movements, and selection of the proper joint sealant.

Load transfer across joints results in reduced loaded-slab deflections and stresses and reduced relative deflections between adjacent loaded and unloaded slabs. Slab deflections at the joint are greatly affected by loss of support along the joint due to upward warping and curling of the slab. If slab deflections are not reduced, they may result in joint-related distress such as pumping, faulting, and corner breaks. Slab deflections and problems associated with deflections can also be reduced by use of high-quality subbases.

Pavement slabs should be free to expand and contract with changes in slab temperature and moisture. Slab movement is restrained by subbase friction and locked (or frozen) dowels. For short slabs, resistance due to subbase friction is not so significant. The magnitude of restraint afforded by locked joints depends on the degree of misalignment and corrosion in the load-transfer device. Excessive restraint of slab movement may result in transverse cracking and spalling at the concrete face around the dowel. Calculations of the amount of restraint needed to cause midslab cracking are given in Table 1.

Figure 3 shows the finite-element representation of a doweled joint used to determine restraint stresses that can develop for a properly aligned but completely frozen dowel. Stresses were computed by using the SAP4 finite-element computer program (4). A temperature drop of 10°F was used. A maximum tensile stress of 3,115 psi developed under the dowel near the joint face. The restraint stress developed at midslab was 230 psi. This stress, together with curling and traffic load stresses, can result in midslab cracking. Restraint stress values would be higher for larger drops in temperature.

Figure 2. Longitudinal joints.

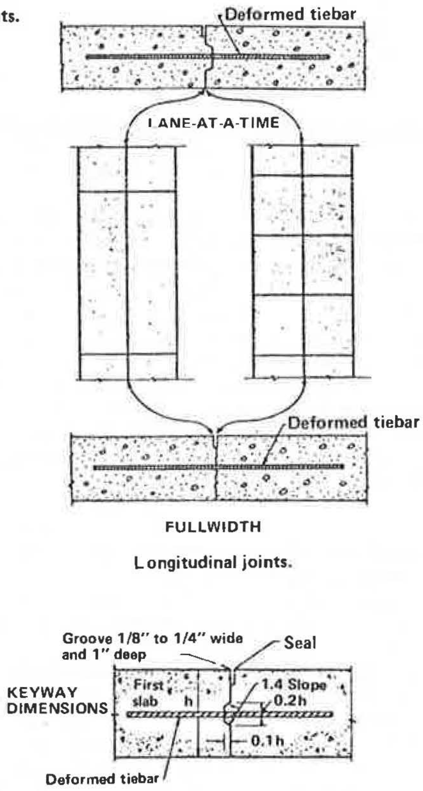


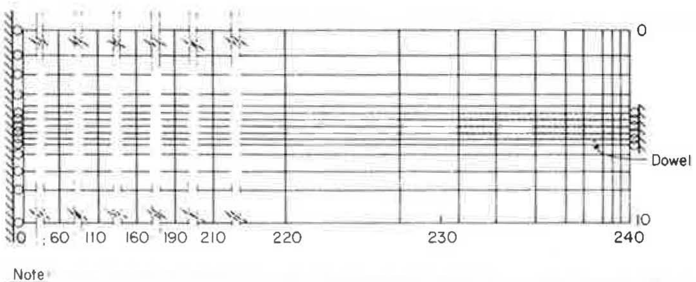
Table 1. Calculated restraint needed to cause midslab cracking.

Age (days)	Strength (psi) Tensile	Strength (psi) Compressive	Concrete Modulus (psi 000 000s)	Allowable Strain (millionth)	Restraint to Cause Cracking[a] (lb/12-in. length)
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: Age, strength, and modulus relations are general and are used for illustration only

[a] t = 10 in.

Figure 3. Finite-element representation for evaluating restraint stresses.



Note

All Dimensions in Inches

Axisymmetric Analysis Performed

It should be noted that spalling of concrete around a dowel is probably progressive. Spalling may be initiated by a smaller drop in temperature, especially when concrete has not attained sufficient strength.

Finally, to ensure good performance at joints, steps must be taken to prevent infiltration of water and incompressible material. This is done by use of poured or preformed sealants.

ANALYSIS OF JOINTS AND LOAD-TRANSFER DEVICES

Analysis and design procedures developed for jointed concrete pavements have basically been of two types: (a) analysis techniques for slabs on elastic foundation to evaluate the response of concrete pavements and (b) studies of individual joint systems. Recent efforts using finite-element analysis techniques have considered the entire jointed pavement system as a single entity.

The earliest works on doweled joint design were presented by Westergaard in 1928 and by Bradbury in 1932. Westergaard (5) presented a procedure for evaluating shear force in dowels and determining dowel spacing. Bradbury (6) presented an analysis of an infinitely long beam resting on an elastic medium. This analysis was used for selection of dowel diameter, length, and spacing. Bradbury presented criteria for working stresses in dowel bars as well as for concrete bearing stresses.

During the 1930s, the Bureau of Public Roads conducted extensive tests of concrete pavements (7). As part of this program, doweled joints with 0.75-in.-diameter, 3-ft-long dowels were tested. Joint widths of 0, 0.5, and 0.75 in. and dowel spacings of 18, 27, and 36 in. were used. The effectiveness of joints in transferring load was determined.

During 1938 Friberg (8,9) presented results of his studies on doweled transverse joints. The analysis of an infinitely long beam resting on an elastic medium was used to simulate dowel embedment in concrete. Expressions were developed for dowel deflection at a joint face and for the relative deflection of joints with dowels. Friberg also presented a discussion of allowable concrete bearing stresses and the effect of dowel misalignment and slab tilt. In 1940 Kushing and Fremont (10) presented a theoretical basis for evaluation of load transfer across a joint.

In 1951 Marcus (11) presented the results of a study conducted to determine the load-carrying capacity of dowels. Tests were conducted on dowels embedded in concrete blocks. Measured bearing stresses ranged from about 6,000 to about 10,000 psi for a 12-in.-deep block. Values of allowable dowel loads were presented for different dowel sizes, embedment lengths, load eccentricities, and depths of concrete below dowels.

American Concrete Institute Committee 325 published a 1956 report on structural design considerations for pavement joints (12). In the report previous studies were used to recommend minimum dowel requirements for expansion and contraction joints.

In 1958 Teller and Cashell (13) reported the results of extensive laboratory studies conducted to evaluate the performance of doweled joints under repetitive loading. Concrete slab sections were tested by applying repeated loads alternately on each side of the joint. The variables investigated were dowel diameter, dowel embedment, joint opening, and slab thickness. Based on study results, it was recommended that the minimum dowel size should approximately equal one-eighth the slab thickness, that embedment lengths of six diameters were adequate for dowels 1 in. and larger, and that narrow contraction joints performed better than expansion joints.

Several investigations have been conducted by the U.S. Army Corps of Engineers to evaluate the performance of keyed longitudinal joints for airport pavements. Generally, it has been found that, for heavy aircraft loading, keyed joints do not perform well. However, for highway-type loading keyed joints perform satisfactorily.

A doweled joint design procedure was developed for U.S. Steel Corporation by using a method of simultaneous equations to solve for dowel loads (14). The design procedure uses allowable bearing stress on concrete, allowable bending and shear stresses in dowels, and maximum ratio of corner to free edge deflection as design criteria.

A recent investigation, conducted at the University of Illinois, evaluated joint behavior for airport pavements (15). A finite-element program was developed to analyze slab-joint systems. An analysis of joint systems was conducted by using finite-element programs developed by others. These include the SAP program (4) and a program developed by the Naval Civil Engineering Laboratory (16). Another recent study conducted by the U.S. Army Engineer Waterways Experiment Station resulted in development of finite-element analysis programs for jointed slabs (17).

REQUIREMENTS FOR JOINT ANALYSIS

An ideal analysis of jointed concrete pavements should be capable of providing sufficient information regarding load transfer along the joint. If dowels are used, analysis results should include dowel shear and moment for each dowel. For aggregate interlock and keyway joints, load transferred per unit width should be calculated. These results can then be used to determine whether the performance of the joint will be satisfactory during the design life of the pavement. For example, if dowel shear is high or if load transferred per unit width for keyed joint is high, then relative deflections across the joint may increase with time and a poorly performing joint may result.

A joint creates a discontinuity in the pavement. This results in a weaker zone adjacent to the joint. For concrete pavements, a free edge is always a critical region. When the load is placed at an edge, stresses and deflections are always higher than when the load is placed in the interior portion of the slab. Therefore, for design purposes, an edge is usually selected as the critical load position.

FINITE-ELEMENT ANALYSIS OF JOINTED CONCRETE PAVEMENTS

A finite-element computer program, JSLAB, has been developed to analyze jointed concrete pavement sections. Joints can be modeled as doweled, aggregate interlock, or keyed. Dowels are represented as thick beams. Aggregate interlock and keyways are represented by springs. Load input is in terms of wheel loads at any location on the slabs. Loss of support and variable support or material properties can be considered. The JSLAB program can be used to evaluate the effect of joints with nonuniformly spaced load-transfer devices.

For doweled joints, dowel properties such as diameter and modulus of elasticity are input directly. For aggregate interlock and keyway joints, a spring stiffness value is required. This value represents the load deflection characteristics of such joints. The stiffness value can be determined from field or laboratory tests.

Representative slab systems that can be analyzed are shown in Figure 4. A finite-element representation of a jointed slab is shown in Figure 5.

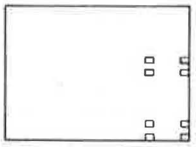
The JSLAB computer program has been verified with closed-form solutions. A detailed description of the program is given elsewhere (18). Example applications of the program are presented to highlight its uses and capabilities.

Single-Axle Load at Longitudinal Tied Joint

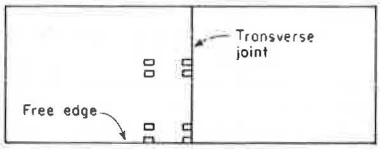
An analysis is presented for an 18,000-lb single-axle load (SAL) placed at a longitudinal tied joint as shown in Figure 6. Two cases are analyzed. Case 1 considers a tied concrete shoulder with a tied keyway represented as a spring with a stiffness of 25,000 lb/in. per inch length of joint. Case 2 considers a single slab without a tied shoulder. Deflection, stress, and load transferred along the joint are shown in Figure 6.

Maximum load transferred across the joint for case 1 was 36.7 lb per inch length of joint or 440 lb per 12-in. length of joint. Joint efficiency at the point of maximum joint deflection is 46 percent. In this paper, joint efficiency is defined as the ratio of deflection of the unloaded slab to deflection of the loaded slab. Table 2 gives calculated pavement stresses and deflections for different slab thicknesses and subgrade support.

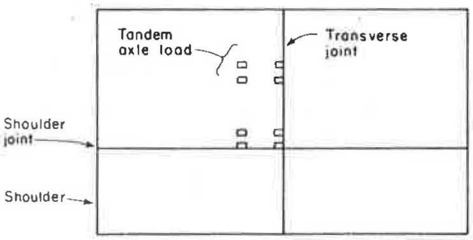
Figure 4. Typical slab systems.



(a) Single Slab

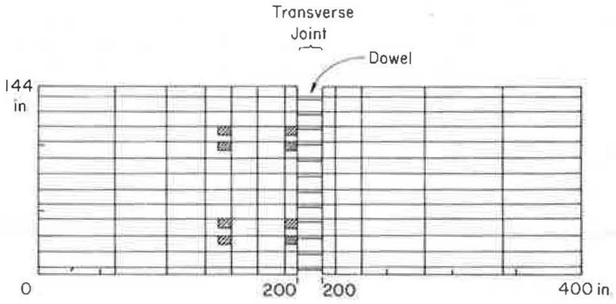


(b) Jointed Slabs



(c) Jointed Slabs with Tied Shoulder

Figure 5. Finite-element representation of typical jointed slab system.



Tandem-Axle Load at Doweled Joint

An analysis is presented for a 36,000-lb tandem-axle load (TAL) placed at a transverse joint. Slab details and load placement are shown in Figure 7. Two cases are analyzed. Case 1 considers a joint with 1.25-in.-diameter dowels uniformly spaced at 12 in. Case 2 considers zero load transfer across the joint. Pavement deflection, stress, and load transferred by each dowel are shown in Figure 7.

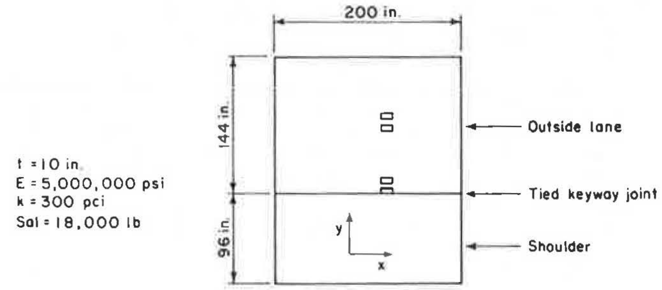
Maximum dowel load is 1,300 lb. Joint efficiency at the point of maximum deflection is 92 percent. Table 3 gives calculated pavement stresses and deflections for different slab thicknesses and subgrade support.

Tandem-Axle Load at Corner

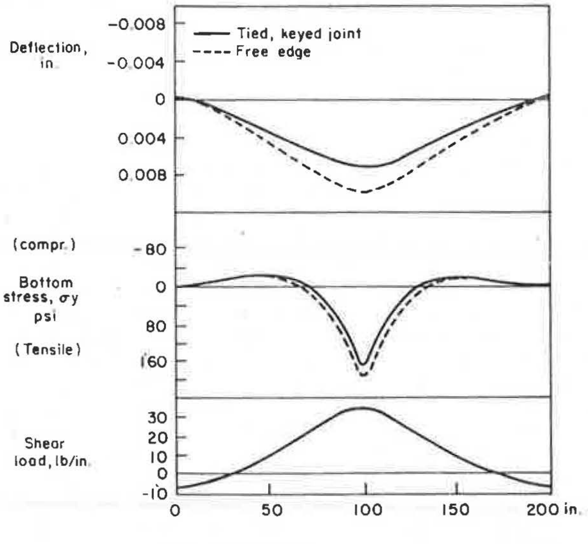
An analysis is presented for a 36,000-lb TAL placed at a corner of a transverse joint. Slab details and load placement are shown in Figure 8. Two cases are analyzed. Case 1 considers a joint with 1.25-in.-diameter dowels uniformly spaced at 12 in. Case 2 considers zero load transfer across the joint. Pavement deflection, stress, and load transferred by each dowel are shown in Figure 8.

Maximum dowel load is 2,700 lb. Joint efficiency at the point of maximum deflection is 83 percent.

Figure 6. Calculated responses for SAL at longitudinal joint.



(a) Slab Section Analized



(b) Response Along Longitudinal Joint Edge

Tables 4 and 5 give calculated pavement deflections for different slab thicknesses and subgrade support with and without a tied shoulder. Use of dowels and a tied concrete shoulder significantly reduces slab deflections.

Subbase Effect on Joint Response

Subbase effect on joint response is demonstrated by varying the value of the modulus of subbase reaction from 100 to 500 pci. Slab details and load placement are the same as shown in Figure 7a. Pavement deflections are shown in Figure 9. Also shown in Figure 9 are variations in joint efficiency at critical locations as a function of subbase quality. No significant variation was apparent in the distribution of dowel loads for the different subbase types.

Curling Analysis

A curling analysis is presented for a single slab. The analysis requires a two-step procedure. In the first step, an analysis is conducted for a weight-

Table 2. Calculated response for SAL at edge.

		No Shoulder		With Tied Shoulder	
Subgrade Modulus (pci)	Slab Thickness (in.)	Slab Deflection (in.)	Slab Stress (psi)	Slab Deflection (in.)	Slab Stress (psi)
100	6	0.033	517	0.018	372
	8	0.025	342	0.014	255
	10	0.020	248	0.012	190
	12	0.018	190	0.011	148
300	6	0.016	425	0.010	324
	8	0.012	279	0.007	221
	10	0.009	202	0.006	164
	12	0.008	156	0.005	128
500	6	0.012	388	0.007	303
	8	0.009	255	0.005	208
	10	0.007	184	0.004	154
	12	0.006	141	0.004	120

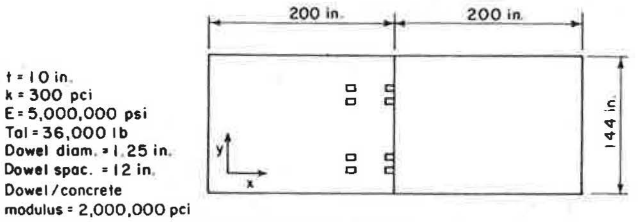
Note: Spring constant value used for longitudinal shoulder joint = 25,000 lb/in. per inch length of joint; 18,000-lb SAL placed at outside lane edge.

Table 3. Calculated response for TAL at transverse joint.

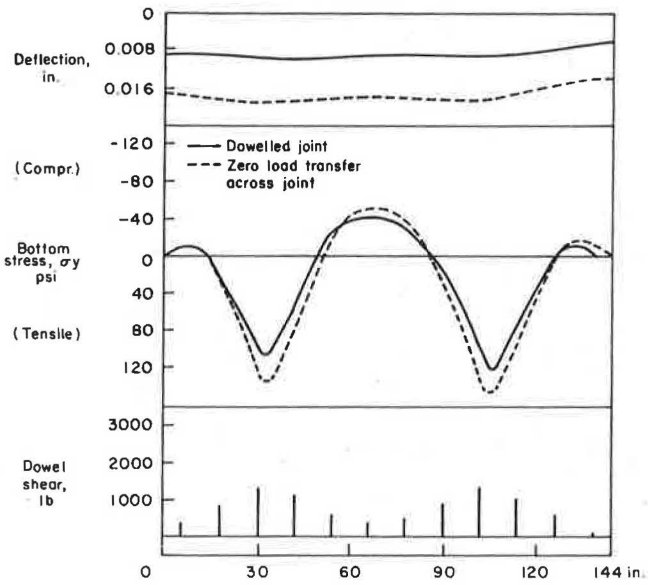
		Free Joint		Doweled Joint		
Subgrade Modulus (pci)	Slab Thickness (in.)	Slab Deflection (in.)	Slab Stress (psi)	Slab Deflection (in.)	Slab Stress (psi)	Dowel Shear (lb)
100	6	0.062	350	0.033	250	1,200
	8	0.055	207	0.029	154	1,200
	10	0.050	137	0.026	105	1,200
	12	0.047	96	0.024	77	1,200
300	6	0.025	319	0.014	230	1,100
	8	0.021	193	0.011	144	1,100
	10	0.019	129	0.010	99	1,100
	12	0.018	92	0.010	74	1,100
500	6	0.017	302	0.009	219	1,100
	8	0.014	185	0.008	139	1,100
	10	0.012	125	0.007	96	1,100
	12	0.012	90	0.006	73	1,100

Note: Tandem axle load of 36,000 lb placed at transverse joint 20 in. inward from edge; dowel diameters are 0.75, 1, 1.25, and 1.25 in. for slab thicknesses of 6, 8, 10, and 12 in., respectively.

Figure 7. Calculated responses for TAL at transverse joint.

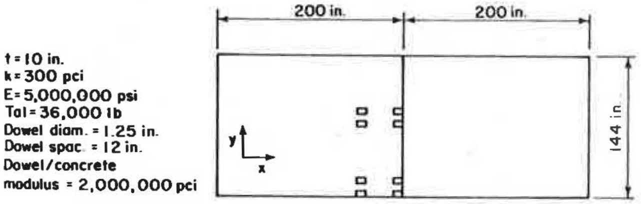


(a) Slab Section Analized

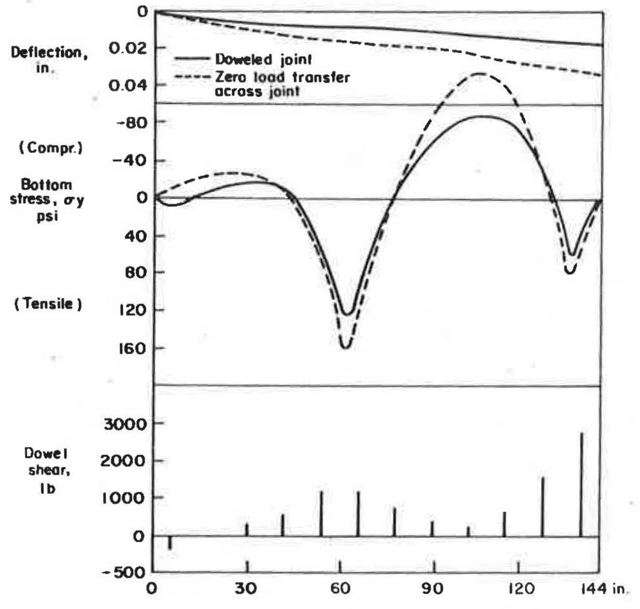


(b) Response Along Transverse Joint

Figure 8. Calculated responses for TAL at corner.



(a) Slab Section Analized



(b) Response Along Transverse Joint

less slab supported only at the midregion. This gives the deformation and apparent stress response for an unrestrained condition. In the second step, slab weight and placement of the slab over a uniform support are incorporated. In addition, an iterative analysis scheme is used to establish loss of support conditions due to curling. Thus, no negative subgrade support is assumed.

Figure 10 shows slab response for a daytime temperature gradient of 3°F/in. of slab depth. The restrained stress is the difference between the apparent stress of the unrestrained condition and the stress obtained for the condition incorporating slab weight. It is seen that a large restraint stress develops in the longitudinal direction. However, only a small restraint develops in the transverse direction. Figure 11 shows the effect of joint spacing on maximum curling restraint stress for a daytime temperature gradient of 3°F/in.

Tied Shoulder Effects

An analysis is presented for a 36,000-lb TAL placed at a corner of a transverse joint. Slab details and load placement are shown in Figure 8. The keyway of the tied shoulder is represented as a spring with a stiffness of 25,000 lb/in. per inch length of joint. Figure 12 shows the effect of a tied

Table 4. Calculated response for TAL at corner: without shoulder.

Subgrade Modulus (pci)	Slab Thickness (in.)	Free Joint Slab Deflection (in.)	Doweled Joint Slab Deflection (in.)	Doweled Joint Dowel Shear (lb)
100	6	0.110	0.060	2,700
	8	0.090	0.048	3,000
	10	0.078	0.041	3,200
	12	0.070	0.037	3,200
300	6	0.048	0.027	2,200
	8	0.039	0.022	2,500
	10	0.033	0.018	2,700
	12	0.029	0.016	2,700
500	6	0.033	0.020	2,000
	8	0.026	0.015	2,300
	10	0.022	0.013	2,400
	12	0.020	0.011	2,400

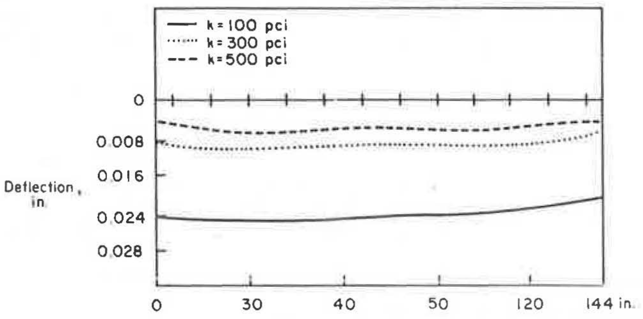
Note: Tandem axle load of 36,000 lb placed at corner; dowel diameters are 0.75, 1, 1.25, and 1.25 in. for slab thicknesses of 6, 8, 10, and 12 in., respectively.

Table 5. Calculated response for TAL at corner: with tied shoulder.

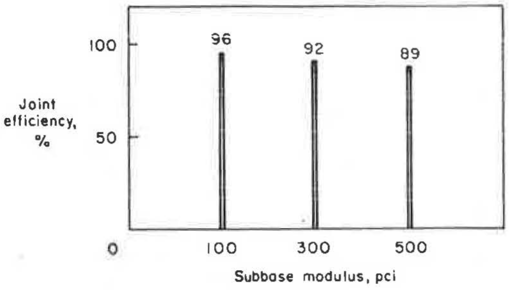
Subgrade Modulus (pci)	Slab Thickness (in.)	Free Joint Slab Deflection (in.)	Doweled Joint Slab Deflection (in.)	Doweled Joint Dowel Shear (lb)
100	6	0.110	0.033	2,000
	8	0.090	0.028	2,100
	10	0.078	0.025	2,300
	12	0.070	0.022	2,300
300	6	0.048	0.016	1,700
	8	0.039	0.013	1,900
	10	0.033	0.011	2,000
	12	0.029	0.010	2,000
500	6	0.033	0.012	1,600
	8	0.026	0.010	1,800
	10	0.022	0.008	1,900
	12	0.020	0.007	1,900

Note: Tandem axle load of 36,000 lb placed at corner; dowel diameters are 0.75, 1, 1.25, and 1.25 in. for slab thicknesses of 6, 8, 10, and 12 in., respectively; spring constant value used for longitudinal shoulder joint = 25,000 lb/in. per inch length of joint.

Figure 9. Calculated subbase effect on slab response.

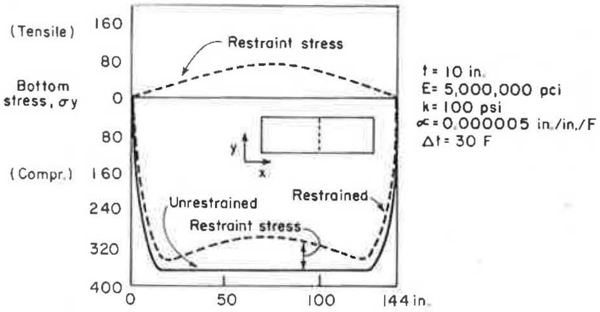


(a) Response Along Transverse Joint

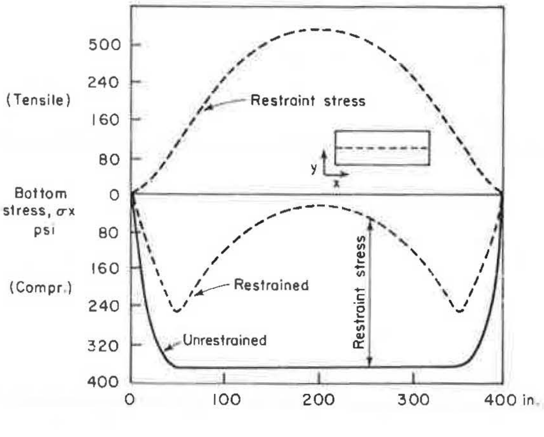


(b) Joint Efficiency

Figure 10. Curling analysis for daytime condition.



(a) Transverse Section



(b) Longitudinal Section

Figure 11. Calculated curling restraint stresses.

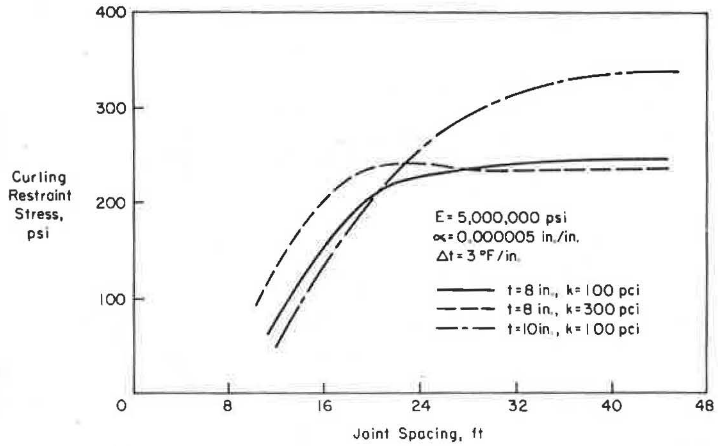
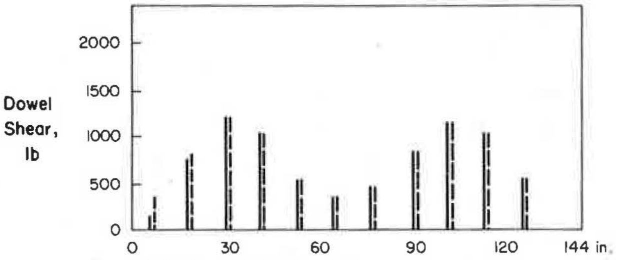
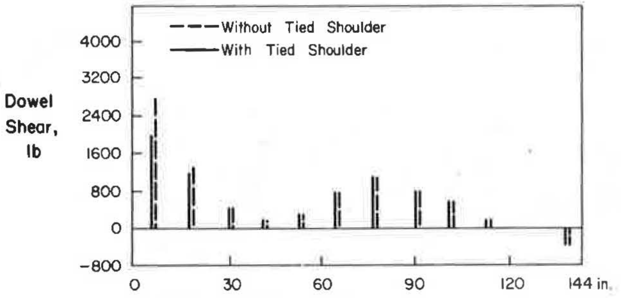


Figure 12. Calculated effect of tied shoulder on dowel shear.



(a) Tandem Axle Load at Joint



(b) Tandem Axle Load at Corner

Table 6. Results of parametric investigation.

Parameter	Slab Deflection (in.)		Joint Efficiency[a] (%)	Maximum Dowel Shear (lb)
	Loaded	Unloaded		
Dowel diameter (in.)				
0.75	0.0188	0.0143	76.1	2,300
1.00	0.0184	0.0147	79.9	2,500
1.25	0.0181	0.0150	82.9	2,700
Dowel modulus of elasticity (psi 000 000s)				
20	0.0181	0.0150	82.9	2,700
29	0.0181	0.0150	82.9	2,700
40	0.0182	0.0149	81.9	2,600
Modulus of dowel-concrete reaction (pci 000 000s)				
0.5	0.0204	0.0127	62.2	1,500
1	0.0190	0.0141	74.2	2,200
2	0.0181	0.0150	82.9	2,700
5	0.0175	0.0157	89.7	3,100
Joint width (in.)				
0.10	0.0181	0.0150	82.9	2,700
0.25	0.0182	0.0150	82.4	2,700
0.50	0.0182	0.0150	82.4	2,600
1.00	0.0182	0.0148	81.8	2,600
Free joint	0.0331	—	—	—

[a] Unloaded slab deflection ÷ loaded slab deflection.

shoulder on magnitudes of dowel shear. For the TAL placed 20 in. inward from the edge, the effect of a tied shoulder on dowel shear is negligible. However, for the TAL placed at the corner location, use of a tied shoulder results in a reduction of dowel shear to 2,000 lb from 2,700 lb without a tied shoulder, a significant reduction. In addition, as given in Table 5, slab corner deflections are considerably reduced when a tied shoulder is used. Thus, the use of tied shoulders is expected to result in significantly improved pavement performance.

PARAMETRIC STUDY

A parametric study was conducted to determine the influence of design parameters on response at the joint. A reference jointed pavement system was established to allow comparisons with joint responses due to different design parameters. The characteristics of the reference jointed pavement system are as follows:

Characteristic	Value
Slab thickness (in.)	10
Concrete modulus of elasticity (psi)	5 million
Modulus of subgrade reaction (pci)	300
Dowels	
Number	12
Diameter (in.)	1.25
Spacing (in.)	12
Modulus of dowel-concrete reaction (pci)	2 million
Dowel modulus of elasticity (pci)	29 million
Joint opening (in.)	0.25

Pavement and joint response was determined for a 36,000-lb TAL placed at a corner. Structural responses of particular interest included slab deflection and dowel shear. When the effect of a particular design parameter was considered, only its input value was changed and all other design parameters were kept constant. Table 6 gives the results of the parametric study.

Dowel Size

The dowel diameters onsidered were 0.75, 1, and 1.25 in. As shown in Table 6, there is a decrease in joint efficiency and maximum dowel shear with a decrease in dowel size. However, the differences between responses for the 1-in.- and 1.25-in.-diameter dowels are not considered significant.

Dowel Modulus of Elasticity

The dowel moduli of elasticity considered were 20 million, 29 million, and 40 million pci. As shown in Table 6, responses were similar in all three cases.

Modulus of Dowel-Concrete Reaction

The values of modulus of dowel-concrete reaction considered were 0.5 million, 1 million, 2 million, and 5 million pci. As shown in Table 6, loaded-slab deflections increase with a decrease in the modulus value. Lower modulus values can be considered to represent conditions when dowels are not seating firmly on the concrete.

Joint Width

Joint widths considered were 0.10, 0.25, 0.50, and 1.00 in. As shown in Table 6, responses were similar in all four cases.

NONUNIFORMLY SPACED DOWELED JOINTS

As part of the study to improve rigid pavement joints, the use of fewer nonuniformly spaced dowels was investigated. Reducing the number of dowels used per joint can result in significant economy. Three cases of nonuniformly spaced doweled joints were analyzed.

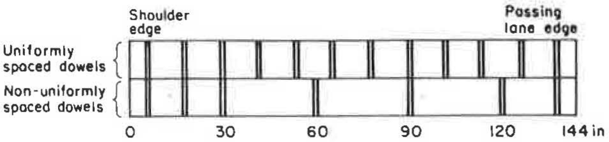
Case 1 considers 7 dowels positioned at the joint as shown in Figure 13a. The 7 nonuniformly spaced dowels were located 6, 18, 30, 60, 90, 120, and 138 in. from the shoulder edge. Calculated dowel shears are shown in sections b and c of Figure 13 for a 36,000-lb TAL placed at a joint and at a corner. In Figure 13, these results are also compared with those for a joint with 12 uniformly spaced dowels.

Maximum dowel shears for the 7- and 12-dowel joints are about the same for the corner load. Maximum dowel shear for the 7-dowel joint is higher than that for the 12-dowel joint when the TAL is positioned at the joint but away from the corner. However, the maximum dowel shear at the corner dowel when the load is placed at the corner controls the doweled joint design.

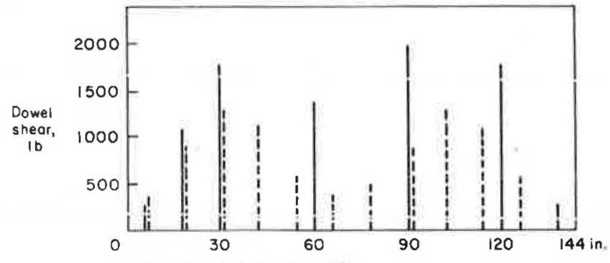
Case 2 considered 6 dowels positioned at the joint in the pattern shown in Figure 14a. The six nonuniformly spaced dowels were located 6, 12, 36, 81, 105, and 135 in. from the shoulder edge. Calculated dowel shears are shown in sections b and c of Figure 14 for a 36,000-lb TAL placed at a joint and at a corner. The response is similar to that obtained for the 7-dowel joint.

Case 3 also considered 6 dowels, but positioned at the joint as shown in Figure 15a. The 6 nonuniformly spaced dowels were located 6, 24, 42, 90, 117, and 135 in. from the shoulder edge. Calculated dowel shear magnitudes are shown in sections b and c of Figure 15 for a 36,000-lb TAL placed at a joint and at a corner. These results are similar to those obtained for the 7-dowel joint. In all three cases, stresses and deflections for the nonuniformly spaced doweled joints are similar to those obtained for the 12-dowel joints with uniform spacing. For joints with fewer than 6 dowels, relative deflections

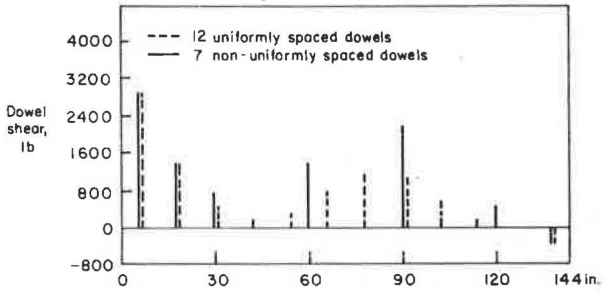
Figure 13. Calculated responses for joint with seven nonuniformly spaced dowels.



(a) Dowel Location

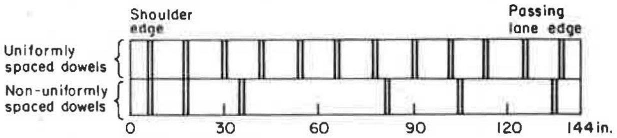


(b) Tandem Axle Load at Joint

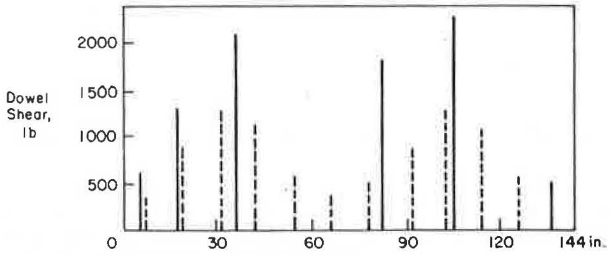


(c) Tandem Axle Load at Corner

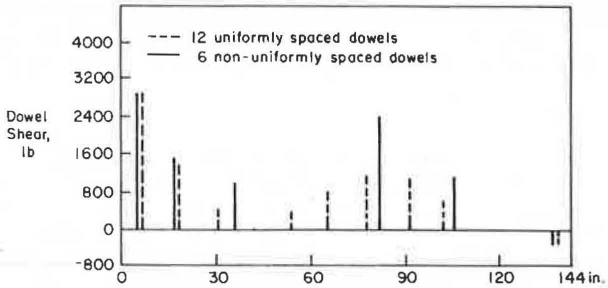
Figure 14. Calculated responses for joint with six nonuniformly spaced dowels: pattern 1.



(a) Dowel Location

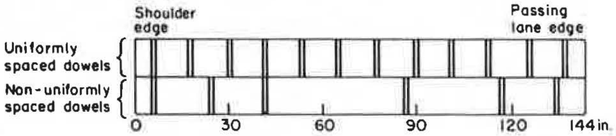


(b) Tandem Axle Load at Joint

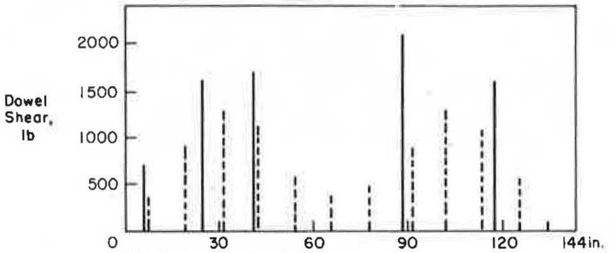


(c) Tandem Axle Load at Corner

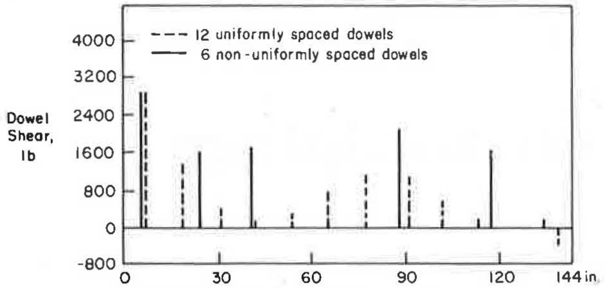
Figure 15. Calculated responses for joint with six nonuniformly spaced dowels: pattern 2.



(a) Dowel Location



(b) Tandem Axle Load at Joint



(c) Tandem Axle Load at Corner

across the joint at locations between the dowels become high. This indicates a potential for faulting for joints with fewer than 6 dowels.

Based on the analysis of nonuniformly spaced dowels, use of only 6 dowels/joint at locations shown in Figure 15a is considered appropriate. The use of fewer dowels per joint would reduce problems associated with misaligned dowels because the total number of possibly misaligned dowels would decrease in proportion to the number of dowels used.

DOWEL EMBEDMENT ANALYSIS

As discussed previously, dowels are generally specified to be 18 in. long. Results of laboratory tests by others indicate that embedment lengths of six diameters were adequate for dowels 1 in. and larger. The effect of dowel embedment length was investigated by using techniques used in analysis of finite beams on elastic foundations (19).

The following design parameters were considered in the analysis.

Characteristic	Value
Dowel diameter (in.)	1.25
Modulus of dowel-concrete reaction (psi 000 000s)	1.5, 2, 2.5
Joint opening (in.)	0.25
Dowel length (in.)	6, 7, 8, 9, 10

Analysis results indicate that dowel deflection at the joint, maximum concrete bearing stress, and maximum dowel bending stress values are not affected by the dowel lengths considered. Laboratory tests conducted at the Construction Technology Laboratories also indicate that deflection response at a joint is similar for dowel embedment lengths of 6, 7, 8, and 9 in. (20).

For construction tolerance requirements, the use of dowels with a minimum length of 14 in. is considered adequate for dowels 1 in. or more in diameter.

SUMMARY

A computerized finite-element analysis procedure for jointed concrete pavement is presented. In this finite-element analysis procedure, joints can be modeled as doweled, aggregate interlock, or keyed. The procedure can be used to evaluate the effect of joints with nonuniformly spaced load-transfer devices.

Examples are presented to illustrate the capabilities of the analytic procedure. Maximum dowel shear is obtained when a tandem-axle load is positioned at a corner. Maximum dowel shear magnitude is about 2,700 lb for the outermost dowel for a 36,000-lb TAL.

Analyses of joints with nonuniformly spaced dowels indicate that 6 dowels/joint/lane would provide response at the joint comparable to that provided by 12 uniformly spaced dowels. In addition to considerable cost savings, the use of fewer dowels per joint can result in less restraint due to possible misaligned dowels and frozen dowels. Analysis results also show that the use of tied concrete shoulders reduces pavement deflections, pavement stresses, and dowel shears. These reductions can be expected to minimize joint faulting, subbase-subgrade erosion, and corner breaks, thereby significantly improving pavement performance.

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The opinions and findings expressed or implied in the paper are ours and are not necessarily those of FHWA.

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Analytic Approach to Concrete Pavement Blowups

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The results of analyses of concrete pavement blowups are presented and discussed. The analyses are based on the assumption that blowups are caused by lift-off buckling of the pavement due to a rise in pavement temperature and moisture. A safe temperature and moisture increase is defined, and the way in which it depends on various parameters, such as pavement thickness, axial shearing resistance along the pavement-soil interface, and the thermal expansion coefficient, is shown. Also shown are the ways in which blowups may be affected by pavement curing temperature, resurfacing layers, and the reduction of pavement stiffness caused by heavy wheel loads and the age of the pavement. The results of the study should contribute to a better understanding of the mechanism of pavement blowups and the determination of the essential parameters. It also provides guidelines for prescribing measures to reduce or totally eliminate blowups in concrete pavements.

Blowups of concrete pavements have been a problem for highway and airport engineers for many years. As early as 1925, the problem was discussed in the Engineering News Record (1). A severe highway blowup that occurred in 1975 in Ohio (2) is shown in Figure 1.

There is general agreement that blowups are caused by axial compression forces induced in the pavement by a rise in temperature and moisture and that they usually occur at joints or cracks. Many highway engineers are of the opinion that a major cause of blowups is infiltration of debris into joints or cracks (3). However, blowups of continuously reinforced concrete pavements (CRCPs) without joints have also been observed (4, p. 52).

In the past few decades, many reports have been published on pavement blowups in the United States. A critical review of blowup studies by Yoder and Foxworthy (3), published in 1972, reveals many inconclusive findings. The status of the research on blowups was summarized by Gress (5,6) in 1976: "To date, work in this area has been qualitative and empirical and has not resulted in an understanding of the blowup mechanism." According to a 1978 report from England by Andrews (7), "the precise mechanism of blowups has not been established." It appears that the rather extensive research effort on blowups of concrete pavements conducted over the past decades did not lead to a solution of the problem because of the lack of a generally accepted theory that would establish the important parameters that affect pavement blowups.

Recently, Kerr and Dallis (8) and Kerr and Shade (9) developed analyses for the blowup of concrete pavements. The essential results of these studies are presented in this paper. The analytic details are presented elsewhere (8,9). In this paper, emphasis is placed on the assumed pavement blowup mechanism, the results obtained (presented as graphs), and the correlation of the pavement parameters that were used in these analyses with various factors that, to some investigators, appeared to affect the occurrence of blowups, as described in the literature (2,3).

BLOWUP MECHANISM AND ANALYTIC RESULTS

It is assumed that blowups are caused by lift-off buckling of a concrete pavement due to compression forces induced in the pavement by a rise in tempera-

Figure 1. Blowup of concrete highway pavement in Ohio.