

Recent Developments in the Design and Specification of Concrete Pavement Systems

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D. G. Zollinger



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PREFACE

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This special publication addresses important issues that are at the center of future developments in concrete pavement design and construction specification. The papers provided in this document were presented in a series of sessions on key pavement design issues held at ACI conventions in Salt Lake City, Utah; Denver, Colorado; and Atlanta, Georgia, and sponsored by ACI Committees 325, Concrete Pavements, and 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete.

It is anticipated that future design development will most notably center on the use of mechanistic concepts, and utilize important material properties that affect the performance of concrete pavement structures.

The papers in this publication address many different aspects of mechanistic design, such as environmental stress, improved pavement design methodology, approaches to performance-based specification, characterization of joint sealants for design purposes, characterization of concrete strength based on fracture properties, and others. The discussions presented in these papers should provide an avenue by which advancements in the critical areas of pavement design can be made possible for improved future design applications.

Editor

D. G. Zollinger

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Thermal Stresses in Square Shaped Concrete Pavements

by J. Silfwerbrand

Synopsis:

Thermal stresses in concrete pavements might be calculated according to a procedure developed by professor J. Eisenmann. The thermal stresses are dependent on the subgrade stiffness. Soft subgrades result in lower stresses. The Eisenmann procedure has been developed to cover square shaped slabs. This procedure is presented in this paper. Two calculation examples are also presented and discussed.

Keywords: Concrete pavements; square slabs; thermal stresses

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1. INTRODUCTION

Concrete pavements are designed for traffic and thermal stresses. In Sweden, the thermal stresses have been calculated according to professor J. Eisenmann¹. He bases his calculations on an effective span length. In the calculation of the effective span length, he considers the effect of the subgrade reaction using a beam element. Soft subgrades shorten the effective span length and, hence, reduce the thermal stresses. The procedure has been used to calculate thermal stresses under Swedish conditions in highway pavements, industrial pavements, and pavements in tunnels²⁻⁴.

The temperature distribution in a concrete pavement can approximately be divided into two parts: (a) a uniform part and (b) a temperature gradient (Fig. 1). The uniform temperature distribution does not cause any major temperature stresses in jointed concrete pavement because the pavement is practically free to move horizontally at the joints. The temperature gradient causes curling or warping and - if the curling is restrained - thermal stresses. Hence, the immediate cause of the stresses is not the temperature, but the dead load that counteracts the curling tendency of the pavement.

During a warm summer day, the top surface of the pavement is heated more than the bottom surface. A positive temperature gradient develops. The pavement slab curls with the central point moving upwards. The dead load of the pavement counteracts the curling and causes flexural tensile stresses in the bottom of the pavement (Fig. 2, left). During the night, the top surface gets cool more rapidly than the bottom surface. A negative temperature gradient develops and the pavement slab edges move upwards. In this case, the dead load causes flexural tensile stresses at the top of the slab (Fig. 2, right). Traffic loading causes flexural tensile stresses in the bottom of the slab, i.e., in the same part of the slab

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as the positive gradient. Consequently, the positive temperature gradient usually is the most interesting one. In the following two sections, positive temperature gradients are dealt with in beams and slabs, respectively.

2. RESEARCH SIGNIFICANCE

Estimations of thermal stresses are necessary in the design of concrete pavements. Eisenmann's beam theory slightly modified to slabs is used in, e.g., Swedish and German pavement design procedures. The purpose of the research described in this paper is to develop a slab theory based on Eisenmann's assumptions. Some calculation examples presented show that the use of this slab theory leads to decreased calculated thermal stresses.

3. THERMAL STRESSES IN BEAMS

A thorough discussion of thermal stresses in beams is given in Eisenmann¹. If the curling is completely restrained, but horizontal movements are possible (Fig. 3), the temperature stress σ_{temp0} is given by the following expression:

$$\sigma_{\text{temp0}} = \frac{E\alpha\Delta\theta \cdot h}{2} \quad (1)$$

where,

E = modulus of elasticity of concrete

α = coefficient of thermal expansion

$\Delta\theta$ = positive temperature gradient in °C/m (top surface warmest)

A tensile stress $+\sigma_{\text{temp0}}$ develops on the bottom surface of the beam and a compressive stress

$-\sigma_{\text{temp0}}$ develops in the top surface of the beam (Fig. 3).

A beam subjected to a positive temperature gradient, resting on a subgrade, and free at the ends will curl. The central part tends to move upwards. The central point of the beam leaves the support only if the upward displacement due to temperature is greater than the downward displacement due to dead load $q=\gamma bh$.

We obtain:

$$w_{\text{temp}} = \frac{\alpha\Delta\theta L^2}{8} > w_q = \frac{5(\gamma bh)L^4}{384Ebh^3/12} \quad (2)$$

where,

h = beam height

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b = beam width

L = beam length

γ = gravity of concrete in N/m^3

By setting these displacements equal, Eisenmann could define a critical length L_{cr} :

$$L_{cr} = \sqrt{\frac{4E\alpha\Delta\theta}{5\gamma}} \cdot h \quad (3)$$

Assuming that $L \leq L_{cr}$, the maximum flexural tensile stress σ_{temp} caused by the dead load is given by the following expressions:

$$\begin{aligned} \sigma_{temp} &= \frac{(\gamma b h) L^2 / 8}{b h^2 / 6} = \frac{3 \cdot \gamma L^2}{4 \cdot h} = \frac{3 \cdot \gamma L^2}{4 \cdot h} \cdot \frac{1}{L_{cr}^2} \cdot \frac{4 E \alpha \Delta \theta \cdot h^2}{5 \gamma} = \\ 1.2 \cdot \frac{E \alpha \Delta \theta \cdot h}{2} \cdot \left(\frac{L}{L_{cr}} \right)^2 &= \\ = 1.2 \cdot \sigma_{temp0} \cdot \left(\frac{L}{L_{cr}} \right)^2 &\quad (4) \end{aligned}$$

The maximum stress arises at mid span on the bottom surface of the beam. We see that the maximum stress for $L = L_{cr}$ is 20 percent higher than the maximum stress σ_{temp} for the completely restrained beam. We can limit the thermal stresses efficiently by reducing the beam length L .

If $L > L_{cr}$, $\sigma_{temp} = 1.2 \cdot \sigma_{temp0}$. It arises at a distance $L_{cr}/2$ from the beam end (Eisenmann¹). In the following, let us assume that $L \leq L_{cr}$.

Eisenmann has proposed a procedure to determine the subgrade influence on the thermal stresses¹. He substitutes the slab length L with an effective span length $L_{ef} < L$. He assumes that the beam ends sink down into the subgrade (Fig. 4). The displacement is w' at the end. The displacement is assumed to diminish linearly and is zero at a distance a' from the end. The subgrade reaction is proportional to the displacement (Winkler foundation). The following equilibrium equation can be established:

$$(\gamma b h) L = 2 \cdot \frac{k w' b a'}{2} \quad (5)$$

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where, k is the modulus of subgrade reaction in N/m^3 . The angle ϕ of rotation of each end consists of two parts depending on temperature gradient and dead load, respectively:

$$\phi = \frac{\alpha \Delta \theta L}{2} + \frac{(\gamma b h) L^3}{24 E b h^3 / 12} \quad (6)$$

Assuming small displacements, $\phi = w'/a'$ and, hence, a' can be determined by combining Eqs. (5) and (6). We obtain:

$$a' = \sqrt{\frac{2 \cdot \gamma h}{k \cdot \left\{ \alpha \Delta \theta + \gamma L^2 / (E h^2) \right\}}} \quad (7)$$

Eisenmann gives simple expressions for certain values of the parameters. The modulus k of subgrade reaction must be known. For a two layer pavement system, Eisenmann gives the following equation for determining k :

$$k = \frac{E_u}{0.83 \cdot h \cdot \sqrt[3]{E/E_u}} \quad (8)$$

where, E_u is the modulus of elasticity of the subgrade. More complicated formulae are available for multi-layer systems (see, e.g., Eisenmann¹).

The effective span length is given by:

$$L_{ef} = L - 2 \cdot a' / 3 \quad (9)$$

Finally, the maximum flexural tensile stress σ_{temp}' can be calculated by using Eq. (4):

$$\sigma_{temp}' = \frac{3 \cdot \gamma L_{ef}^2}{4 \cdot h} = 1.2 \cdot \sigma_{temp0} \cdot \left(\frac{L_{ef}}{L_{cr}} \right)^2 \quad (10)$$

In his book, Eisenmann did not discuss the influence of varying temperature gradients and different k values on the effective span length. Considering Eq. (7), we see that for small k values (soft subgrades) and if L approaches $\sqrt{E \alpha \Delta \theta / \gamma} \cdot h$, a' approaches infinity. Due to geometrical reasons, a' cannot exceed $L/2$. Consequently, $L_{ef} \leq 2L/3$. However, also a span length reduction from L to $2L/3$ reduces the maximum stresses with more than 50 percent.

Eisenmann's estimation of the subgrade influence on the thermal stresses is an engineering approach, but of course, a rather rough approximation. The

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assumption that the beam edges, that have sunk down into the subgrade, are straight instead of curved will, of course, give an erroneous estimation of the support length a' . This error must, however, be compared with the error in estimating the modulus k of subgrade reaction. In many cases, the latter error will be far larger than the first one.

4. THERMAL STRESSES IN SLABS

Eisenmann uses roughly the same method to calculate thermal stresses in slabs. For many cases, the slab stresses can be computed simply from the beam stresses by dividing the beam stresses by $(1-\nu)$, where ν is Poisson's ratio. For $\nu=0$, e.g., Eisenmann's slab stress is 25 percent higher than his beam stress. In the following, we consider that the slab will obtain a thermal curvature in two perpendicular directions.

Consider a square shaped slab subjected to a positive, linear temperature gradient $\Delta\theta$. This means that the slab must be able to move horizontally without any restraint. It might be difficult to fulfil this demand completely in a practical case, anyhow, it is interesting to compute the thermal stresses due to a linear gradient separately. The slab thickness h is assumed to be small in comparison to the slab length a . Hence, elementary plate theory can be used. If all slab edges are built in, maximum flexural tensile stresses of the magnitude σ_{temp0} will arise at the bottom surface. σ_{temp0} has the value of

$$\sigma_{temp0} = \frac{E\alpha\Delta\theta \cdot h}{2(1-\nu)} \quad (11)$$

If the slab edges, on the other hand, are free to move, the slab will curl. If the dead load is neglected, the interior part of the slab will leave the subgrade and the slab will be supported at the corners only. In the real case, the dead load $q=\gamma h$ counteracts this upward deflection. If we proceed in the same manner as Eisenmann does for beams, a critical slab length a_{cr} could be found by setting the upward movement due to temperature equal to the downward displacement due to dead load.

The temperature gradient causes a spherical deflection surface with radius R (see, e.g., Timoshenko and Woinowsky-Krieger⁵). The radius is given by the following equation:

$$\frac{1}{R} = \alpha\Delta\theta \quad (12)$$

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and, hence, the displacement difference w_{temp} between slab center and corners is:

$$w_{\text{temp}} = \frac{a^2}{4R} = \frac{\alpha \Delta \theta \cdot a^2}{4} \quad (13)$$

The downward displacement due to dead load can be determined by solving the plate bending equation numerically. The plate bending equation is given by, e.g., Timoshenko:

$$\frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{q}{D} \quad (14)$$

where,

w = deflection

q = uniformly distributed load in N/m^2

$D = Eh^3/(12 \cdot (1 - \nu^2))$

x, y = rectangular coordinates

Corner-supported square shaped slabs subjected to uniformly distributed load q have been dealt with by, e.g., Silfwerbrand⁶ using the finite difference method. For Poisson's ratio $\nu=0.2$ the central deflection w_q has been estimated as:

$$w_q = 0.0261 \cdot \frac{qa^4}{D} = 0.0261 \cdot \frac{(\gamma h)a^4}{Eh^3/(12 \cdot (1 - \nu^2))} \quad (15)$$

Setting $w_{\text{temp}} = w_q$, we obtain the following expression for the critical slab length a_{cr} :

$$a_{\text{cr}} = \sqrt{0.798 \cdot \frac{E\alpha\Delta\theta}{\gamma(1-\nu^2)}} \cdot h = 0.893 \cdot \sqrt{\frac{E\alpha\Delta\theta}{\gamma(1-\nu^2)}} \cdot h \quad (16)$$

For $\nu=0.2$, the bending moments m_1 and m_2 at slab center and at mid span of an edge, respectively, are given by the following expressions:

$$m_1 = 0.110 \cdot (\gamma h)a^2 \quad (17)$$

$$m_2 = 0.153 \cdot (\gamma h)a^2 \quad (18)$$

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Corresponding flexural tensile stresses at the bottom of the slab are given by the following expressions:

$$\begin{aligned}\sigma_{\text{temp1}} &= \frac{m_1}{h^2/6} = \frac{0.1101 \cdot (\gamma h) a^2}{h^2/6} = \frac{0.6606 \cdot \gamma a^2 h}{a_{cr}^2} \cdot \frac{1}{a_{cr}^2} \cdot 0.798 \cdot \frac{E \alpha \Delta \theta \cdot h^2}{\gamma (-v^2)} \\ &= 1.054 \cdot \frac{E \alpha \Delta \theta \cdot h}{2(1+v)(1-v)} \cdot \left(\frac{a}{a_{cr}}\right)^2 = \frac{1.054}{1+v} \cdot \sigma_{\text{temp0}} \cdot \left(\frac{a}{a_{cr}}\right)^2 \\ &= 0.878 \cdot \sigma_{\text{temp0}} \cdot \left(\frac{a}{a_{cr}}\right)^2\end{aligned}\quad (19)$$

$$\sigma_{\text{temp2}} = 1.221 \cdot \sigma_{\text{temp0}} \cdot \left(\frac{a}{a_{cr}}\right)^2 \quad (20)$$

Consequently, maximum flexural tensile stress appears at mid span of the edges. The edge stress (σ_{temp2}) is about 40 percent higher than the central stress (σ_{temp1}).

If the slab is resting on a soft subgrade, the areas close to the corners will sink down into the subgrade (Fig. 5). Assume that each area has a plane, triangular shape forming the base of a pyramid. The smaller sides of the pyramid have the length a' . The height of the pyramid is w' . The gravity center of the pyramid is situated at a distance $a'/(2\sqrt{2})$ along the diagonal from the corner. This model suffers from the same weakness as Eisenmann's beam model, i.e., the slab parts, that have sunk down into the subgrade, are assumed to be plane. The slab model contains, however, an improvement: the slab supports are assumed to be located at the gravity center of the subgrade reactions. In Eisenmann's beam model, the resultant to the subgrade reaction is assumed to act at the beam ends when he computes the angle ϕ of rotation (Eq. (6)).

Assuming that the intensity of the subgrade reaction is proportional to the displacement, we can establish the following equation of equilibrium:

$$(\gamma h) a^2 = 4 \cdot \frac{k w' a^2 / 2}{3} \quad (21)$$

The angle of rotation along the diagonal at the corner is denoted ϕ . Assuming small displacements, we obtain

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$$\phi = \frac{w'}{a' / \sqrt{2}} \quad (22)$$

The temperature gradient and the dead load contribute both to the angle:

$$\phi = \phi_{\text{temp}} - \phi_q \quad (23)$$

The temperature part ϕ_{temp} can be determined easily using the knowledge of the spherical deflection:

$$\phi_{\text{temp}} = \frac{a}{\sqrt{2} \cdot R} = \frac{\alpha \Delta \theta \cdot a}{\sqrt{2}} \quad (24)$$

If $\partial w / \partial x$ and $\partial w / \partial y$ are known, the angle of rotation along the diagonal $\phi_q = \partial w / \partial n$ is given by (see, e.g., Timoshenko⁵):

$$\phi_q = \frac{\partial w}{\partial n} = \frac{\partial w}{\partial x} \cdot \frac{\partial x}{\partial n} + \frac{\partial w}{\partial y} \cdot \frac{\partial y}{\partial n} = \frac{\partial w}{\partial x} \cdot \frac{1}{\sqrt{2}} + \frac{\partial w}{\partial y} \cdot \frac{1}{\sqrt{2}} \quad (25)$$

For the square, $\partial w / \partial x = \partial w / \partial y$. A value of $\partial w / \partial x$ can be estimated by solving the plate bending problem above numerically. We obtain:

$$\phi_q = \beta \cdot \frac{q a^3}{D} = \beta \cdot \frac{(\gamma h) a^3}{E h^3 / (12(1 - \nu^2))} \quad (26)$$

where, β is a factor depending on the location of the corner support (Fig. 6). Combining Eqs. (21), (22), (23), (24), and (26), we obtain the following expression for a' :

$$a' = \sqrt[3]{\frac{3 \gamma h a / k}{\alpha \Delta \theta - 12 \sqrt{2} (1 - \nu^2) \beta \gamma a^2 / (E h^2)}} \quad (27)$$

where, k can be estimated using Eq. (8). If the supports move from the corners along the diagonal, the bending moment m_1 and m_2 will be reduced. We may write:

$$m_1 = \mu_1 \cdot 0.110 \cdot \gamma h a^2 \quad (28)$$

$$m_2 = \mu_2 \cdot 0.153 \cdot \gamma h a^2 \quad (29)$$

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where, μ_1 and μ_2 are reduction factors (Figs. 7 and 8). Hence, the flexural tensile stresses can be calculated with the following expressions:

$$\sigma_{\text{temp1}}' = 0.878 \cdot \mu_1 \cdot \sigma_{\text{temp0}} \cdot \left(\frac{a}{a_{cr}} \right)^2 \quad (30)$$

$$\sigma_{\text{temp2}}' = 1.221 \cdot \mu_2 \cdot \sigma_{\text{temp0}} \cdot \left(\frac{a}{a_{cr}} \right)^2 \quad (31)$$

σ_{temp0} is given by Eq. (11), $\nu=0.2$.

The length a' of the support cannot be solved explicitly. A suitable calculation process is as follows:

- 1) assume an a' value, e.g., $a'_{\text{assumed}} = a/10$,
- 2) read β for a support position at $0.25 \cdot a'_{\text{assumed}}$ from Fig. 6,
- 3) calculate a' from Eq. (27),
- 4) if $a' \neq a'_{\text{assumed}}$, repeat steps 2 and 3,
- 5) if $a' = a'_{\text{assumed}}$, read μ_1 and μ_2 from Figs. 7 and 8, respectively, and
- 6) calculate σ_{temp1}' and σ_{temp2}' from Eqs. (30) and (31).

5. CALCULATION EXAMPLES

Thermal stresses are computed and evaluated for four different examples (Table 1). Examples Nos. 1A and 1B are based on examples in Eisenmann¹. Examples Nos. 2A and 2B are based on Swedish conditions.

The examples show that the resulting thermal stresses in the slab center are considerably lower than the stresses in the beams (20 %). The calculations also show that maximum tensile stress in the slab appears along the edges, at mid span. These stresses are somewhat larger than Eisenmann's beam stresses (10 %). The edge stresses are, however, considerably lower than the thermal stresses in a completely restrained slab subjected to the same thermal gradient (10 - 40 %).

6. CONCLUDING REMARKS

A method has been developed to calculate thermal stresses in square shaped slabs. The method forms an analogue to Eisenmann's procedure to calculate thermal stresses in beams. Calculations show that the thermal stresses in the slab center are considerably lower than thermal stresses in beams. On the other hand, the maximum slab stresses, appearing along the edges, at mid span, are

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somewhat larger than Eisenmann's beam stresses. Also the edge stresses are, however, considerably lower than the thermal stresses in a completely restrained slab.

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TABLE 1—CALCULATION RESULTS

Type of structure		Beam				Slab			
Example No.		Ex 1A	Ex 1B	Ex 2A	Ex 2B	Ex 1A	Ex 1B	Ex 2A	Ex 2B
Variable	Unit								
E	MPa	30000	30000	36000	36000	30000	30000	36000	36000
v		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
α	(°C) ⁻¹	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
γ	MN/m ³	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024
$\Delta\theta$	°C/m	90	90	60	60	90	90	60	60
h	m	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
L or a	m	6	6	5	5	6	6	5	5
E _u	MPa	64	147	50	150	64	147	50	150
σ_{temp0}	MPa	2.70	2.70	2.16	2.16	3.38	3.38	2.70	2.70
L _{cr} or a _{cr}	m	6.00	6.00	5.37	5.37	6.11	6.11	5.47	5.47
σ_{temp}	MPa	3.24	3.24	2.25	2.25				
σ_{temp1}	MPa					2.85	2.85	1.98	1.98
σ_{temp2}	MPa					3.97	3.97	2.76	2.76
k	MN/m ³	50	150	34	145	50	150	34	145
0.25a' _{sw} /a						0.066	0.049	0.088	0.058
β						0.039	0.046	0.031	0.042
a'	m	1.03	0.60	1.25	0.60	1.57	1.17	1.77	1.16
0.25a'/a						0.066	0.049	0.088	0.058
L _{ef}	m	5.31	5.60	4.17	4.60				
σ_{temp}'	MPa	2.54	2.83	1.56	1.90				
μ_1						0.73	0.80	0.65	0.76
μ_2						0.71	0.78	0.62	0.74
σ_{temp1}'	MPa					2.08	2.28	1.29	1.51
σ_{temp2}'	MPa					2.82	3.10	1.71	2.04

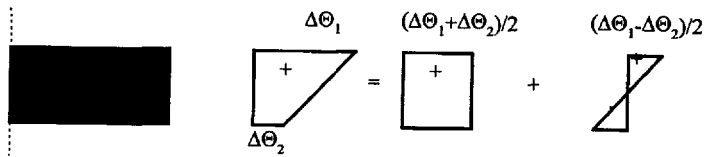


Fig. 1—The temperature distribution in the pavement is divided into two parts.

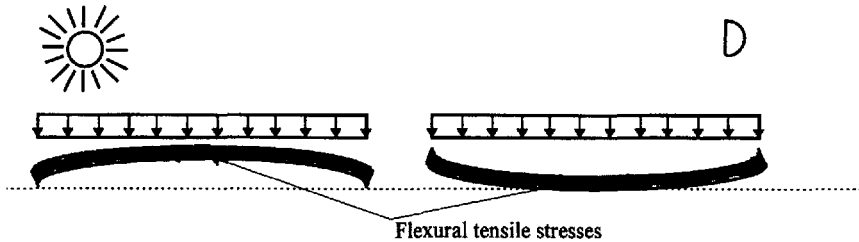


Fig. 2—The dead load causes flexural tensile stresses in the curled pavement, under heating (left) and cooling (right)

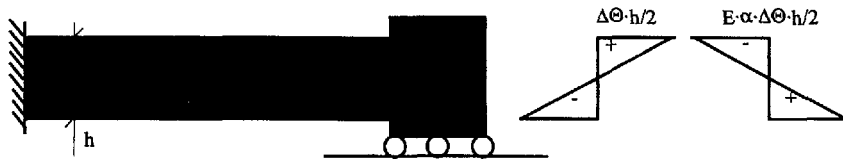


Fig. 3—The thermal gradient causes thermal stresses in a beam with built-in ends.

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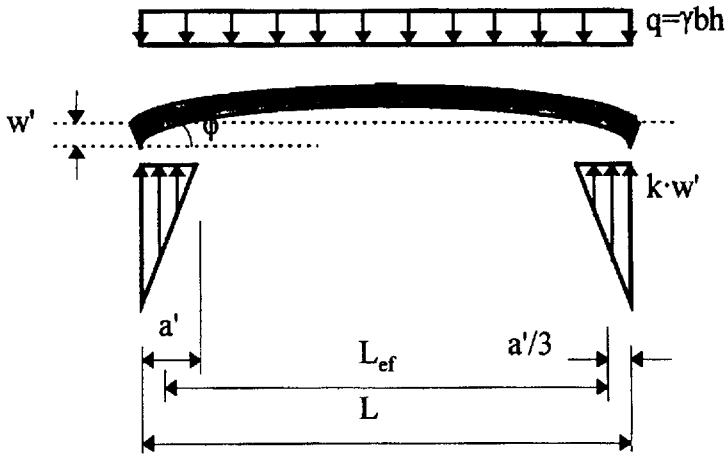


Fig. 4—The beam ends sink down into the subgrade,

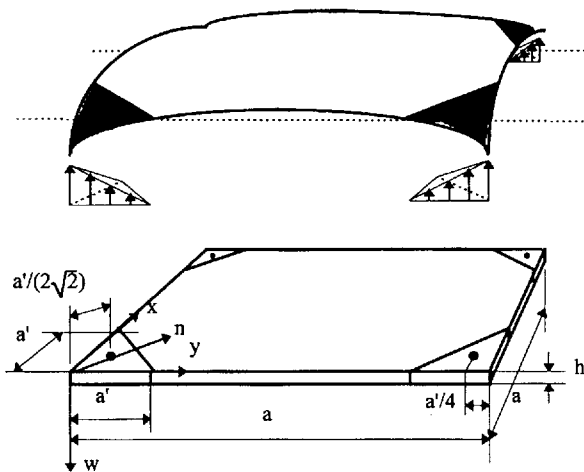


Fig. 5—The slab corners sink down into the subgrade producing pyramidal subgrade reaction distributions. Note that the x and y coordinates of the gravity center of the pyramid are $0.25a'$.

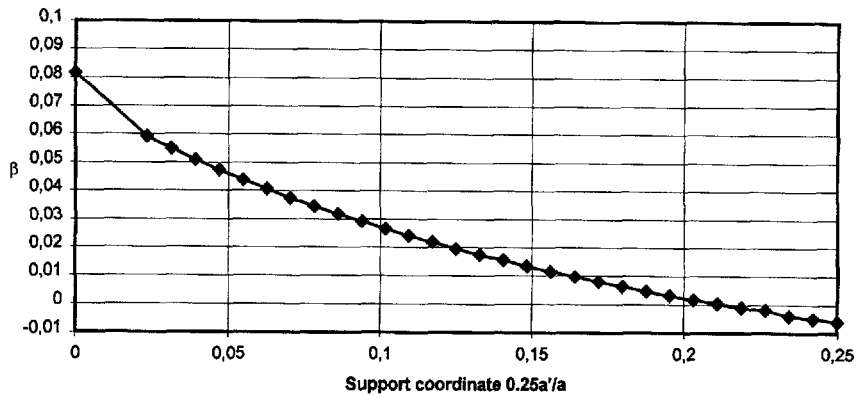


Fig. 6—The angular factor β as a function of support location. In order to prevent the subgrade reaction pyramids from intersecting, a'/a should be limited to $a'/a \leq 0.5$ and, hence, the support coordinate is limited to $0.25 a'/a \leq 0.125$.

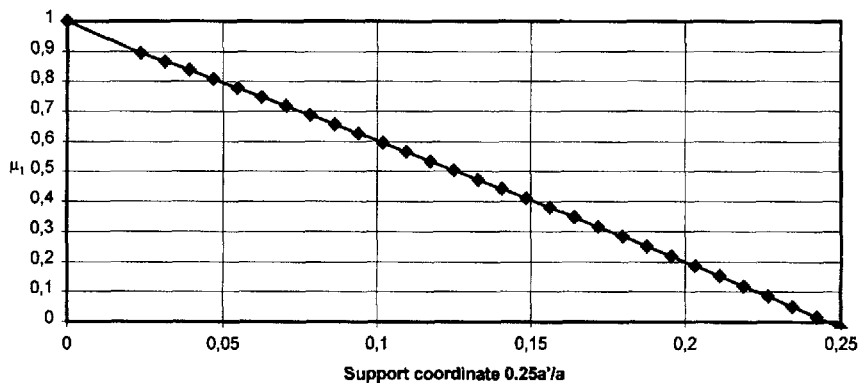


Fig. 7—The moment reduction factor μ_1 as a function of support location.

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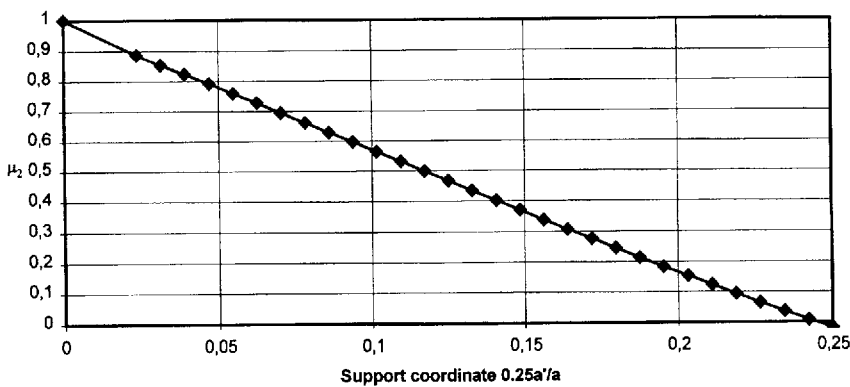


Fig. 8—The moment reduction factor μ_2 as a function of support location.

SP 181-2

Improved Concrete Pavement Design Methodology for Better Performance

by E. Owusu-Antwi and M. Darter

Synopsis: Concrete pavement design is still largely empirical, although, there are instances where analytical methods based on theoretical principals have been used. This paper presents the results of work to formulate the concepts for the development of a unified pavement analysis and design system for the improved performance of airport concrete pavements. The improved analysis and design system takes into account realistic material behavior over service life; environmental effects; realistic pavement loading; and a realistic assessment of pavement damage in the analysis and design process, to come up with better performing pavements. These concepts are to form the basis of a pavement analysis and design system to be developed in subsequent applied research.

A central component of the system proposed is a 3-dimensional finite element analysis based primary response model, applicable to the nonlinear analysis of concrete pavements. This primary response model incorporates the appropriate material constitutive models that will permit a realistic representation of the behavior of the current and future materials used in concrete pavements. Using this primary response model, a data base of the outputs of nodal displacements, stresses, strains and local damage measures can be generated for a given pavement structure, for the applicable traffic and environmental loading conditions. The data generated is then used in a damage assessment procedure the results of which are used to predict the development of the key distress types and roughness for concrete pavements. This provides for greater design reliability and cost-effective pavement design.

A major advantage of the mechanistic design procedure envisaged is its applicability to realistic rehabilitation design, which is likely to become very important in the coming decades, during which the demand for rehabilitation design is expected to supersede that for new construction design. The unified pavement analysis and design concept provides an effective system for the evaluation of the performance of existing concrete pavements from nondestructive testing results. This includes the evaluation of the in-situ material properties of existing pavements from the results of such nondestructive testing, using backcalculation procedures.

Keywords: Concrete pavements; finite element method; strains; stresses

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INTRODUCTION

The demands on airport pavement facilities are expected to increase substantially in the coming decades. Although, most projections point towards considerable increases in the volume of air travel through the next century, it is doubtful that such increases will be accompanied by corresponding increases in the number of airports in the country. In anticipation of this, efforts are underway by aircraft manufacturers and the airline industry to move to a new generation of wide-bodied aircraft with maximum takeoff weights in excess of one millions pounds and that can carry the substantial travel volumes expected. Pavement engineers have to provide airport pavements that are capable of meeting the enormous demands of the future aircraft.

Typically, empirical procedures based on the past observation of performance of pavements have been relied upon for the new design of airport pavements. Only a select number of consultants have used mechanistic-empirical procedures that combine pavement responses from analytical methods and performance data from pavement research and observation, for the analysis and design of new airport pavements. Also, apart from the occasional new runway or taxiway that is built at existing airports, most of the pavement work involves the rehabilitation of existing pavements. Rehabilitation design has mostly been based on empirical and mechanistic-empirical procedures as well.

Clearly, current procedures for both new and rehabilitation design will not be adequate for analyzing new designs and materials to withstand the loads generated by the new types of aircraft. The current designs fail to take into account all aspects of the pavement engineering problem including the correct characterization of

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material properties, environmental effects, and aircraft loadings. Procedures for the assessment of damage accumulation in pavements have also not been adequately defined. Therefore, providing pavements capable of carrying the loads imposed by the future generation of aircraft for a wide range of environmental conditions and pavement materials will be one of the most challenging aspects of pavement analysis and design facing pavement engineers in the future.

A unified concept proposed for the analysis and design of airport pavements that uses the most advanced technology available for both new and rehabilitation construction to give better performing pavements. The concepts are also applicable to highway pavements. The concepts were developed for both rigid and flexible pavements; however, their applications to rigid airport pavements is emphasized.

PAVEMENT ANALYSIS AND DESIGN NEEDS

Many significant technical issues need to be addressed in order to adequately design airport concrete pavements that will provide performance throughout their service lives. These include the ability to obtain proper design inputs, and the use of a realistic primary response model to determine the stresses, strains, displacements, and local damage that result from multiple load applications under varying environmental conditions. An adequate assessment of the resulting cumulative damage that leads to the different types of distress that eventually occur is also essential.

However, most of current concrete pavement design methods are based on idealized analytical methods, such as the Westergaard analysis of a free edge or interior loaded slab resting on a Winkler foundation. Examples are the Federal Aviation Administration (FAA) and the Portland Cement Association (PCA) design methods for rigid pavements(2,3). These methods usually require empirical modifications, such as the modification made in the FAA pavement design method to accommodate the load transfer that occurs at joints, wherein edge stresses are reduced by 25 percent when load transfer is provided. Another major limitation is that these procedures can only consider two layers, although actual pavements may be comprised of several layers.

Some attempts have been made in recent years to develop better procedures for the analysis and design of concrete pavements which will result in improved performance. An example is a rigid pavement design procedure which relies on linear elastic theory developed by the Corps of Engineers (4). However, this procedure does not adequately consider the effect of thermal gradients or the different joint designs that provide varying amounts of load transfer. Additional limitations are associated with overlay design considerations, nondestructive testing

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of pavement layer properties, reflective cracking considerations, and damage assessment.

With such limitations in the current analysis and design methods, there have been numerous examples of pavements failing earlier than anticipated (?). The empirical and mechanistic-empirical methods mentioned above are limited with respect to the proper characterization of materials, traffic loading conditions and, especially, the environment. They are also limited in their ability to treat nonlinear or deformation dependent and time dependent material/soil changes, geometric conditions such as joints, and layer interface conditions. They also do not directly treat all of the key types of pavement failures that may occur using a realistic damage assessment. These limitations preclude a practical prediction of pavement performance for the various operating conditions experienced, and do not allow the design engineer to have an effective control over the analysis and design process.

UNIFIED PAVEMENT ANALYSIS AND DESIGN SYSTEM FRAMEWORK

The concepts for a methodology to address current design and analysis needs identified were formulated in an FAA project to develop a unified pavement analysis and design system for all types of airport pavements (1). The three basic components proposed for the unified pavement analysis and design system are as follows:

- (1) A primary response model applicable to the realistic solution of pavement problems involving the realistic modeling of complex 3-dimensional loading and boundary conditions.
- (2) Proper constitutive relations for new and existing pavement materials that take into account the time and deformation dependent characteristics of the materials.
- (3) Proper models for assessing the nonlinear accumulation of damage in pavements due to the effects of traffic and environmental loading over time.

The unified pavement system with these components must be applicable to the analysis and design of new pavements, as well as to the strengthening of existing pavements and the accurate interpretation of nondestructive test results.

In formulating a framework for this unified pavement analysis and design system, consideration was given to the need to utilize the most recent advances in several areas of engineering, and at the same time address the practical needs in

pavement analysis and design. The requirements of a realistic primary response model, which is central to the unified pavement analysis and design system, drove the development of the framework.

A major requirement of the framework was that it permit the realistic solution of complex pavement problems, by specifically allowing a realistic representation of the nonlinear behavior of pavement materials and a better representation of the 3-D loading and boundary conditions of concrete pavements. Since concrete pavement material properties change with time, often accompanied by changing loading and boundary conditions, a framework was developed that also addresses this issue. In addition, provisions were made in the framework to permit the determination of outputs that will allow the assessment of damage to a concrete pavement structure as a result of these changing conditions.

Figure 1 is an illustration of the framework developed. The unified pavement model proposed is comprised of a core primary response model for structural analysis to determine the responses of the pavement system subjected to traffic and environmental loads. For a particular set of inputs, specific geometry, and material design, the primary response model is used to determine the stresses, strains, displacements, and damage measures from which the structural integrity of the design is determined.

The history of the primary response model output under changing conditions are used in a damage assessment to determine the adequacy of a design. This is done by predicting the occurrence of key pavement distress types from the results of the damage assessment. A design which is determined to be unacceptable, in terms of performance as reflected in the occurrence of key distress types and roughness, is revised and the analysis process repeated until an acceptable design is obtained.

Role of Primary Response Model

A primary response model that combines the most advanced technology currently available in finite element analysis (FEA) and the practical requirements of pavement analysis and design is proposed. The central component of the unified pavement analysis and design system is a primary response model with dynamic, nonlinear, and time dependent capabilities. The primary response model proposed is comprised of a 3-D nonlinear FEA kernel with constitutive models for nonlinear material behavior. Also, the model incorporates local damage models in the FEA kernel to account for the effects of damage on subsequent iterations.

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Inputs

The main inputs of the proposed primary response model can be grouped under, (I) the constitutive models and property data for the materials used in concrete pavements, (ii) loading conditions, (iii) environmental conditions, and (iv) other design inputs. Much of the success of the unified pavement model will depend on how well the required inputs to the primary response model are defined and are reliably obtained.

Constitutive Models and Material Property Data--A major input to the unified pavement analysis and design system are the constitutive models and property data for the pavement materials used. For concrete pavements, these materials fall into the categories of portland cement concrete, stabilized materials, subgrade soils and other materials or new materials such as composites and fiber reinforced materials.

In current pavement analysis and design approaches, these materials are idealized as materials with deformation and time independent constitutive relations, (i.e. linear elastic), and are characterized by fundamental parameters and property data such as Young's modulus E , shear modulus G , Poisson's ratio ν , and the modulus of subgrade reaction k .

Since such material models do not realistically represent the actual behavior of concrete pavement materials, constitutive models that are able to do so and account for nonlinear material behavior are required. Some distinguishing characteristics that require particular attention in the development of constitutive models for concrete pavement materials include the brittle fracture of cement concrete and stabilized materials, and the yield surfaces of subgrade soils that include a consideration of volumetric sensitivity.

Loading Conditions--A wide range of load magnitudes applied through many different gear types with different wheel bases and threads are experienced by airport pavements. The manner or rate of application of the loads also vary depending on the location of a pavement section. For example, the loading condition on an apron is very different from that on a runway. A problem faced by the pavement engineer is how to characterize these loading conditions over the service life of a pavement for analysis and design. To be able to do this, one must take into account current and future traffic distribution patterns, current and future aircraft loading characteristics, and future aircraft growth rates. The distribution patterns include such factors as traffic mix, the time distribution of traffic, and the lateral and longitudinal distribution of traffic. The loading characteristics include such factors as gear type, maximum takeoff weight, number of coverages, tire pressure, contact area stress distribution, and speed and dynamic effects.

The current procedures used such as the equivalent single wheel load (ESWL) concept, the FAA procedure based on the equivalent annual departures of a design aircraft (2), and the Aircraft Classification Number (ACN) (5), do not take most of these factors into account. Therefore, mechanistic-based procedure is required to convert both the past and future mixed aircraft traffic into a realistic representation of loading on pavements for use in the unified pavement analysis and design system.

Environmental Conditions--The two most important environmental variables that need to be taken into account in the analysis and design of concrete pavements are temperature and moisture. Daily temperature and moisture variations can lead to expansion and contraction of concrete pavements, thermal and moisture gradients which result in curling and warping stresses in portland cement concrete pavements, and changes in material properties. In the long term, temperature and moisture variations can also lead to freeze-thaw damage effects, soil swelling, and frost heave, and subgrade softening due to saturation.

Most of the current conventional methods of analysis and design do not adequately take into account the effects of temperature and moisture in the design process, but leave the control of their detrimental effects to construction procedures that will minimize their effect. Thus, for example, the effects of curling and warping stresses are often only considered empirically through the selection of the joint spacing that will limit the stresses and strains that cause them, and sometimes by algebraically adding them onto the effect of vehicle loads. To permit the proper characterization of the effects of the environment, models incorporated into the unified pavement analysis and design system which will allow the following to be taken into account are required:

- Seasonal and daily temperature and moisture profiles at various depths.
- Temperature and moisture gradients.
- Frost penetration and frost heave.
- Thaw weakening.
- Suction.
- Moisture-stiffness relationships.

Other Design Inputs--Another important aspect of pavement analysis and design is the selection of the pavement geometry, materials, boundary and initial conditions, and other features to characterize the pavement in a representative manner for subsequent analyses. Currently, there are no rational procedures for dealing directly with such design parameters as load transfer, joint spacing, reinforcement, and layer interface conditions. In the unified pavement model, mechanistic-based principles are required to represent such factors in the primary response model. 3-D FEA models will allow most of these features to be realistically represented and permit an accurate analysis of the pavement problem.

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Characterizing Cumulative Damage

Another critical aspect of conventional pavement analysis and design is the postprocessing of the outputs from the initial analysis (primary response model) for a useful interpretation of the results obtained and to determine lifetime structural adequacy. Typically, postprocessing has been limited to the graphical presentation of the results obtained, for example, in the form of principal stress, shear stress, displacement, and failure criteria contour plots. In pavement analysis and design, in addition to such graphical representation of results, the accurate interpretation of the engineering significance of results is essential to satisfying structural integrity requirements. This is because failure in pavements is usually due to the repeated action of loads, and not the long term action of a single major load. Therefore, to optimize design several analysis and design iterations to determine whether the particular design is appropriate for the repeated occurrence of numerous sets of conditions is essential.

Consequently, postprocessing must involve assessing the damage to the pavement due to the repeated application of the various kinds of loads in order to predict performance. One can then determine whether a design will be adequate for the given conditions over time. If the design is not adequate, the materials and/or geometry of the design must be changed and the entire process of analysis repeated.

The interpretation of the outputs in this manner is useful for obtaining a pavement system with improved performance.

Such interpretation of the engineering significance of the structural analysis results from pavements has been conducted using simple damage assessment concepts in the fashion of Miner's cumulative damage theory. A limitation of this approach is the assumption that the magnitude and sequence of loading, and the history of damage do not influence the future accumulation of damage. Studies show this not to be the case (6). Consequently, the assessment of pavement damage within the context of mechanistic analysis that takes such factors into account is required as a useful and integral part of the unified pavement analysis and design system. This will allow a realistic assessment of damage resulting from the repeated application of aircraft and environmental loading.

Analytical Capabilities

Advances in modern finite element analysis are now at a point where there can be very close simulation of the behavior of most designs under the actual conditions they are subjected to. The analytical capabilities required for the primary response model to enable the analysis and design of all types of concrete pavements include the generation of the finite element model for any particular design, representation of linear and nonlinear loading and boundary conditions, realistic material modeling

capabilities, efficient solution algorithms for the finite element analysis procedure, and a graphical interface to display the results.

Preprocessing--Preprocessing for the primary response model is comprised of model development, the application of load and boundary conditions, and the specification of the material properties for the pavement structure to be analyzed.

A graphical processor capable of automatic isoparametric generation of the finite element mesh for a design based on a library of structural elements for pavements is envisioned. Also, a library of stress elements comprised of 2-D and 3-D element types, that will enable the physical representation of all aspects of pavements is required as part of the primary response model.

Examples of the types of elements recommended for use in the primary response model for model generation are shown in figure 2 (1). The 8-node brick (or solid) elements with one point quadrature and hourglass control are recommended for modeling a large part of the pavement layer(s). Solid beam elements such as the 2-node bar element shown in figure 2 are recommended for the dowel bars at joints, and the capability for the addition of reinforcement to elements for composite modeling of materials like steel and fiber reinforced concrete. Discrete springs of the type shown in figure 2 are recommended for use as first-order interface elements to represent the conditions at "soft" joints or cracks, and slideline elements can be used to model the interface and contact conditions between the different pavement layers. To decrease memory requirements and increase computation speed, infinite domain elements of the kind shown in figure 2 are recommended for representation of the infinite effect of most, if not all, of the subgrade soil.

A mesh generator capable of using any combination of the elements provided in the library, each with the appropriate material model, even in cases where different material models are used in the same structure, is recommended. A graphic processor which will allow the mesh generator to interface with other software such as Autocad7 is proposed.

The ability to represent the wide range of loading and boundary conditions that occur on pavements is essential to the unified pavement analysis and design system. The loading conditions that need to be represented include the usual point loads, distributed loads, and edge or axial loads. In addition the preprocessor must have the ability to represent the effect of loads due to environmental variations. Specifically, techniques are required for depicting the effect of temperature and moisture loading, such as through the use of a specified displacement to represent the displacement due to curling and warping.

A preprocessor with the ability to apply to the model the various boundary conditions (such as foundation conditions and constraints such as at joints) is recommended. In most instances the loads on pavements are applied repeatedly and

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the boundary conditions may change over time. The preprocessor must provide the capabilities to characterize the repeated nature of the loads applied and any changes in the boundary conditions thereof. Other capabilities required for the preprocessor include mesh editing, geometric transformations including reflection, rotation, translation, scaling and mirror imaging, and automatic mesh rezoning.

Material Modeling--For the primary response model to work properly, material models need to be provided for portland cement concrete, granular subbase materials, fine-grained subgrade soils, and the composite or futuristic materials that are likely to be used in pavements in the coming years. The material models should very much closely model the multi-dimensional response of concrete pavement materials to traffic and environmental loading over time. A library of material that is comprised of a hierarchy of models for the major classes of concrete pavement materials is recommended. The models must give a correct representation of the directional dependence of the material properties, accurately describe their deformation and time dependent properties, and take into account the effects of all types of damage on material properties over time. Details of the appropriate material constitutive models for the primary response model recommended are presented subsequently.

Solution Process--One aspect of the primary response model that has an important influence on its success or failure is the solution procedure or algorithm that is adopted for the finite element analysis. Preliminary work shows that realistic modeling of the 3-dimensional response of pavements requires a large number of nodes and a corresponding large number of equations (1). In addition, iterative analysis methods are required to resolve the nonlinear response of the pavement materials. This greatly increases the computer time required for solution. Thus a solution procedure that requires less memory and computer time than the traditional methods currently used is required.

One traditional approach that is often used involves a direct solution of a linearized system of equations within a nonlinear iterative algorithm, such as the modified Newton-Raphson method. A more efficient approach involves the use of the preconditioned conjugate-gradient technique as an iterative linear solver or a replacement for the traditional Newton-Raphson iterative algorithm (1). This approach reduces memory requirements for complex nonlinear pavement problems by a factor of 10-100, making it possible to solve large and realistic problems on smaller computers and with greatly reduced computation costs/times.

Other enhancing features recommended for the primary response model include automatic load/time stepping and recovery from divergent solutions. Such features will ensure convergent solutions at a minimum cost. Restart files that allow the segmented solution of problems and give protection against unexpected aborts are recommended. Capability should also be provided for use of the data from the

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restart files for postprocessing at any stage of a run. Preliminary experience indicates that the solution approach outlined can be effective (1).

Postprocessing--The results generated from the primary response model include the stresses, strains, displacements, and damage measures for each load/time step. This data has to be efficiently postprocessed for a proper interpretation and application of the results. Some of the special graphical postprocessing features recommended for the unified pavement analysis and design system are as follows::

- (1) A feature that allows the display of the deformed and undeformed geometry of a model to show static deformations, possibly with provisions for the superposition of the two shapes.
- (2) Contour/fringe plots for any of the scalar outputs obtained for a determination of the critical areas of a model. Continuous contour lines or color shadings are recommended for showing the surface contours of the displacements, stresses, strains, velocities and accelerations on the various elements or on full mesh plots. Additional features recommended include automatic or user definition of the intervals and ranges for the contours, and the capability to obtain a contour plot during a run, or by postprocessing of the results output to a file.
- (3) Graphical plots of variables as a function of location, load, time (history plots), or other variables.
- (4) Vector plots of the scalar outputs at the nodes of a model, that show the value of the outputs either by color or length.
- (5) A feature which allows the selective scanning and reformatting of the output obtained for further postprocessing. This further postprocessing will include the use of the output as input to other postprocessors for damage assessment, and for printing of the output in user specified formats and tables.

Development of Software

A 3-D FEA software that incorporates the features outlined above is recommended. Since a lot of the material models to be incorporated into the primary response model are yet to be fully developed, software that is developed in a step-by-step process involving gradually building onto a basic unified pavement model is recommended.

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An initial code with capabilities for linear static/dynamic analysis is envisaged. This basic code should incorporate linear elastic material constitutive models and should be adequate for the structural analysis of designs with static or quasi-static loads, dynamic loads, and linear boundary conditions. Ultimately, features to permit the solution of nonlinear problems involving both material and geometric nonlinearities should be incorporated into the model. This can be accomplished by progressively improving the code to account for realistic material properties through the implementation of the appropriate and more complex constitutive models. Additionally, features can be incorporated into the software to allow transient analysis for cases where there are impact responses typically of less than 50×10^{-6} seconds duration.

Although, this process can take considerable calendar time, as it will be dependent on the speed with which the appropriate constitutive models which account for material nonlinearities are developed, a parallel effort for the development of the unified pavement model and the constitutive models that feed into it, will keep delays in the development of the analysis and design system to a minimum.

The final product of this developmental process should be a unique public-domain code with capabilities for 3-D simulations and particularly suitable for linear and nonlinear analysis of pavements. An advantage of this stepwise developmental process is that a version of the software will be available for use by practicing engineers at the end of each of the stages of development identified. At the end of each stage, the program can be demonstrated and validated without the "ultimate" constitutive models, and where necessary any feedback from selected users incorporated into the analysis and design system.

A 3-D FEA based unified pavement analysis and design system that will run on a PC is recommended. It is expected in the initial stages, that the primary response model proposed will be run on currently available workstations with run-times in the tens of hours for full nonlinear analysis of pavement systems. However, with the major advances in the computing power of workstations and PCs in the next few years, these run-times will be reduced to minutes. In addition, efficient memory management techniques (virtual memory) can be employed to ensure the solution of large complex problems on the next generation of computers.

MATERIAL CONSTITUTIVE MODELS

The development of the proper material constitutive models to be incorporated into the primary response model is a very essential part of the unified analysis and design system. A library of the proper material constitutive models are necessary

if the unified analysis and design system is to be used to solve the complex pavement problems that are constantly faced by pavement engineers. The constitutive models must be able to realistically account for the time and deformation dependent properties of the materials used in airport concrete pavements.

A PCC pavement is generally comprised of a top concrete layer, sometimes placed on a subbase which may be stabilized or unstabilized, all of which are then placed on a prepared subgrade. In most instances, cement or asphalt are used as the stabilizing agent for the subbase layer. Constitutive models which represent the generalized stress-strain behavior are therefore required for each of the different layers since their mechanical behavior is different. Constitutive models are also needed for the futuristic materials that are expected to be used for pavements in the coming decades.

Models able to represent the isotropic, orthotropic, anisotropic, and time-dependent material properties are needed for the unified pavement analysis and design system. The generalized models required include those for materials that display linear elastic, nonlinear elastic, viscoelastic, elastoplastic, and elastic-plastic responses. All these models must have the ability to take into account the effects of fracture, fatigue, and damage on material properties over time. Yield surfaces that include volumetric sensitivity are also required for the subgrade or foundation soils.

More often than not, the global and idealized constitutive models that are used in pavement analysis are not adequate for characterizing the physical behavior of pavement materials over time. They may only be representative of the initial conditions of the materials and are not able to take into account the effects of factors such as aging, micro-cracking, plastic or irreversible strains, and other forms of damage that occur in the pavement materials over time. Constitutive models that take these factors into account are necessary, since the materials used in pavements are constantly undergoing changes. Also, the analysis of pavements inherently involves many sources of non-linearities which make it necessary to solve problems in increments tied to the load/time stepping.

In the last two decades, with the advent of numerical methods such as the finite element method, work has been conducted on material modeling that takes advantage of incremental analysis to take into account the different sources of non-linearities (7,8). These models are able to reflect the effects of aging, micro-cracking, plastic or irreversible strains, and other forms of damage. Incremental constitutive models of this kind are recommended for the unified pavement analysis and design system. These models have also been referred to as hierarchical single surface (HISS) constitutive models by other researchers (9,10).

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The incremental models recommended are classes of constitutive models, to which parameters that characterize the previous stress-strain history of materials can be added to describe the increasingly complex response of the materials. To a large extent, the parameters in these models describe the deformed state of the materials at any particular time, and are able to account for the effect of any progressive local damage on the properties of the materials, and on the subsequent behavior of the materials (7,8). Thus, depending on the parameters that are added, a single basic constitutive model can be used to represent the pre-failure, failure, and post-failure behavior of a particular pavement material. A library of such constitutive models are recommended for each of the major pavement material types.

For each class of constitutive model a data base of the constitutive parameters will be required. Generally, these parameters are functions of environmental variables such as temperature and moisture, and also change with factors such as aging, load history, and the other forms of damage. The constitutive parameters that will make up this data base can be determined through a comprehensive laboratory testing program. Other names give to these parameters include "hardening parameters", "internal variables", and "memory variables" (8).

For PCC pavements, the two most important materials for which constitutive models are required are portland cement concrete and the subgrade soil. Some of the constitutive models that can serve as a basis for the development of the hierarchical constitutive models for portland cement concrete and for subgrade soils are presented below.

Portland Cement Concrete

Generally, the behavior of portland cement concrete can be classified as elastic or elastic-plastic. Typical stress-strain curves obtained for cement concrete in compression are shown in figure 3 (11). The basic constitutive models recommended for portland cement concrete as the building blocks for the incremental constitutive models for the primary response model, therefore, are of the Cauchy type, the Green (hyperelastic) type, or the incremental (hypoelastic) type. A knowledge of the tangent and secant moduli of the materials are required for the incremental constitutive models. An example of a basic hypoelastic constitutive model is as follows:

$$\dot{\sigma}_{ij} = 2 \left[\left(\frac{K_s}{2} \frac{G_s}{3} \right) \delta_{ij} \delta_{kl} + G_s \delta_{ik} \delta_{jl} + \eta e_{ij} e_{kl} \right] \dot{\epsilon}_{kl}$$

where

$$\begin{aligned}\eta &= 4(G_t - G_s)/3\gamma_{oct}^2 \\ K_t &= \text{tangent modulus} \\ G_s &= \text{secant modulus} \\ \delta_{ij} &= \text{Kronecker delta} \\ \sigma_{ij} &= \text{stress rate tensor} \\ \varepsilon_{ij} &= \text{strain rate tensor}\end{aligned}$$

Subgrade Soils

There are at least three alternative types of constitutive relations recommended for use as the basis for building the complex incremental models required to characterize the subgrade soils for pavements. Soils typically behave as linear or nonlinear viscoelastic materials at moderate loading rates. For such cases, viscoelastic constitutive models of the following form are recommended (1):

$$\sigma_{ij} = \delta_{ij} \int_0^t [K(tt') \frac{2}{3} G(tt')] \frac{d\varepsilon_{kk}}{dt'} dt' + 2 \int_0^t G(tt') \frac{d\varepsilon_{ij}}{dt'} dt'$$

where $K(t)$ and $G(t)$ are the relaxation moduli in dilatation and shear, respectively, and all the other parameters are as defined before. Figure 4 shows typical creep and creep recovery data on subgrade soil obtained from incremental creep tests, from which it is possible to evaluate the creep compliance function or the relaxation modulus function (11).

Elastic-plastic constitutive relations, which imply the existence of a yield function that take the dilatancy effects in subgrade soils into account, can also be used. Considerable work has been done to develop various types of yield criteria dependent on associative and non-associative flow rules that use isotropic hardening or kinematic hardening. A model suggested by Lade splits the strain into three components—the elastic strain, plastic collapse strain, and the plastic expansive strain. The plastic collapse strains are determined from a spherical yield surface and associated flow rule; and the plastic expansive strains are evaluated from a conical yield surface and non-associated flow rule (12).

A soil model by Prevost is the third alternative suggested. The model is an elastoplastic anisotropic hardening model, and can be used to characterize a wide range of stress-strain-strength responses for cohesive and cohesionless soils. Mechanical property variations that are a result of arbitrary changes in the direction of loading, unloading, and reversal of loading can be taken into account by this model (12). An elastic-viscoplastic constitutive relation for clay developed by Sharma also takes dilatancy effects into account (13). This constitutive relation is as follows:

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$$\dot{\varepsilon}_{ij} = \frac{\dot{S}_{ij}}{2G} + \frac{\dot{\sigma}_{KK}}{3K} \delta_{ij} + \gamma < \Phi(F) > \alpha \delta_{ij} + \frac{S_{ij}}{2\sqrt{J_2}}$$

where,

$$< \Phi(F) > = 0 \text{ for } \varepsilon_p \geq 0.002$$

$$< \Phi(F) > = F + (1 - e^{-30F}) \text{ for } \varepsilon_p \geq 0.002$$

$$F = \frac{\alpha J_1 + \sqrt{J_2}}{k(\varepsilon_p)} - 1$$

$$\begin{aligned} \alpha &= 0.856 \varepsilon_p^{0.156} \\ k &= 73.5 \varepsilon_p^{0.115} \\ G &= 1.21 \times 10^5 \text{ psi} \\ E &= 3.35 \times 10^5 \text{ psi} \\ K &= 3.58 \times 10^6 \text{ psi} \\ \gamma &= 186 \text{ psi sec} \end{aligned}$$

The dynamic yield function was obtained by plotting the data as shown in figure 5. Figure 6 shows the variation of the dilatancy coefficient, γ , with uniaxial plastic strain.

PAVEMENT DAMAGE ASSESSMENT

For a particular pavement structure with defined materials and design parameters, damage begins to accumulate when the pavement is subjected to a combination of aircraft traffic and environmental loading. A damage analysis is required to determine when these repeated loading cycles and the resulting accumulated damage will reach a limit that will cause the pavement to fail according to some pre-defined failure criteria.

A unified pavement analysis and design system is particularly suitable for such analysis. The incorporation of a 3-D FEM based primary response model will enable the simulation of pavement problems to generate, in real-time, a database of nodal displacements, strains, stresses, and other damage measures (e.g., equivalent plastic strain), for every load/time step. This data can then be analyzed to give a measure of the cumulative damage experienced by the pavement over time. Such an approach requires the proper engineering interpretation of the output obtained from the primary response model in order to correctly relate it to the cumulative damage sustained by the pavement. The results from the cumulative damage

assessment procedure will indicate whether a particular pavement meets the requirements it is designed for.

For concrete pavements, the major forms of damage are cracking caused by localized stresses; fatigue cracking caused by repeated loading; and aging caused by the environment. Both types of cracking lead to the re-distribution of stresses in a pavement structure, while aging leads to the altering of the constitutive behavior of the pavement materials. The resulting damage also increases the susceptibility of the pavement to further damage. At any point in time, the history of a pavement system vis-a-vis prior cracking and prior material aging, and the current environmental (temperature and moisture) conditions, will affect its response to a particular load. In addition, the several failure modes will interact with each other. This increases the complexity of the problem of finding the best damage accumulation procedure that must account for all these factors.

In the most often applied damage accumulation procedure in concrete pavement analysis, the critical stresses or strains are calculated for selected discrete combinations of the load and environmental conditions. The assumption is made that the pavement structure and material behavior basically remain constant throughout the life of the pavement structure. The contribution to damage of each of these combinations is calculated from the critical stresses or strains. The damages are then summed up to represent the total damage accumulated by the entire system. Such a procedure obviously fails to account for the complexities discussed in the preceding section. A more realistic damage accumulation procedure is one that is able to take into account the ever changing material behavior and pavement structure, as well as the interacting effects of the various forms of damage in the determination of subsequent damage.

$$\sum_{\substack{\text{Load} \\ \text{Temperature} \\ \text{Moisture} \\ \text{Time} \\ \text{etc.}}} \left\{ \begin{array}{l} \text{Finite} \\ \text{Element} \\ \text{Analysis} \end{array} + \begin{array}{l} \text{Constitutive} \\ \text{Models} \end{array} = \begin{array}{l} \text{Stress} \\ \text{Strain} \\ \text{Displacement} \\ \text{Local Damage} \end{array} \right\} - \text{Cumulative Damage}$$

The basic concept proposed for the assessment of cumulative damage in concrete pavements over time is shown by equation 4. The stress, strain, displacement and local damage in the brackets represent the actual nodal outputs obtained from the primary response model per load/time step. By the nature of the primary response model proposed, these stresses, strains, displacements, and local damage measures for each load/time step, will take previously accumulated damage into account. However, there is still the major hurdle of developing the best method for the summation of the damage per load/time step to determine the total damage within the present limitations of computer capabilities.

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For the typical 20 to 40-year analysis period for airport concrete pavements, a summation procedure geared towards the simulation of the actual pavement through its entire life will translate into thousands of cycles of finite element analyses. Each of these cycles have to be evaluated if the effect of factors such as the repeated traffic loading, temperature and moisture changes, material aging, load transfer changes, and other local damage, are to be modeled accurately. In addition, the combination of load and environmental conditions for each particular load/time step has to be determined in a non-deterministic manner. An ultimate and realistic damage assessment approach will involve the process where the damage generated for each load step is summed up for the entire analysis period. This will require an unrealistic amount of computer time to simulate the typical 20 to 30-year analysis period for pavements.

In a more practical approach, the analysis period can be broken up into a small number of increments (e.g. hourly, daily, seasonally), within which material properties, temperature and moisture conditions, and all other conditions are assumed to remain constant for all practical purposes and given conservative values. The average damage for each increment (e.g., hourly increment) can then be determined with some degree of accuracy, and the damages for the increments summed up to give the total damage over the analysis period. A procedure which provides for a sufficient number of iterations or increments to approximate reality is envisaged.

Postprocessing of the damage determined is essential to clearly show its effect on the pavement structure being analyzed. Unlike the postprocessing that is done to illustrate the results obtained after each load/time step of the primary response model, this should have the goal of showing the areas of the pavement structure that experience some kind of distress as a result of accumulated damage.

REHABILITATION DESIGN

It is very likely that most of the work in the analysis and design of airport pavements in the future will involve the rehabilitation of existing pavements. One major improvement that is expected to be offered by a unified pavement analysis and design system will be in the area of the evaluation of the structural condition of concrete pavements, and the use of the results from such evaluations in innovative rehabilitation designs based on mechanistic principles. The structural evaluation of existing airport pavements will no doubt require that data are obtained by nondestructive methods to minimize or prevent pavement facility shut-downs at airports. Likewise, fast-track construction measures are required for the rehabilitation of the pavements found to be in need of repairs to ensure that they are opened to traffic as soon as possible.

Currently, and for the foreseeable future, nondestructive deflection testing seems to be a method that holds a lot of promise in the area of pavement structural evaluation. A number of backcalculation procedures are also currently available for determining the in-situ properties of existing pavements from such deflection results. However, there is often the tendency for users to obtain varied results with these backcalculation procedures. This stems from the inability of most of these procedures to realistically model what actually happens when pavements are loaded since they are in most cases based on principles that are not mechanistic. Also, although there have been considerable advances in understanding the fundamental behavior of the individual pavement materials, knowledge about their behavior within a pavement system is still limited. More so is the understanding of the effect of the environment, the process of aging, and the effect of repeated traffic on the performance of pavements.

The unified pavement analysis and design system recommended, with its capabilities for the realistic modeling of pavement problems, offers many advantages in the analysis and design of rehabilitation that has not been possible in the past. It provides a sound theoretical basis for the interpretation of nondestructive testing results, since its development is based on mechanistic principles. Consequently, it is expected that the engineering significance of nondestructive test results based on the unified pavement analysis and design system will be independent of the type of equipment used.

The unified analysis and design system will also provide the appropriate mechanistic methods for the determination of pavement material properties from nondestructive test results. With the incorporation of the proper constitutive relations that account for the effects of temperature, moisture, and aging in the primary response model, the material properties determined using the unified system will be much close to the actual values and repeatable.

With these capabilities, the unified pavement analysis and design system can be efficiently applied to the design of rehabilitation for existing pavements. Essentially, once an existing pavement structure is realistically modeled, the same principles used for new construction can be relied upon for rehabilitation analysis and design. Because the evaluation of the existing pavement and the design of the rehabilitation to be applied to it will be based on mechanistic principles, however, the results obtained can be expected to be an improvement over those obtained with existing empirical and mechanistic-empirical procedures.

SUMMARY AND RECOMMENDATIONS

The concepts for the development of a unified pavement analysis and design system that will improve the performance of concrete pavements have been presented in this paper. The main features of the analysis and design system proposed include a central primary response model based on 3-D FEA with the capabilities for a realistic structural analysis of pavements under varying traffic loading, environmental, and material conditions. Implementation of this 3-D FEA model will permit the solution of complex pavement problems with non-linearities in terms of the material behavior, geometry, and boundary conditions. A powerful solution procedure that will result in reduced memory requirements and allow the solution of complex pavement problems on smaller computers has been proposed for implementation. The solution procedure will result in an increase in computation speeds by a factor of between 5 and 10 in comparison to the traditional solution procedures.

Advanced preprocessing features proposed include automatic mesh generation using 3-D elements that will allow a realistic representation of the various pavement characteristics and a wide range of load and boundary conditions. Pavement engineers will be able to represent mechanical loads as point, distributed, or axial loads, and represent changing boundary conditions. Advanced graphical postprocessing capabilities will also allow the efficient interpretation and reporting of the results obtained from the primary response model. This will include the ability to plot the deformed and undeformed shapes of a model (either separately or superimposed over each other), color contours, and X-Y plots of all the scalar variables obtained as a function of location, load, time (history plots), or other variables.

An essential part of the primary response model will be a library of incremental constitutive models for the major classes of pavement materials. The advantage of using incremental constitutive models is that, for each of these classes of materials the constitutive models can be progressively modified by the addition of parameters to better describe the materials as their physical behavior become more complex. This will give a more effective way of accounting for the effect of changing environmental and loading conditions and past damage on material behavior.

The concepts have been proposed for a mechanistic procedure for assessing the cumulative damage experienced by a design over its life as a result of the repeated application of traffic loads under different environmental conditions, and changing material and structural conditions. This procedure involves an incremental summation of damage over an analysis period that takes the history dependence of damage into account.

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The development of a powerful, 3-D finite element framework with fast static/dynamic solution algorithms and associated library of elements is emphasized. A stepwise incorporation of constitutive models to take account of increasingly complex material properties is recommended. With the progressive development of the unified pavement analysis and design system proposed, an analysis and design system capable of handling existing pavement evaluation, new design, and the design of strengthening overlays and other rehabilitation involving the use of nondestructive testing to obtain in-situ material properties is envisaged as the end product.

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DISCLAIMER

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