MECHANISTIC DESIGN AND ANALYSIS PROCEDURE FOR DOWELED JOINTS IN CONCRETE PAVEMENTS

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INTRODUCTION

A Portland cement concrete (rigid) pavement system consists of a number of slabs, finite in length and width, over one or more constructed and natural supporting layers. The response of such a pavement is largely controlled by joints or other discontinuities, which, by their nature, are structurally weakened planes in the system. Consequently, the effectiveness of joints is a primary concern in concrete pavement analysis and design.

For over three-quarters of a century, dowels have been used as load transfer devices in jointed concrete pavements. Dowels are smooth, round bars with bond intentionally prevented on one end to allow longitudinal movement of the slabs. They are thought to enhance load transfer, prevent faulting, reduce pumping, and reduce corner breaks. Most design criteria for dowel bars are empirical. For example, Federal Aviation Administration (FAA) Design Circular AC 150/5320-6C prescribes diameter, length, and spacing of dowel bars (Table 1) based upon pavement thickness (*1*).

The concept of load transfer is fundamental to the FAA rigid pavement design criteria. The philosophical basis of load transfer is very simple: the maximum stresses and deflections in a loaded slab can be reduced if a portion of the applied load is transferred to an adjacent slab. If a joint is capable of transferring load, statics dictates that the portion of the applied load supported by the *loaded slab*, P_L, and the complementary load supported by the adjacent slab, P_U, commonly referred to as the *unloaded slab*, must sum to the total applied wheel load P, i.e.,

$$P_L + P_U = P \tag{1}$$

Load may be transferred across a joint by shear and/or bending moment. However, it has been commonly argued that load transfer is primarily by shear (*2, 3*). If the slabs on both sides of the joint are identical in thickness and elastic properties, and if a pure shear load transfer mechanism is assumed, the maximum bending stress responses near the edge of the slabs are related by:

$$\sigma_L + \sigma_U = \sigma_f \tag{2}$$

where σ_L is the maximum bending stress in the loaded slab, σ_U is the maximum bending stress in the adjacent unloaded slab, and σ_f is the maximum bending stress for the corresponding free edge condition (no load transfer). Similarly, maximum slab deflections near the edge are related by:

$$\Delta_L + \Delta_U = \Delta_f \tag{3}$$

where Δ_L is the maximum edge deflection of the loaded slab, Δ_U is the maximum edge deflection of the adjacent unloaded slab, and Δ_f is the corresponding maximum free edge deflection (no load transfer).

Deflection load transfer efficiency (LTE_δ) is defined as the ratio of the deflection of the unloaded slab to the deflection of the loaded slab, as follows:

$$LTE_\delta = \frac{\Delta_U}{\Delta_L} \tag{4}$$

Similarly, stress load transfer efficiency (LTE_σ) is defined as the ratio of the edge stress in the unloaded slab to edge stress in the loaded slab, as follows:

$$LTE_\sigma = \frac{\sigma_U}{\sigma_L} \tag{5}$$

Load transfer (LT) in the FAA rigid pavement design procedure is defined as that portion of the free edge stress that is carried by the adjacent unloaded slab:

$$LT = \left(\frac{\sigma_U}{\sigma_f}\right) = \left(1 - \frac{\sigma_L}{\sigma_f}\right) \tag{6}$$

All three of these load transfer measures are commonly expressed as percentages. It should be noted from the above equations that the ranges of LTE_δ and LTE_σ are from zero to 100%, while the range of LT is from zero to 50%. Equation 6 can be related to Equation 5 as follows:

$$LT = \frac{LTE_\sigma}{1 + LTE_\sigma} \tag{7}$$

The FAA design criteria prescribe $LT = 25$ %, effectively reducing the design stress and allowing a reduced slab thickness. This accepted value is primarily based upon observations from experimental pavements trafficked from the mid-1940's to the mid-1950's (*4*). If the load transfer requirement is violated through a degradation of the joint system, the pavement life can be significantly reduced.

HISTORICAL DEVELOPMENTS

Friberg (*5*) presented an analysis of stresses in doweled joints based upon the work of Timoshenko and Lessels (*6*). His analysis was based upon considering the dowel as a semi-infinite beam on a Winkler foundation. His basic relationship for dowel-concrete bearing stress, σ_b [FL^{-2}], was

$$\sigma_b = K\,\Delta_o \tag{8}$$

where

K = modulus of dowel support [FL^{-3}]
Δ_o = deflection of the dowel with respect to the concrete at the face of the joint [L]

Friberg's (*5*) analysis of dowel bar support is shown in Figure 1. Grinter (*7*) reported that the value of K depended on the modulus of the slab concrete, E; the thickness of the slab, h; and the modulus of subgrade reaction, k. Reported values of K vary greatly. Tabatabaie (*8*) reported finding values in the literature from 0.08×10^6 MPa/m (0.3×10^6 psi/in.) to 8.6×10^6 MPa/m (32×10^6 psi/in.). The value typically assumed is 0.41×10^6 MPa/m (1.5×10^6 psi/in.).

Friberg's (*5*) relationship for the value of Δ_o under a dowel bar carrying a transferred load, P_t, is

$$\Delta_o = \frac{P_t}{4\beta^3 E_d I_d}(2 + \beta\omega) \tag{9}$$

where

ω = joint opening [L]
E_d = modulus of elasticity of the dowel [FL^{-2}]
I_d = moment of inertia of dowel bar [L^4]
β = relative stiffness of the dowel-concrete system [L^{-1}]

Friberg (*5*) adopted Timoshenko's (*6*) definition of the relative stiffness of a bar embedded in concrete as

$$\beta = \sqrt[4]{\frac{Kd}{4E_dI_d}} \tag{10}$$

where d is the diameter of the dowel bar. The bearing stress on the concrete at the joint face then becomes from Equation 8:

$$\sigma_b = \frac{KP_t}{4\beta^3 E_d I_d}(2+\beta\omega) \tag{11}$$

Interpreting data obtained using the finite element code ILLI-SLAB, Ioannides and Korovesis (*9*) developed the concept of a dimensionless joint stiffness for the doweled joint expressed by the ratio $D/sk\ell$ where D is the stiffness of a vertical spring element, s is the dowel spacing , and ℓ is Westergaard's radius of relative stiffness for the slab-subgrade system, defined as

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} \tag{12}$$

where μ is the Poisson's ratio of concrete. The value of D reflects the vertical stiffness contributed by the support of the concrete, called the dowel-concrete interaction (*DCI*), and the vertical stiffness offered by beam bending, C. These two contributions are summed as springs in series, leading to:

$$D = \frac{1}{\frac{1}{DCI} + \frac{1}{12C}} \tag{13}$$

The value of DCI can be calculated assuming the dowel to be a beam on a spring foundation (Friberg analysis) using the following relationship:

$$DCI = \frac{4\beta^3}{(2+\beta\omega)} E_d I_d \tag{14}$$

Comparing this relationship with Equation 9 reveals that DCI is identical with the ratio P_t/Δ_o in the Friberg analysis and has dimensions of $[FL^{-1}]$. The term C in Equation 13 is defined by the relationship:

$$C = \frac{E_d I_d}{\omega^3(1+\phi)} \tag{15}$$

where

$$\phi = \frac{12E_d I_d}{G_d A_z \omega^2} \tag{16}$$

G_d is the shear modulus of the dowel bar, given by

$$G_d = \frac{E_d}{2(1+\mu_d)} \tag{17}$$

A_z is the effective cross-sectional area in shear and is assumed to be 0.9 times the circular area as follows:

$$A_z = 0.9\left(\frac{\pi d^2}{4}\right) \tag{18}$$

WESTERGAARD-TYPE SOLUTION FOR EDGE LOAD TRANSFER

Ioannides and Hammons (*10*) presented the results of a study which effectively broadens the Westergaard-type solution to explicitly include load transfer. In his 1948 paper, Westergaard (*11*) briefly outlined a solution for the edge load transfer problem, but this work was limited by his implicit assumption that deflection load transfer and stress load transfer were identical. Model studies and full-scale tests in the 1940's and 1950's conducted by the Corps of Engineers, and more recently by finite element investigations (*9, 12*), disproved this assumption.

In 1949, Mikhail S. Skarlatos (*13*) described his analytical investigations in which he defined a dimensionless joint stiffness, f, in terms of the radius of relative stiffness, modulus of subgrade reaction, and a joint stiffness parameter, q. The latter represents the force transferred across a unit length of joint per unit differential deflection across the joint as follows:

$$f = \frac{q}{k\ell} \tag{19}$$

Using this approach, Skarlatos developed relationships involving integral equations for the maximum stress and deflection on the unloaded side of the joint. Skarlatos ignored environmentally-induced responses in order to make the problem tractable. Using modern personal computers and powerful mathematical software, Ioannides and Hammons (*10*) were able to perform the necessary integrations for square loaded areas of various sizes, 2ϵ by 2ϵ. Following the same approach as Westergaard, closed-form equations for the maximum deflection and maximum bending stress on the unloaded side of a joint capable of load transfer were developed. Together with Westergaard's edge loading equations, the relationships developed by Ioannides and Hammons (*10*) can be used to investigate the load transfer problem.

The results of the analytical development work were used to develop a series of closed-form relationships convenient for routine engineering calculations. Nonlinear regression was used to develop the following expression for LTE_δ as a function f and ϵ/ℓ:

$$LTE_\delta = \frac{1}{1 + \log^{-1}\left[\dfrac{0.214 - 0.183\left(\dfrac{\epsilon}{\ell}\right) - \log f}{1.180}\right]} \tag{20}$$

Likewise, nonlinear regression was used to develop an expression for LTE_δ as a function of LTE_σ and ϵ/ℓ. The following regression formula was obtained:

$$LTE_\delta = \frac{\left[1206\left(\frac{\epsilon}{\ell}\right) + 377\right] LTE_\sigma^2 - 693\left(\frac{\epsilon}{\ell}\right) LTE_\sigma^3}{1 + 689\left(\frac{\epsilon}{\ell}\right) LTE_\sigma + \left[370 - 154\left(\frac{\epsilon}{\ell}\right)\right] LTE_\sigma^2} \quad (21)$$

Nonlinear regression was used to develop an expression for LTE_σ as a function of ϵ/ℓ and LTE_δ. The resulting algorithm was:

$$LTE_\sigma = \frac{\left[10.14\left(\frac{\epsilon}{\ell}\right) + 4.00\right] LTE_\delta - \left[4.3\left(\frac{\epsilon}{\ell}\right) + 3.98\right] LTE_\delta^2}{21.03 + \left[5.74\left(\frac{\epsilon}{\ell}\right) - 20.98\right] LTE_\delta} \quad (21)$$

The functional forms of these regression algorithms were arbitrary from an engineering viewpoint, and were selected from among a large number of choices investigated.

IMPLEMENTATION FOR DESIGN OF DOWELED JOINTS

The contributions of Friberg (*5*), Skarlatos (*13*), Ioannides and Korovesis (*9*), and Ioannides and Hammons (*10*) can be synthesized to develop mechanistic design criteria for dowels in rigid pavements. For a doweled joint, the dimensionless ratio $D/sk\ell$ is identical to Skarlatos' dimensionless joint stiffness given in Equation 19, where

$$q = \frac{D}{s} \quad (22)$$

The relationships presented above were used to develop a personal computer spreadsheet that allows a designer to interactively select the required dowel diameter and spacing to yield a desired value of load transfer.

Figure 2 shows the layout of the spreadsheet, which has been designed such that any consistent set of units may be used. In the upper left-hand block of the spreadsheet, the user is prompted to enter the thickness of the pavement slab, the modulus of subgrade reaction, the radius of the loaded area, and a trial dowel diameter. Suggested values for dowel diameter follow the FAA criteria (Table 1) and range from 19 mm (3/4 in.) to 51 mm (2 in.) in increments of approximately 6 mm (1/4 in.).

In the center left-hand block of the spreadsheet, commonly assumed structural parameters are listed pertaining to pavement and dowels. These values may be changed at the designer's discretion. The elastic properties of the Portland cement concrete are often set at conservative values for engineering design. The elastic properties of the dowel are values commonly assumed for steel. The default value for the modulus of dowel reaction is the commonly assumed value, although wide variations of this value have been reported in the literature. The three default values for dowel spacings are the three values currently allowed by FAA (Table 1). The user has the option to use other values of dowel spacing at his or her discretion.

The lower left-hand block contains a listing of useful parameters which have been calculated from the required and optional input. These spreadsheet cells have been protected so that the user may not alter or override the formulae with user input values.

The graph on the right-hand side of the spreadsheet shows the calculated value of load transfer (based upon the user's input) as a function of joint opening and dowel spacing for the trial value of dowel diameter. The plots in the graph are automatically updated as the user interacts with the spreadsheet by providing the required and optional input values. By observing the changes in the graph, the user can interactively select a combination of dowel diameter and dowel spacing to

achieve a desired load transfer.

SENSITIVITY STUDY

A study was conducted to ascertain the sensitivity of the proposed dowel design criteria to the dimensionless load ratio ϵ/ℓ, the modulus of dowel support K, and the joint opening ω. The effect of ϵ/ℓ and ω on load transfer is illustrated in Figure 3. The joint opening has been made dimensionless in a manner analogous to the use of a span-to-depth ratio for beams; the dimensionless mechanistic variable for joint opening is $\beta\omega$, as indicated by Equation 11. As is evident in Figure 2, *LT* is relatively insensitive for values of ω less than approximately 0.5 times the dowel diameter. In Figure 3, as ϵ/ℓ increases, *LT* increases monotonically toward the maximum value of 50% as ϵ/ℓ grows without bound.

In Figure 4 the effects the modulus of subgrade reaction and joint opening on load transfer are shown. In this graph *K* has been normalized by the ratio d/E_d. Not unexpectedly, *LT* increases as *K* increases, almost linearly on the semi-log plot.

IMPLEMENTATION FOR EVALUATION OF DOWELED JOINTS

Nondestructive deflection testing of pavements using Falling Weight Deflectometer (FWD) devices has gained considerable popularity in the last fifteen years. The most common application of such testing is in the backcalculation of layer moduli for the assessment of the structural condition of existing pavements and for the design of overlays. A closed-form backcalculation procedure developed using the principles of dimensional analysis (*14,15*) has been extensively used in the estimation of *in situ* structural stiffness parameters of concrete pavements. Midslab deflection testing is used for this purpose. The procedure typically leads to an estimate of the radius of relative stiffness, ℓ, of the slab-subgrade system, as well as of the effective subgrade modulus, k, and of the slab Young's modulus, *E*. Through further application of the principles of dimensional analysis, the procedure was extended to the interpretation of edge deflection testing yielding estimates of the load transfer effectiveness of concrete pavement joints (*12*). The following is a brief outline of the combined midslab-edge evaluation procedure (*16*):

(a) With the FWD at a midslab location, drop the weight, *P*, and measure deflections D_0, D_1, D_2 and D_3 at 0, 305, 610, 915 mm (0, 12, 24 and 36 in.) from the center of the loading plate. Night or early morning testing may be preferable in order to maximize contact between the slab and base near the interior of the slab.

(b) Calculate the *AREA* (in inches) of the deflection basin using:

$$AREA\ (in.) = \frac{6}{D_0}\left[D_0 + 2\ (D_1 + D_2) + D_3 \right] \tag{23}$$

(c) Backcalculate the radius of relative stiffness, ℓ, of the pavement system using the appropriate relationship between this parameter and *AREA*, pertaining to the particular plate-sensor arrangement considered (*14,15*). For the 300 mm.-diameter FWD plate and the four sensor arrangement noted in (a), above, the following regression formula can be employed, leading to an estimate of ℓ in inches:

$$\ell\ (in.) = \left(\frac{\ell n \left[\frac{(36 - AREA)}{2673.64} \right]}{-2.93} \right)^{4.75} \tag{24}$$

(d) Estimate the load size ratio (a/ℓ) for this midslab location, where *a* is the radius of the FWD plate (150 mm (5.9055 in.)).

(e) Move the FWD to an edge location, drop the weight, *P*, and measure the deflections at conjugate points on the loaded and unloaded sides of the joint, Δ_L and Δ_U, respectively.

(f) Calculate the deflection load transfer efficiency of the joint, LTE_δ (Equation 4)

(g) Using the values of LTE_δ and of (a/ℓ) determined in this fashion, backcalculate the corresponding value of the stress load transfer efficiency, LTE_σ (Equation 21) and load transfer, *LT* (Equation 7). If the total loaded area remains constant, the error associated with substituting a square loaded area (described by the length of the side, 2ϵ) for a circular loaded area (described by the radius, *a)* is negligible.

Implicit in this determination is the conservative assumption that the midslab ℓ-value is valid at the edge, as well. A consistent discrepancy between field observations and his predictions prompted Westergaard (*11*) to speculated that "the

explanation nearest at hand would seem to be that the values of k should be greater for the edge than the value that gives best results for the interior of the area." Similarly, model tests by Carlton and Behrmann (*17*) led those Corps of Engineers investigators to the conclusion that the k value for interior loading was found to be "approximately half the value of k measured at the edge and corner," the latter two being practically the same. Finite element results by Ioannides (*18*) suggest a more gradual increase in k from interior to edge to corner ($k_{edge}/k_{interior} = 1.2$; $k_{corner}/k_{interior} = 1.5$). A gradual transition is also suggested by the analytical and field investigations of Teller and Sutherland (*19*) . The latter indicate that $k_{interior}$ is approximately equal to k_{edge} , and both are considerably smaller than k_{corner}. More recently, Crovetti (*20*) has delved in more detail into the relation of interior and edge parameters. His data suggest that $k_{edge}/k_{interior}$ is approximately equal to 2.5 and that $k_{corner}/k_{interior}$ is approximately equal to 5.

(h) Estimate the value of the dimensionless joint stiffness, f, and other joint parameters, including the modulus of dowel support, K.

APPLICATION TO FIELD DATA

An *in situ* concrete pavement joint evaluation procedure akin to the one outlined above was recently used by engineers at the U.S. Army Engineer Waterways Experiment Station in a comprehensive examination of the performance of joints at a variety of civilian airports around the continental United States (*21*). Included in that study were four pavement features at Denver International Airport (DIA). The FAA has a major research project at DIA in which a portion of Runway 34L/16R is instrumented to study the response and performance and the pavement. A typical pavement section for the features tested at DIA is shown in Figure 5. Table 2 shows the results of backcalculating the modulus of dowel support, the dimensionless joint stiffness, stress load transfer efficiency, and load transfer given the measured deflections from tests conducted with the FWD. Only doweled construction joints are included in analysis. All doweled joints were constructed with 38-mm (1-1/2 in.) diameter, 508-mm (20-in.) long dowels spaced at 457 mm (18 in.).

The results shown in Table 2 indicate that backcalculated mean values of the modulus of subgrade reaction varied from 589,000 MPa (2,170,000 psi) to 2,390,000 MPa (8,800,000 psi), with coefficients of variation ranging from 28.8% to 86.3%. This type of variability in the modulus of dowel support is consistent with that reported by other researchers who have tried to determine its value. Backcalculated mean values of load transfer ranged from 19.1% to 26.3% with coefficients of variation from 4.2% to 14.7%. These results indicate that backcalculated values of load transfer are not as variable as backcalculated values of modulus of dowel support.

CONCLUSIONS

The methods provided in this paper represent a rational, mechanistic method for analysis, design, and evaluation of dowel joints in concrete pavements and constitute a considerable improvement over previous empirical methods. The methodology proposed is based upon sound analytical principles and is easily implemented in a personal computer spreadsheet. The required inputs to the analytical model are the slab thickness, modulus of subgrade reaction, and the radius of the loaded area. All other model inputs can be set at default values or be modified at the designer's discretion. Dowel bar diameters and spacings can then be interactively modified by the designer to yield a given level of load transfer capability at the joint.

The same simple relationships can be used to evaluate the load transfer efficiency of in-service joints simply by entering deflection values across the joint obtained from a FWD or other device capable of measuring deflections on each side of a joint. The method can be used to backcalculate joint material and structural properties, as well as stress load transfer at the joint.

The design and analysis procedures set forth in this paper ignore the effects of curling and warping caused by environmental conditions such as temperature and moisture gradients through the depth of the slab. Obviously, daily and seasonal temperature and moisture cycles have a significant influence on pavement response. It is possible that environmental responses may be greater than load-induced responses. Further investigations would be required to study the effects of environmentally-induced responses on procedures presented here.

LIST OF TABLE TITLES

TABLE 1 Dimensions and Spacings of Steel Dowels (1)

TABLE 2 Results from Denver International Airport

TABLE 1 Dimensions and Spacings of Steel Dowels (*1*)

Slab Thickness (mm)	Dowel Diameter (mm)	Dowel Length (mm)	Dowel Spacing (mm)
152 - 178	19	457	305
203 - 305	25	483	305
330 - 406	32	508	381
432 - 508	38	508	457
533 - 610	51	610	457

Note: The above criteria are given in FAA AC/5320-6C in customary units (inches). THE FAA does not currently use SI criteria for pavement design. (1 mm = 0.0394 in.)

TABLE 2 Results from Denver International Airport

Statistic	Measured LTE_δ	Backcalculated K (MPa/m)	f	LTE_σ	LT (%)
		RUNWAY 17-35 (ϵ/ℓ = 0.150, n = 24)			
Mean	0.704	592,627	4.888	0.237	19.1
COV (%)	10.2	86.3	54.1	18.7	14.7
Maximum	0.859	2,287,066	13.089	0.356	26.2
Minimum	0.576	185,190	2.249	0.176	14.9
Range	0.283	2,101,876	10.840	0.180	11.3
		RUNWAY 16-34 (ϵ/ℓ = 0.151, n = 45)			
Mean	0.715	589,290	4.874	0.242	19.4
COV (%)	8.4	43.5	31.4	13.4	11.0
Maximum	0.811	1,268,721	8.500	0.305	23.4
Minimum	0.520	130,933	1.688	0.154	13.3
Range	0.291	1,137,787	6.812	0.151	10.0
		CONCOURSE B/C (ϵ/ℓ = 0.135, n = 70)			
Mean	0.867	1,739,474	15.255	0.358	26.3
COV (%)	2.1	28.8	15.6	5.7	4.2
Maximum	0.908	3,558,170	23.712	0.420	29.6
Minimum	0.821	874,391	9.255	0.299	23.0
Range	0.087	2,683,779	14.457	0.120	6.5
		APRON 8-26 (ϵ/ℓ = 0.154, n = 45)			
Mean	0.842	2,394,918	11.848	0.343	25.5
COV (%)	3.8	57.4	34.4	11.6	8.4
Maximum	0.914	6,754,713	23.519	0.444	30.7
Minimum	0.787	1,114,239	7.324	0.291	22.5
Range	0.128	5,640,474	16.195	0.153	8.2

1 MPa/m = 3.684 psi/in.

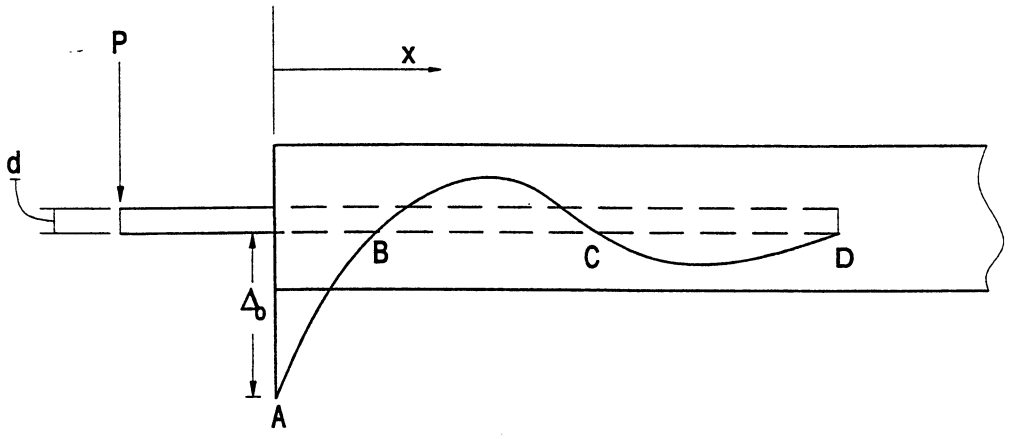
FIGURE 1 Friberg's (*2*) Analysis of Dowel Bar Support

FIGURE 2 Printout of Spreadsheet for Mechanistic Design of Dowels

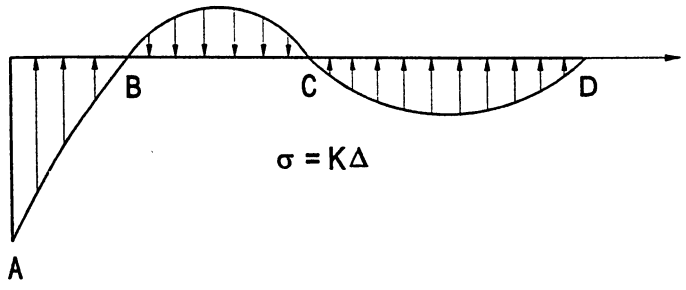
FIGURE 3 Effect of Load Size and Joint Opening on Load Transfer

FIGURE 4 Effect of Modulus of Dowel Support and Joint Opening on Load Transfer

FIGURE 5 Pavement Structure, Denver International Airport



(a) Relative dowel-concrete deflection diagram



(b) Bearing stress diagram

FIGURE 1 Friberg's (*2*) Analysis of Dowel Bar Support

Dowel Design Chart

Required Input			
Thickness of Slab:	h =	0.3	L
Modulus of Subgrade Reaction:	k =	55	F/L^3
Radius of Loaded Area:	a =	0.15	L
Dowel Diameter:	d =	0.038	L

Optional Input (May Be Changed at Designer's Discretion)			
Modulus of Elasticity of PCC:	E =	27,600	F/L^2
Poisson's Ratio of PCC:	μ =	0.15	
Modulus of Elasticity of Dowel:	E_d =	200,000	F/L^2
Possion's Ratio of Dowel:	μ_d =	0.3	
Modulus of Dowel Reaction:	K =	400,000	F/L^3
Dowel Spacing 1:	s_1 =	0.3	L
Dowel Spacing 2:	s_2 =	0.38	L
Dowel Spacing 3:	s_3 =	0.46	L

Calculated Parameters			
Radius of Relative Stiffness:	ℓ =	1.037	L
Loaded Area:	A =	0.071	L^2
Equivalent Length of Square Loaded Area:	2ε =	0.266	L
Dimensionless Load Ratio:	ε / ℓ =	0.128	
Dowel Moment of Inertia:	I_d =	1.0235E-07	L^4
Effective Shear Area:	A_z =	0.0010207	L^2

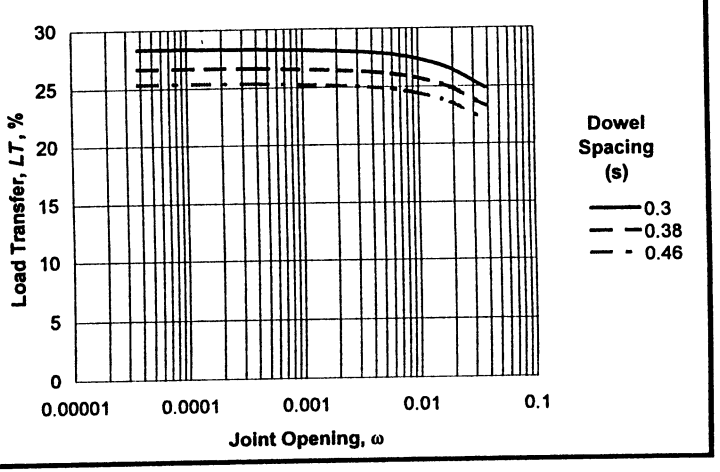


FIGURE 2 Printout of Spreadsheet for Mechanistic Design of Dowels

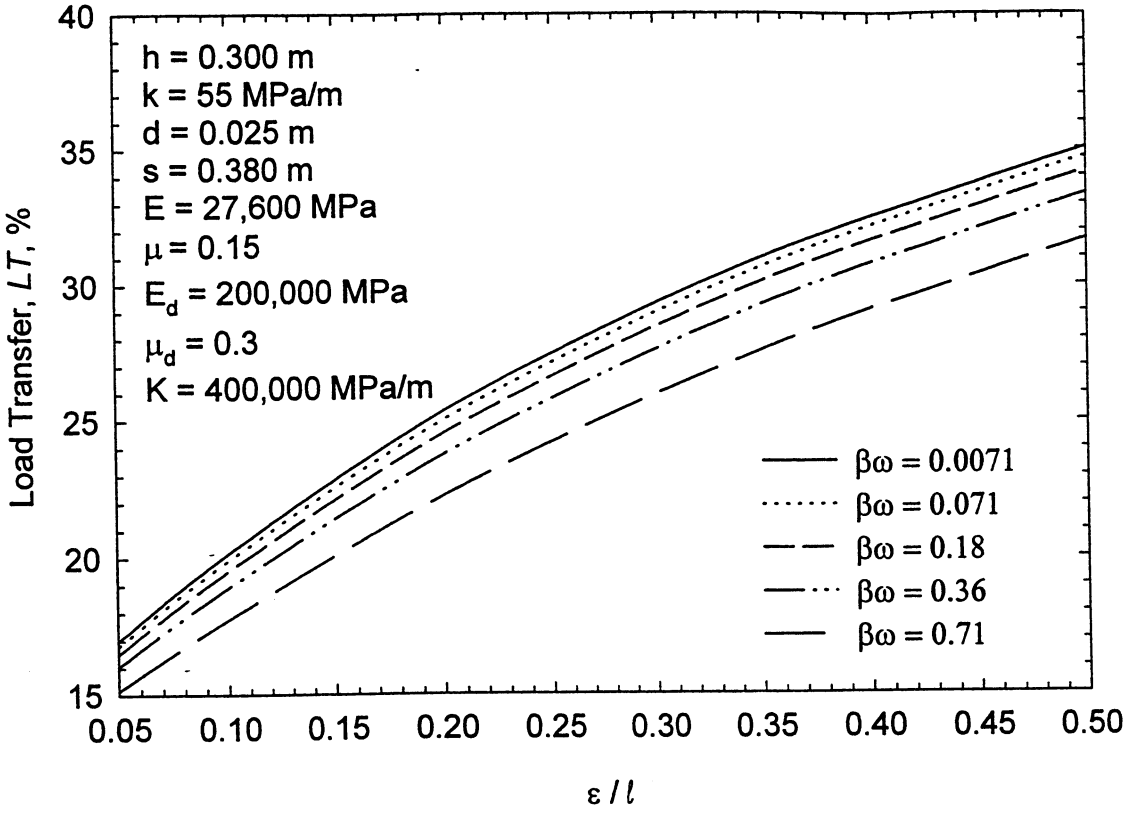


FIGURE 3 Effect of Load Size and Joint Opening on Load Transfer

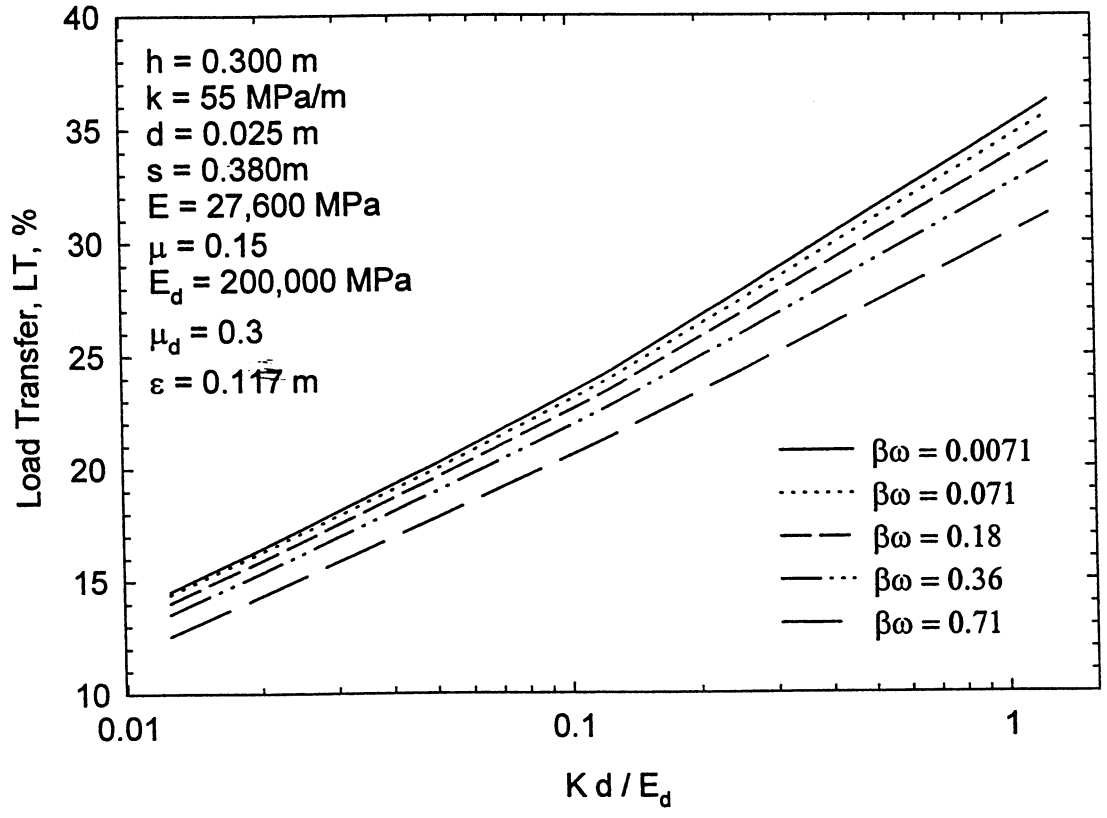


FIGURE 4 Effect of Modulus of Dowel Support and Joint Opening on Load Transfer

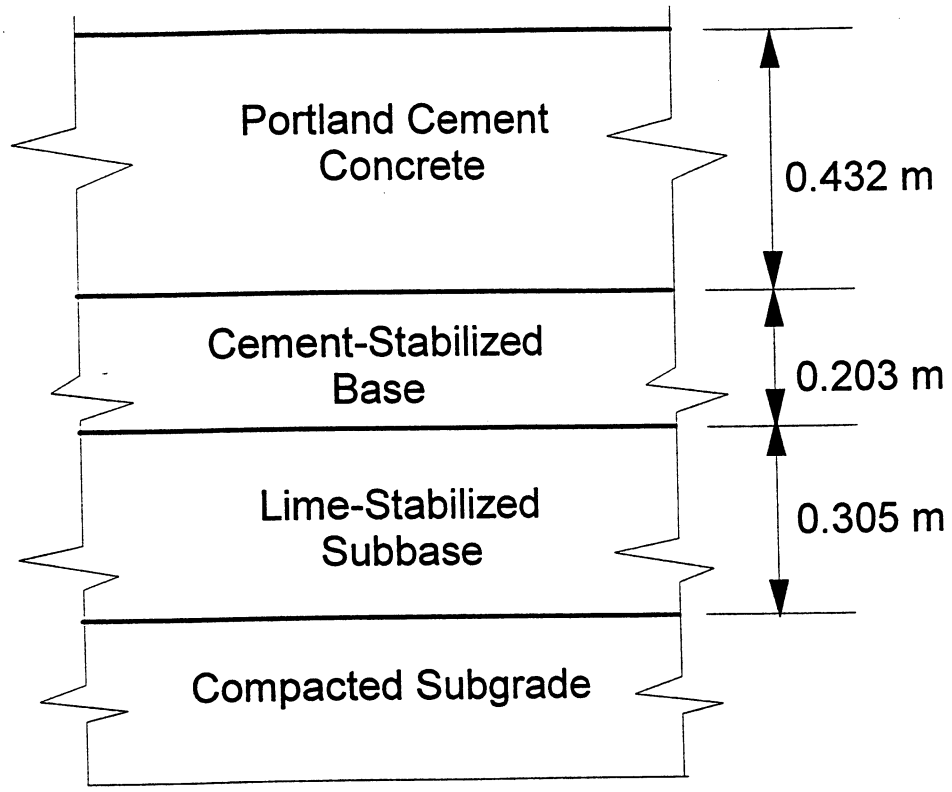


FIGURE 5 Pavement Structure, Denver International Airport

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