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PARAMETER STUDY OF LOAD TRANSFER AND CURLING EFFECTS ON RIGID PAVEMENT DEFLECTIONS

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ABSTRACT

Extensive re-backcalculation analysis of the test sections of the Long Term Pavement Performance (LTPP) general pavement studies indicated that extreme difficulties in interpreting in situ deflection measurements of rigid pavements has been encountered, probably due to the effects of temperature curling, moisture warping and loss of subgrade support. Thus, the effects of adjacent slabs and temperature curling on rigid pavement deflections were investigated in this study.

The ILLISLAB finite element program was used for the analysis. Both dense liquid and elastic solid foundation options were analyzed. To allow the analysis of a curled slab resting on an elastic solid foundation, some proper corrections have been made and verified. Two additional dimensionless variables were identified for the curling effects on elastic solid foundation. Both doweled and undoweled joints were treated as having shear load transfer only. Many factorial finite element runs have been carefully selected and conducted to obtain generalized deflection databases. Prediction models for deflection adjustment factors were developed using local regression techniques. Continuous research effort is still underway to develop an integrated backcalculation program to facilitate the analysis of more practical rigid pavement backcalculation problems.

KEY WORDS

Concrete (rigid) pavements, deflection, load transfer, curling, ILLISLAB, finite element analysis, dimensional analysis, backcalculation, nondestructive deflection testing (NDT)

INTRODUCTION

Nondestructive deflection testing (NDT) devices have been widely adopted to obtain surface deflection data in order to evaluate existing pavement conditions using backcalculation procedures. Hoffman and Thompson (1981) proposed the AREA concept to backcalculate the modulus values of a rigid pavement system. Ioannides *et al.* (1989) indicated that there exists a unique relationship between AREA and the radius of relative stiffness for a given load radius and pre-specified sensor locations. Closed-form backcalculation procedures and graphical solutions for concrete pavements with a single slab layer (Ioannides *et al.* 1989; Ioannides 1990; Li *et al.* 1996; Fwa *et al.* 1998) are currently available. Li *et al.* (1997, 1998) further proposed a backcalculation algorithm for infinitely large rigid pavements with two slab layers through the use of an equivalent single slab layer based on the concept of equivalent flexural rigidity. Hall (1991) solved Losberg's deflection equation through direct integration of Bessel functions using Microsoft FORTRAN IMSL library and presented two nonlinear regression models for the unique relationship between AREA and the radius of relative stiffness using falling weight deflectometers (FWD). This approach was adopted by AASHTO (1993) for the evaluation of existing concrete pavements and for the design of overlays. Crovetti (1994) further indicated that finite slab size, the locations of loading plate (interior, edge and corner of the slab), and the presence of adjacent slabs or a tied concrete shoulder may all affect pavement surface deflections.

Lin *et al.* (1998) validated the applicability of the backcalculation formulation proposed by Hall and Mohseni (1991) with measured deflections by a series of road rater tests and predictions by the ILLISLAB program. The study was based on the results of a pilot study on the structural characteristics and design of rigid pavements for the construction of the Second Freeway in Taiwan. Lee *et al.* (1997, 1998) further proposed a modified deflection ratio procedure based on the principles of dimensional analysis for the backcalculation of concrete pavements using various NDT devices, i.e., dynaflect, road rater, and FWD. Prediction models were developed using the two-step modeling approach proposed by Lee and Darter (1994b) for three different loading plate locations and implemented in a prototype backcalculation program (TKUBAK) for a finite single slab.

It is noted, however, that in most practical cases the effect of adjacent slabs should play an important role for rigid pavement backcalculation under edge and corner loading conditions. Extensive re-backcalculation of general pavement study (GPS) test sections of the long term pavement performance (LTPP) program (1997) was not very successful. Particularly, extreme difficulties in interpreting in situ deflection measurements of rigid pavements has been encountered using multi-layered elastic backcalculation programs, probably due to the effects of temperature curling, moisture warping and loss of subgrade support. Thus, the effects of adjacent slabs and temperature curling on rigid pavement deflections will be further investigated using plate theory approach.

CLOSED-FORM DEFLECTION EQUATIONS

Losberg (1960) has provided the following equations for the deflection of a Portland cement concrete (PCC) slab resting on a dense liquid foundation (Winkler) and an elastic solid foundation under a uniformly distributed load:

$$w = \begin{cases} \dfrac{P}{\pi a}\displaystyle\int_0^\infty \frac{J_0(\alpha r)J_1(\alpha a)}{k + D\alpha^4} d\alpha & \text{Winkler Foundation} \\ \dfrac{2P}{\pi a C}\displaystyle\int_0^\infty \frac{J_0(\alpha r)J_1(\alpha a)}{\alpha\left(1+\alpha^3\ell_e^3\right)} d\alpha & \text{Elastic Solid Foundation} \end{cases} \tag{1}$$

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}}, \quad \ell_e = \sqrt[3]{\frac{Eh^3(1-\mu_s^2)}{6(1-\mu^2)E_s}} = \sqrt[3]{\frac{2D}{C}} \tag{2}$$

$$C = \frac{E_s}{(1-\mu_s^2)}, \quad D = \frac{Eh^3}{12\left(1-\mu^2\right)} \tag{3}$$

Where:

w = surface deflection at any radial distance r, [L];
J_0, J_1 = Bessel function of zero order and first order, respectively;
P = applied load, [F];
a = radius of the applied circular load, [L];
h = thickness of PCC slab, [L];
C = modified modulus of elasticity of the subgrade, [FL^{-2}];
D = bending stiffness of the slab, [FL];
k = modulus of subgrade reaction, [FL^{-3}];
E, E_s = modulus of elasticity of the PCC slab and subgrade, [FL^{-2}];
μ, μ_s = Poisson's ratio of the PCC slab and subgrade; and
ℓ, ℓ_e = radius of relative stiffness for Winkler foundation and elastic solid foundation, [L].
[F] and [L] represent the dimensions of force and length, respectively.

Based on the assumptions of an infinite or semi-infinite slab over a Winkler foundation, Westergaard has also presented the following maximum deflection equations for three circular loading conditions, i.e., interior, edge, and corner for a Poisson's ratio of 0.15 (Ioannides *et al.* 1985):

$$w_0 = \begin{cases} \dfrac{P}{8k\ell^2}\left\{1+\dfrac{1}{2\pi}\left[\ln\left(\dfrac{a}{2\ell}\right)-0.673\right]\left(\dfrac{a}{\ell}\right)^2\right\} & \text{Interior Loading} \\ \dfrac{0.431P}{k\ell^2}\left[1-0.82\left(\dfrac{a}{\ell}\right)\right] & \text{Edge Loading} \\ \dfrac{P}{k\ell^2}\left[1.1-0.88\left(\sqrt{2}\dfrac{a}{\ell}\right)\right] & \text{Corner Loading} \end{cases} \tag{4}$$

Where w_0 is the Westergaard's maximum deflection at the interior, edge, and corner of the slab. Furthermore, according to Losberg, the maximum deflection at the center of an interior load for elastic solid foundation may also be expressed as follows:

$$w_0 = \frac{2P}{C\ell_e}\left[0.19245-0.0272\left(\frac{a}{\ell_e}\right)^2+0.0199\left(\frac{a}{\ell_e}\right)^2\ln\left(\frac{a}{\ell_e}\right)\right] \tag{5}$$

Crovetti (1994) further proposed the following two equations to estimate the maximum deflection of an edge loading and a corner loading for elastic solid foundation:

$$w_0 = \begin{cases} \frac{2P}{C\ell_e}\left[0.441-1.022\left(\frac{a}{\ell_e}\right)+1.175\left(\frac{a}{\ell_e}\right)^2\right] & \textit{Edge Loading} \\ \frac{2P}{C\ell_e}\left[0.7383-1.036\left(\frac{a}{\ell_e}\right)+0.577\left(\frac{a}{\ell_e}\right)^2\right] & \textit{Corner Loading} \end{cases} \quad (6)$$

MODIFICATION AND VALIDATION OF F.E. PROGRAM

The ILLISLAB finite element (F.E.) program (Korovesis 1990) originally developed at the University of Illinois was used for the analysis due to its simplicity and proven accuracy. A more realistic assumption of partial contact between the slab-subgrade interface was allowed and the self-weight of the concrete slab was also considered. To allow the analysis of a curled slab resting on an elastic solid foundation, some necessary corrections have been made to the original ILLISLAB codes using Microsoft FORTRAN PowerStation software package (1994) to reflect minor syntax errors and differences between workstation and personal computer versions. The analysis of loading plus curling on elastic foundation is not possible without such, since all nodes are showing same deflections or unreasonable results while using the original codes. The validity of these modifications has been verified numerically and graphically through extensive investigations of the structural response characteristics of the finite element model under various loading and curling conditions (Sheu 1999). The characteristics of slab deflections subjected to individual and combined effects of a single-wheel corner load and a temperature differential were also investigated. The fundamental difference of slab deflections in both Winkler and elastic solid foundations was more pronounced in the cases of loading plus self-weight and self-weight only. Thus, it is noted that the more realistic assumption of partial contact between the slab-subgrade interface as well as the self-weight of the concrete slab should be considered in the analysis of slab deflections.

PARAMETER STUDY OF THE EFFECT OF TEMPERATURE CURLING

Since the center of the slab was assumed to be flat and the deflection was zero, Westergaard (1926) did not explicitly consider the self-weight effect in his deflection equation. However, the effect of self-weight and the loss of subgrade support are included in the ILLISLAB model through an iterative procedure (Korovesis 1990). The deflection at the center is determined by $\gamma h/k$, where γ is the unit weight of the concrete slab, $[FL^{-3}]$. To account for the aforementioned theoretical difference, Lee and Darter (1994) identified the following two dimensionless variables (D_p and D_γ) and a concise relationship for the combination effect of loading plus curling on Winkler foundation:

$$D_\gamma = \frac{\gamma h^2}{k\ell^2} \quad (7)$$

$$D_p = \frac{Ph}{k\ell^4} = 12(1-\mu^2)\frac{P}{Eh^2} \quad (8)$$

$$\frac{\sigma}{E}, \frac{\delta h}{\ell^2}, \frac{qh}{k\ell^2} = f\left(\frac{a}{\ell}, \alpha\Delta T, \frac{L}{\ell}, \frac{W}{\ell}, \frac{\gamma h^2}{k\ell^2}, \frac{Ph}{k\ell^4}\right) \quad (9)$$

Where σ and q = slab bending stress and vertical subgrade stress; δ = slab deflection; α = slab thermal expansion coefficient, [T^{-1}]; ΔT = linear temperature differential through the slab thickness, [T]; and [T] = dimension of temperature.

Similarly, there exists no closed-form solution for the case of loading plus curling on elastic solid foundation. We will further assume the exchangeability of the mechanistic variables using the principles of dimensional analysis, such as ℓ versus ℓ_e; and ℓ^2/h versus ℓ_e^2/h, for Winkler foundation and elastic foundation, respectively. Where ℓ^2/h is the deflection factor identified by Lee and Darter (1994), has the same dimension as length, and can be used as an indicator for the extent of loss of subgrade support. By taking the ratio of self-weight deflection versus ℓ_e^2/h, the following dimensionless parameter, $D_{\gamma e}$ was defined to represent the relative deflection stiffness due to the self-weight of the concrete slab and the possible loss of subgrade support:

$$D_{\gamma e} = \frac{\gamma h^2}{E_s \ell_e} \qquad (10)$$

It was hypothesized that the resulting ILLISLAB deflection due to curling alone may be well characterized by L/ℓ_e, W/ℓ_e, $\alpha\Delta T$, as well as this additional parameter ($D_{\gamma e}$). While keeping the above four parameters constant but varying other pertinent input parameters at the same time, sixteen ILLISLAB runs were performed to validate this hypothesis. The ILLISLAB dimensionless deflections ($\delta h/\ell_e^2$) were numerically confirmed to be equal to each other as given in Table 1.

Table 1 Identification of $D_{\gamma e}$ Factor for Curling Only on Elastic Foundation

ΔT (°F)	α (10^{-6}/°F)	H (in.)	E (Mpsi)	E_s (ksi)	L (in.)	W (in.)	ℓ_e (in.)	γ (pci)	Deflection (in.)	$\delta h/\ell_e^2$ (10^{-3})
10	11	5.66	5	5.5	112.8	169.3	28.2	0.145	0.0416	0.296
10	11	6.76	4	7.5	112.8	169.3	28.2	0.139	0.0349	0.296
10	11	15.53	3	8.5	225.7	338.5	56.4	0.060	0.0613	0.299
10	11	18.44	2	9.5	225.7	338.5	56.4	0.047	0.0514	0.298
20	5.5	5.66	5	5.5	112.8	169.3	28.2	0.145	0.0416	0.296
20	5.5	6.76	4	7.5	112.8	169.3	28.2	0.139	0.0349	0.296
20	5.5	15.53	3	8.5	225.7	338.5	56.4	0.060	0.0613	0.299
20	5.5	18.44	2	9.5	225.7	338.5	56.4	0.047	0.0514	0.298
30	3.67	5.66	5	5.5	112.8	169.3	28.2	0.145	0.0416	0.296
30	3.67	6.76	4	7.5	112.8	169.3	28.2	0.139	0.0349	0.296
30	3.67	15.53	3	8.5	225.7	338.5	56.4	0.060	0.0614	0.299
30	3.67	18.44	2	9.5	225.7	338.5	56.4	0.047	0.0514	0.298
40	2.75	5.66	5	5.5	112.8	169.3	28.2	0.145	0.0416	0.296
40	2.75	6.76	4	7.5	112.8	169.3	28.2	0.139	0.0349	0.296
40	2.75	15.53	3	8.5	225.7	338.5	56.4	0.060	0.0613	0.299
40	2.75	18.44	2	9.5	225.7	338.5	56.4	0.047	0.0514	0.298

Note: L/ℓ_e = 8.0, W/ℓ_e = 6.0, $\alpha\Delta T$ = 1.1E-04, and $D_{\gamma e}$ = 3.0E-05. (1 in = 2.54 cm, 1 °F = 5/9 °C, 1 psi = 6.9 kPa, 1 pci = 0.271 kPa/mm, 1lbs = 4.45 N)

By the same token, this "deflection-ratio" concept was applied again in searching for another dimensionless parameter for the effect of an applied wheel loading on a curled slab due to a linear temperature differential on elastic solid foundation. Losberg's deflection equation (1) may be repressed as the relationship of a nondimensional deflection (w^*) with normalized radial distance ($s = r/\ell$ or r/ℓ_e) and normalized load radius (a/ℓ or a/ℓ_e) as follows:

$$w^* = \begin{cases} \dfrac{wk\ell^2}{P} = \dfrac{wD}{P\ell^2} = f\left(\dfrac{a}{\ell}, \dfrac{r}{\ell}\right) & \textit{Winkler Foundation} \\[2ex] \dfrac{wC\ell_e}{2P} = \dfrac{wD}{P\ell_e^2} = f\left(\dfrac{a}{\ell_e}, \dfrac{r}{\ell_e}\right) & \textit{Elastic Foundation} \end{cases} \tag{11}$$

The maximum deflection can be represented by two parameters: a/ℓ_e and $2P/(C\ell_e)$. The second one is a deflection factor, which is analogous to $P/(E_s\ell_e)$ and has the same dimension as length. By taking the ratio of this deflection factor $P/(E_s\ell_e)$ versus ℓ_e^2/h, the following dimensionless parameter, D_{Pe}, which may be used as an indicator to represent the relative deflection stiffness due to the external wheel load and the loss of subgrade support:

$$D_{Pe} = \frac{Ph}{E_s\ell_e^3} \tag{12}$$

Thus, it was also hypothesized that the following six dimensionless parameters: a/ℓ_e, L/ℓ_e, W/ℓ_e, $\alpha\Delta T$, $D_{\gamma e}$ and D_{Pe} would adequately describe the primary structural responses for the combined effect of loading plus thermal curling. To numerically validate this hypothesis, sixteen ILLISLAB runs were performed and summarized in Table 2.

Table 2 Identification of D_{Pe} Factor for Loading plus Curling on Elastic Foundation

ΔT (°F)	α (10^{-6}/°F)	h (in.)	E (Mpsi)	E_s (ksi)	L (in.)	W (in.)	ℓ_e (in.)	γ (pci)	P (lbs)	a (in.)	Deflection (in.)	$\delta h/\ell_e^2$ (10^{-3})
10	11	5.66	5	5.5	112.8	169.3	28.2	0.145	654	2.82	0.0448	0.319
10	11	6.76	4	7.5	112.8	169.3	28.2	0.139	747	2.82	0.0376	0.319
10	11	15.53	3	8.5	225.7	338.5	56.4	0.060	2950	5.64	0.0662	0.323
10	11	18.44	2	9.5	225.7	338.5	56.4	0.047	2775	5.64	0.0554	0.321
20	5.5	5.66	5	5.5	112.8	169.3	28.2	0.145	654	2.82	0.0448	0.319
20	5.5	6.76	4	7.5	112.8	169.3	28.2	0.139	747	2.82	0.0376	0.319
20	5.5	15.53	3	8.5	225.7	338.5	56.4	0.060	2950	5.64	0.0662	0.323
20	5.5	18.44	2	9.5	225.7	338.5	56.4	0.047	2775	5.64	0.0554	0.321
30	3.67	5.66	5	5.5	112.8	169.3	28.2	0.145	654	2.82	0.0448	0.319
30	3.67	6.76	4	7.5	112.8	169.3	28.2	0.139	747	2.82	0.0376	0.319
30	3.67	15.53	3	8.5	225.7	338.5	56.4	0.060	2950	5.64	0.0662	0.323
30	3.67	18.44	2	9.5	225.7	338.5	56.4	0.047	2775	5.64	0.0554	0.321
40	2.75	5.66	5	5.5	112.8	169.3	28.2	0.145	654	2.82	0.0448	0.319
40	2.75	6.76	4	7.5	112.8	169.3	28.2	0.139	747	2.82	0.0376	0.319
40	2.75	15.53	3	8.5	225.7	338.5	56.4	0.060	2950	5.64	0.0662	0.323
40	2.75	18.44	2	9.5	225.7	338.5	56.4	0.047	2775	5.64	0.0554	0.321

Note: $a/\ell_e = 0.1$, $L/\ell_e = 8.0$, $W/\ell_e = 6.0$, $\alpha\Delta T = 1.1\text{E-}04$, $D_{\gamma e} = 3.0\text{E-}05$, and $D_{Pe} = 3.0\text{E-}05$. (1 in. = 2.54 cm, 1 °F = 5/9 °C, 1 psi = 6.9 kPa, 1 pci = 0.271 kPa/mm, 1lbs = 4.45 N)

While keeping these six parameters constant but changing any individual input variables, the resulting ILLISLAB dimensionless deflections ($\delta h/\ell_e^2$) were numerically confirmed to be equal to each other. Consequently, the following relationship, which may well represent the combined effect of loading plus thermal curling on elastic solid foundation, was identified:

$$\frac{\sigma}{E}, \frac{\delta h}{\ell_e^2}, \frac{qh}{E_s \ell_e} = f\left(\frac{a}{\ell_e}, \alpha\Delta T, \frac{L}{\ell_e}, \frac{W}{\ell_e}, \frac{\gamma h^2}{E_s \ell_e}, \frac{Ph}{E_s \ell_e^3}\right) \quad (13)$$

PARAMETER STUDY OF THE EFFECT OF ADJACENT SLABS

The presence of adjacent slabs has a great impact on the deflection of rigid pavements, especially for edge and corner loading conditions. However, due to some persistent problems in running the ILLISLAB codes for multiple slabs on elastic solid foundation, the following numerical analysis is only limited to slabs resting on Winkler foundation. Three loading conditions, i.e., corner, longitudinal edge and transverse edge loading, were analyzed for doweled and undoweled pavements resting on Winkler foundation. The pertinent input parameters are as follows: two adjacent slabs, finite slab length (L) = finite slab width (W) = 5.73 m (18.8 ft), slab thickness h = 23.0 cm (9.06 in.), tire pressure p = 6.9 MPa (100 psi), loaded radius a = 28.66 cm (11.28 in.), μ=0.15, E_c=27.6 GPa (4E+06 psi).

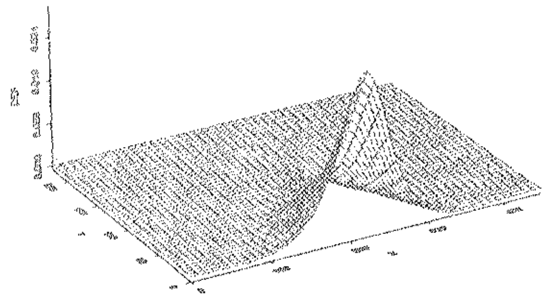
The resulting modulus of subgrade reaction k = 108.4 kPa/mm (400 pci), aggregate interlock factor AGG = 3.89E+03 GPa (5.64E+08 psi). Properties of the dowel bars: dowel diameter d = 44.5 mm (1.75 in.), dowel modulus of elasticity = 248 GPa (3.60E+07 psi), dowel spacing =30.48 cm (12 in.), dowel Poisson's ratio = 0.25, dowel concrete interaction DCI = 20.6 GPa (2.99E+06 psi). The width of joint opening is assumed to be ω = 3.6 mm (0.14 in.). The results of numerical analysis and graphical interpretation as given in Figure 1 showed that the unloaded slab had higher deflection than the other loaded slab, thereby contradicting with the reality for dowel-jointed pavements. Note that only half of the slab width was shown in Figure 1(e) and 1(f) due to symmetry loading.

This observation also agrees very well with earlier literature presented by Guo, *et al.* (1993, 1995). Based on theoretical analysis and numerical examples, Guo, *et al.* have concluded that "the neglect of equilibrium condition of the dowel-bar stiffness matrix causes significant differences in prediction of dowel-bar forces and critical slab stresses" in the earlier version of JSLAB and the existing ILLISLAB FE programs. Consequently, a component dowel-bar model has been developed and implemented in the JSLAB-92 program. However, with the prevailing understanding of in situ phenomena (Tabatabai and Barenberg 1978), the effect of adjacent slabs will be treated as having pure shear load transfer (no moment transfer) for both doweled and undoweled pavements in this study.

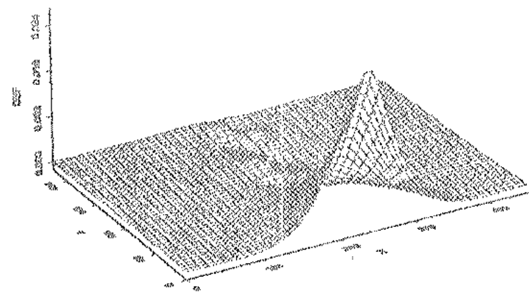
According to earlier studies conducted by Ioannides and Korovesis (1990, 1992), the deflection load transfer efficiency (LTE_δ) is defined by the ratio of the deflection measurements at the loaded (δ_L) and unloaded (δ_U) side of the slab. Korovesis (1990) has also proposed the following regression equation to backcalculate the in situ joint stiffness or the aggregate interlock factor (AGG):

$$LTE_\delta = \frac{1}{0.01 + 0.012\left(\frac{AGG}{k\ell}\right)^{-0.849}} \quad (14)$$

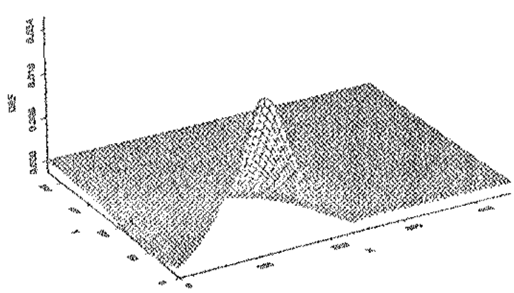
Special research efforts have been conducted through numerical examples as well as extensive search through the ILLISLAB codes for the effect of adjacent slabs in this study. It



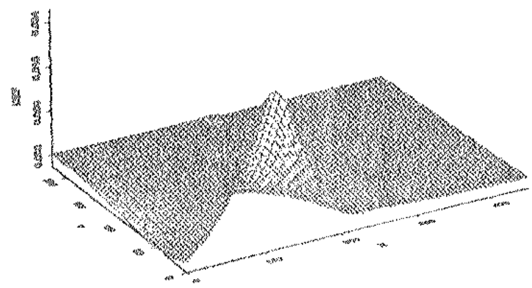
(a) Corner Loading (Undoweled)



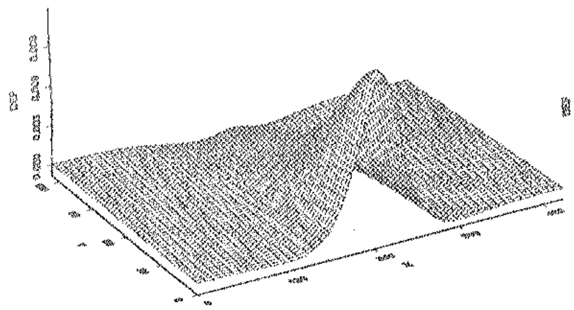
(b) Corner Loading (Doweled)



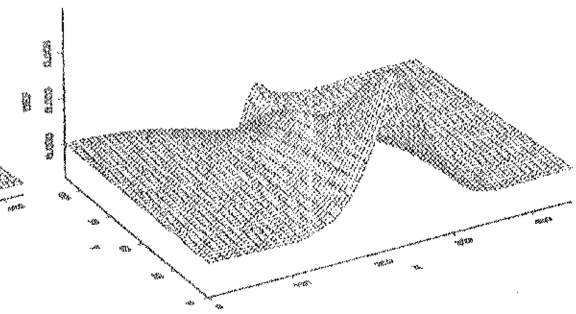
(c) Longitudinal Edge Loading (Undoweled)



(d) Longitudinal Edge Loading (Doweled)



(e) Transverse Edge Loading (Undoweled)



(f) Transverse Edge Loading (Doweled)

Figure 1 Effects of Undoweled and Doweled Joints on Slab Deflections

was noted that both doweled and undoweled joints share the same stiffness matrix if only pure shear load transfer is considered. The same joint stiffness matrix was also used for both Winkler and elastic foundations in the ILLISLAB codes. The normalized load radius (a/ℓ) has no effect on the joint stiffness matrix. The effect of adjacent slabs can be determined by a deflection adjustment factor (R_{LTE}), defined as the ratio of the deflections on multiple slabs (δ_m) and a single slab (δ_s) as follows:

$$R_{LTE} = \frac{\delta_m}{\delta_s} = f(LTE_\delta) \qquad (15)$$

It is worth of mentioning that this deflection adjustment factor (R_{LTE}) is independent of the normalized load radius (a/ℓ) and different foundation models, i.e., Winkler and elastic foundations. A series of ILLISLAB FE runs were conducted based on the following data ranges: L/ℓ=W/ℓ=8.0, a/ℓ=0.05~0.4, AGG/$k\ell$=0.00025~50000 to illustrate this relationship. As shown in Figure 2, this curve may be well fitted by a second-degree polynomial regression equation as:

$$R_{LTE} = 0.992127 - 0.008069961(\text{LTE}_\delta) + 0.00003178733(\text{LTE}_\delta)^2 \qquad (16)$$

In which, the number of observation (N) is 150; the standard error of estimate (SEE) is 0.0052; and the coefficient of determination (R-squared) is 0.999.

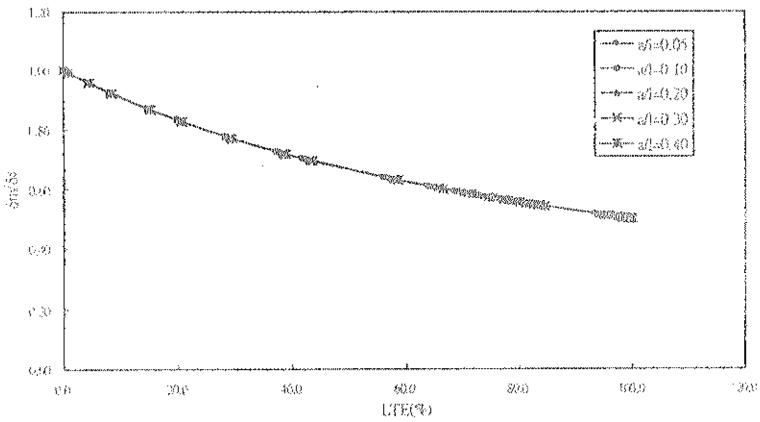


Figure 2 Relationship of Deflection Adjustment Factor (R_{LTE}) versus LTE_δ

DEVELOPMENT OF PAVEMENT DEFLECTION DATABASES

With the two dimensionless parameters identified in this study, it is possible to develop several generalized pavement deflection databases for future predictions and backcalculation purposes. Many series of factorial finite element runs over a wide range of pavement designs have been carefully selected and conducted.

Effect of Finite Slab Size

According to earlier studies using the principles of dimensional analysis, the effect of finite slab size on deflection measurements may be determined by:

$$R_{LW} = \frac{\delta_i}{\delta_w} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}\right) \text{ or } R_{LW} = \frac{\delta_i}{\delta_{Losberg}} = f\left(\frac{a}{\ell_e}, \frac{L}{\ell_s}, \frac{W}{\ell_e}\right) \qquad (17)$$

In which, δ_i = ILLISLAB deflection, [L]; δ_W = Westergaard's maximum deflection equations for Winkler foundation (interior, edge and corner), [L]; $\delta_{Losberg}$ = Maximum deflection equations by Losberg (interior) or Crovetti's regression equations (edge and corner) for elastic solid foundation, [L]; and R_{LW} = Deflection adjustment factor for finite slab size, [L].

Separate databases for the effect of finite slab size were developed for three loading conditions, i.e., interior, edge and corner loading, for both Winkler and elastic foundations. The ranges of dimensionless parameters were chosen as follows: L/ℓ=2~7, W/ℓ=2~7, and a/ℓ=0.05~0.4.

Effect of Adjacent Slabs

As discussed earlier, the effect of adjacent slabs can be well characterized by equation (16). The factorial ILLISLAB FE runs were based on the following data ranges: $L/\ell=W/\ell=8.0$, a/ℓ=0.05~0.4, $AGG/k\ell$=0.00025~50000. This model can be used for both Winkler and elastic foundations. However, no adjustment is needed for the case of interior loading on infinitely large slabs.

Effects of Thermal Curling

It is worth mentioning that the results obtained from ILLISLAB F.E. analysis are theoretical "absolute deflections". However, these results are different from the in situ deflection measurements of a curled slab. For real world problems, the "relative deflections" are measured as the difference in deflection between the prior-to-loading and after-loading conditions. The effect of a curled slab on the "relative deflections" measured in field may be determined by the following relationship:

$$R_T = \frac{\delta_{T+P} - \delta_T}{\delta_w} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \alpha\Delta T, \frac{\gamma h^2}{k\ell^2}, \frac{Ph^2}{k\ell^4}\right) \tag{18}$$

Where, δ_{T+P} = ILLISLAB deflections for loading plus curling, [L]; δ_T = ILLISLAB deflections due to thermal curling, [L]; and R_T = Deflection adjustment factor for the effect of a curled slab. Separate databases for loading plus curling and curling alone were developed based on the following ranges of dimensionless variables: L/ℓ =2~17, W/ℓ =2~17, a/ℓ =0.05~0.4, $\alpha\Delta T$=-2.2E-04 ~ 2.2E-04, D_γ=1.8E-05 ~ 3.07E-05, D_P=3.5E-05 ~ 60.0E-05.

For illustration purposes, the complicated interactions among interior / corner loading, thermal curling, and self-weight of the slab are shown in Figure 3 for the case of a/ℓ=0.05 and W/ℓ=2.0, where dimensionless deflection is equal to $\delta h/\ell^2$.

Considering an interior load applied on an infinite-sized slab (L/ℓ =17, W/ℓ =17) resting on Winkler foundation, Figure 4 depicts the primary relationship among R_T, $\alpha\Delta T$, and a/ℓ by neglecting the possible influence of D_P and D_γ. Generally speaking, the effect of thermal curling on measured relative deflections is negligible for an infinite-sized slab and when $\alpha\Delta T$ < 1.0E-04. Nevertheless, this effect becomes more pronounced when a/ℓ and $\alpha\Delta T$ increase.

ON-GOING DEVELOPMENT OF AN INTEGRATED BACK-CALCULATION PROGRAM

Through the use of the principles of dimensional analysis and the identification of

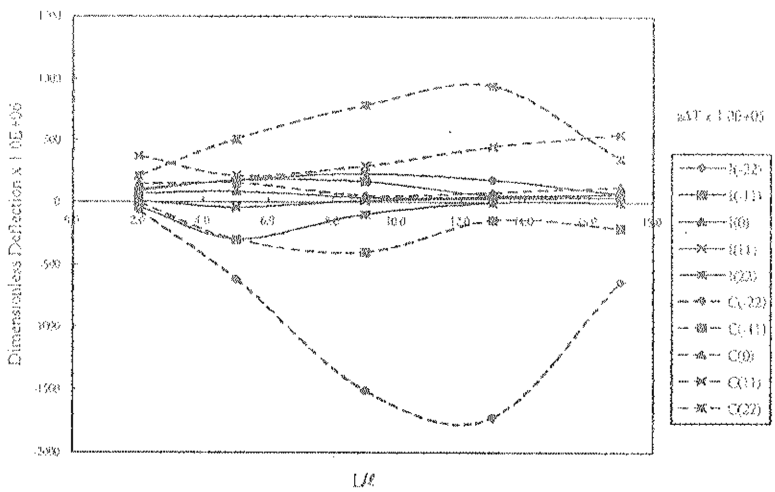


Figure 3 Effect of Loading plus Curling at the Interior (I) or Corner (C)

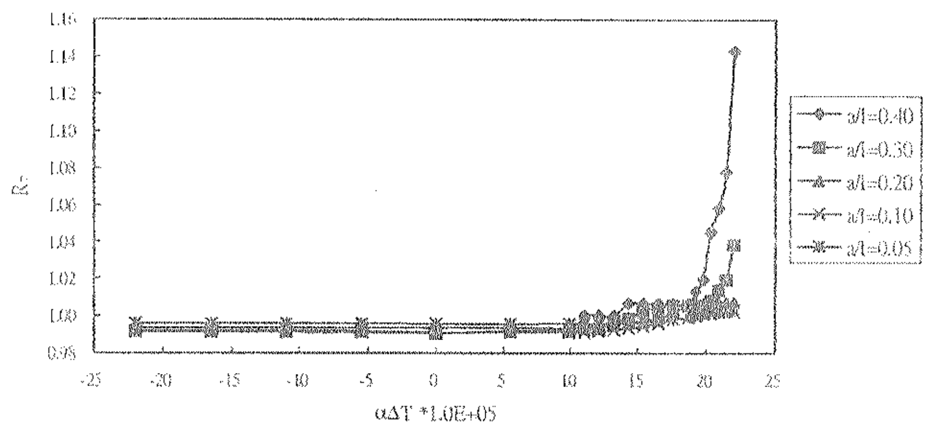


Figure 4 Effect of Thermal Curling on Slab Deflections

dimensionless parameters, this study can cover more practical rigid pavement backcalculation problems. Different backcalculation approaches have been developed that incorporate the widely used AREA deflection basin concept and the modified deflection ratio procedure (Lee *et al.* 1998). A prototype window-based computer program (TKUBAK) developed earlier using the Microsoft Visual Basic 4.0 software package (1995) is currently valid for a single slab and loading condition only. A closed-form backcalculation procedure, which closely simulates the ILLIBACK program (Ioannides *et al.* 1989), was developed using FORTRAN PowerStation software package (Microsoft, Inc. 1994) in this study.

Application of Locally-Weighted Regression (LOESS) Technique

To model a multi-dimensional response surface so as to obtain more accurate predictions, several popular modeling techniques have been considered. Ripley (1993) discussed many statistical aspects of neural networks and tested it with several benchmark examples against traditional and modern regression techniques, such as generalized discriminant analysis, projection pursuit regression, local regression, tree-based classification, etc. Ripley concluded that in one sense neural networks are little more than non-linear regression and allied optimization methods. "Two-layer networks can approximate arbitrary continuous functions does not change the validity of more direct approximations such as statistical smoothers, which certainly 'learn' very much faster." Projection pursuit regression highlights the value of differentiated units and other training schemes and offers computation shortcuts through forward and backward selection. Statistical and subject-related knowledge can be used to guide modeling in most real-world problems and so enable much more convincing generalization and explanation, in ways which can never be done by 'black-box' learning systems (Ripley, 1993).

In an attempt to increase the accuracy of prediction models using projection pursuit regression technique (Lee and Darter 1994; Lee *et al.* 1997, 1998), the locally weighted regression (LOESS) technique, an approach to regression analysis by local fitting developed by Cleveland and Devlin (1988), was introduced in this study. The LOESS approach uses a smoothing technique for fitting a nonlinear curve to the data points locally, so that any point of the curve depends only on the observations at that point and some specified neighboring points. The number of neighbors (k) is specified as the percentage of the total number of points or "span". Local regression models provide much greater flexibility in fitting a multi-dimensional response surface as a series of many sub-divided regions with single smooth functions of all the predictors. There are no restrictions on the relationships among the predictors. Cleveland and Grosse (1991) provided computational methods for local regression. This algorithm is available in the S-PLUS statistical package (Mathsoft, Inc. 1997). As currently implemented, locally quadratic models may have at most 4 predictor variables and locally linear models may have at most 15 predictors. The original FORTRAN and C codes for the LOESS algorithm can also be obtained from the ftp site: "ftp research.att.com."

CONCLUSIONS AND RECOMMENDATIONS

The effects of load transfer and curling on rigid pavement deflections were investigated in this study. To allow the analysis of a curled slab resting on an elastic solid foundation, some proper corrections have been made. The effect of adjacent slabs was treated as having shear load transfer only (no moment transfer) for both doweled and undoweled pavements. Two additional dimensionless variables have been identified and verified for the effects of loading plus curling for elastic solid foundation through parameter study using the principles of dimensional analysis. Many series of finite element factorial runs over a wide range of pavement designs have been carefully selected and conducted. Several generalized deflection databases were developed for future predictions and backcalculation purposes.

A new regression technique, locally weighted regression (LOESS), was adopted in this study in an attempt to increase the accuracy of prediction models. Prediction models for deflection adjustment factors at different pavement conditions were developed using local regression techniques to more accurately estimate actual pavement responses. A closed-form backcalculation procedure, which closely simulates the ILLIBACK program, was developed in this study. Various prediction models for deflection adjustment factors at different pavement conditions were developed using local regression techniques to estimate actual pavement responses more accurately.

At the current stage, the LOESS prediction models can only be used under the S-PLUS statistical software packages. Continuous research effort is still underway to develop an integrated backcalculation program, which can account for the effects of finite slab sizes, adjacent slabs, and thermal curling to facilitate the analysis of more practical rigid pavement backcalculation problems.

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