Pavement Analysis and Design

TE-503 A/TE-503

Lecture-14
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DTEM

Rigid Pavement Design

CALIBRATED MECHANISTIC DESIGN PROCEDURE

As with flexible pavements, the calibrated mechanistic design procedure involves the application of structural models to calculate pavement responses, the development of distress models to predict pavement distress from structural responses, and the calibration of the predicted distress with the observed distress on in-service pavements.

Figure shows the general methodology for rigid pavement design. This figure is similar to Figure 11.1 for flexible pavements, except for step 5 on structural models and step 8 on distress models.

The structural models for rigid pavement analysis are more advanced than the distress models. Several finite element programs can be used as structural models, but most of the distress models are regression equations derived empirically with a large scatter of data. The major types of distress to be modeled include fatigue cracking, pumping, faulting and joint deterioration for jointed concrete pavements and punchouts for continuous reinforced concrete pavements. Some steps in Figure are described in Sections 11.1.1 and 11.1.2; only the steps involving these new models are discussed in this section. Most of the models presented herein were developed by the University of Illinois and described in Report 1-26 (NCHRP, 1990).

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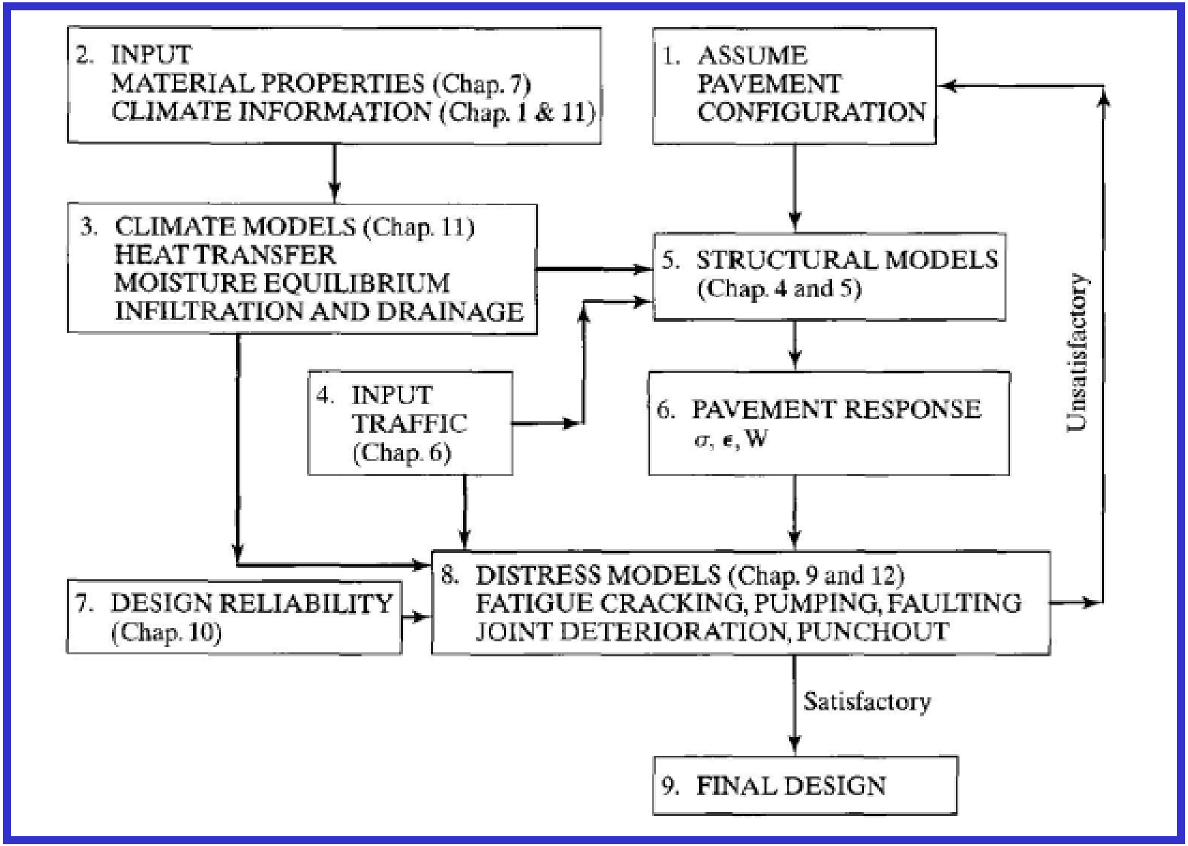
CALIBRATED MECHANISTIC DESIGN PROCEDURE



2. INPUT
MATERIAL PROPERTIES (Chap. 7)
CLIMATE INFORMATION (Chap. 1 & 11)

1. ASSUME
PAVEMENT
CONFIGURATION

3. CLIMATE MODELS (Chap. 11)
HEAT TRANSFER
MOISTURE EQUILIBRIUM
INFILTRATION AND DRAINAGE

5. STRUCTURAL MODELS
(Chap. 4 and 5)

4. INPUT
TRAFFIC
(Chap. 6)

6. PAVEMENT RESPONSE
σ, ϵ, W

Unsatisfactory

8. DISTRESS MODELS (Chap. 9 and 12)
FATIGUE CRACKING, PUMPING, FAULTING
JOINT DETERIORATION, PUNCHOUT

7. DESIGN RELIABILITY
(Chap. 10)

Satisfactory

9. FINAL DESIGN

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Structural Models

To analyze rigid pavement systems accurately, Report 1-26 (NCHRP, 1990) indicated that the structural models used must have the following minimum capabilities:

1. To analyze slabs of any arbitrary dimensions
2. To analyze systems with two layers (slab and subbase), either bonded or unbonded, with the same or different material properties
3. To analyze slab systems on either a liquid or a solid subgrade
4. To analyze slab systems with either uniform or nonuniform support, so that loss of support due to erosion or other causes can be taken into account
5. To analyze multiple slabs with load transfer across the joints or cracks
6. To consider slab warping and curling simultaneously with load responses
7. To analyze slabs with variable crack spacings for CRCP design
8. To analyze slabs with any arbitrary loading conditions, including single or multiple wheels, variable tire pressures, and loads applied at arbitrary assigned distances from cracks, joints, or slab edges
9. To analyze pavement systems with arbitrary shoulder conditions, including asphalt shoulders, tied concrete shoulders, and extended driving lanes with asphalt or concrete shoulders beyond the extended slab.
10. To analyze systems with nonuniform slab or shoulder thicknesses

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

Structural Models

After reviewing several finite element models, Report 1-26 recommended the use of ILLI-SLAB as the basic model for the analysis of rigid pavements. The KENSLABS program also meets all the preceding requirements.

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

Fatigue Cracking Models

As with flexible pavements, the accumulation of fatigue damage can be expressed as a summation of damage ratios, defined as the ratio between predicted and allowable number of load repetitions. However, instead of relating to tensile strain, the allowable number of load repetitions is related to the stress ratio, which is the ratio between the flexural stress and the modulus of rupture. The same probability concept used to define percent area cracked can be used to define percent of slabs cracked.

Truck Load Placement

The fatigue of concrete can cause both transverse cracking, which initiates at the pavement edge midway between transverse joints, and longitudinal cracking, which initiates in the wheelpaths at transverse joints, usually at the wheel path nearest the slab centerline. Figure shows the most critical loading and stress locations to be considered for fatigue analysis. Transverse cracking is caused by the midslab edge loading, and longitudinal cracking is caused by the joint loading. The lateral distribution of traffic means that wheel loads are not applied at the same location, so only a fraction of the load repetitions need be considered for fatigue damage.

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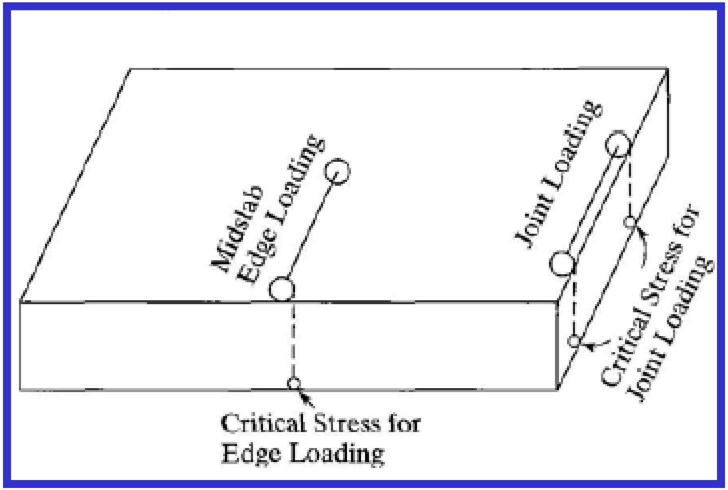
CALIBRATED MECHANISTIC DESIGN PROCEDURE

Fatigue Cracking Models



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CALIBRATED MECHANISTIC DESIGN PROCEDUR E

Fatigue Cracking Models

Report 1-26 suggested the use of an equivalent damage ratio, EDR, for each critical loading position. EDR is the ratio of the traffic applied at a critical location that will produce the same accumulated fatigue damage as the total traffic distributed over all locations. It was demonstrated in Report 1-26 that an EDR of 0.05 to 0.06 can be used for the midslab edge loading with asphalt shoulders and that an EDR of 0.25 to 0.28 can be used for joint loading. For edge loading with tied concrete shoulders, the EDR ranges from 0.12 to 0.34. Therefore, the truck-load placement, which is not a factor in flexible pavement design, must be carefully considered in rigid pavement design.

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Curling Stress

Report 1-26 suggested the use of combined loading and curling stresses for determining the stress ratio and thus the allowable number of load repetitions. In addition to the number of periods and load groups, a new loop indicating curling conditions is included:

$$D_r = \sum_{i=1}^{p} \sum_{k=1}^{3} \sum_{j=1}^{m} \frac{n_{i,k,j}}{N_{i,k,j}}$$

In this equation, Dr is the accumulated damage ratio over the design period at the critical location, *i* is the counter for periods or subgrade support values, *p* is the total number of periods, *k* is the counter for three curing conditions (day, night, and zero temperature gradient), *j* is the counter for load groups, *m* is the total number of load groups, *ni,k* is the predicted number of load repetitions for the *jth* load group, *kth* curling condition and *ith* period, and *Ni,k,j* is the allowable number of load repetitions for the *jth* load group, *kth* curling condition, and *ith* period.

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$$D_r = \sum_{i=1}^{p}\sum_{k=1}^{3}\sum_{j=1}^{m}\frac{n_{i,k,j}}{N_{i,k,j}}$$

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Curling Stress

The inclusion of curling stress complicates the computation, because the traffic has to be divided into three time periods, each with a different temperature gradient. It does not appear reasonable to combine loading and temperature stresses, since they do not occur at the same frequency. A pavement may be subject to thousands of load repetitions per day due to traffic, but the number of repetitions due to temperature curling is mostly only once a day. If curling stresses cannot be ignored and longer panel lengths have significant effects on fatigue cracking because of higher curling stresses, it is more reasonable to consider the damage ratios due to loading and curling separately and then combined, as illustrated by the Shahin-McCullough model for flexible pavements.

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$$D_r = \sum_{i=1}^{p} \sum_{k=1}^{3} \sum_{j=1}^{m} \frac{n_{i,k,j}}{N_{i,k,j}}$$

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Curling Stress

Curling may not affect the fatigue life significantly because the curling stress may be subtracted from or added to the loading stress, thus neutralizing the effect. The edge stress is further reduced by moisture warping because the moisture contents at the bottom of slab are very frequently higher than those at the top. The curling stress should be much reduced when new pavements are to be constructed with reasonably short panel lengths. The calibration of the model can further minimize the effect of curling stress. For example, Figure shows a plot of calibrated performance curves for jointed concrete pavements relating the percent slabs cracked to the accumulated damage ratio. The stress ratio used in calculating the fatigue relationships shown in the figure included both loading and curling stresses. If curling stresses were eliminated from this calculation, different performance curves would be obtained. However, the percent slabs cracked should not be significantly affected if the same procedure, either including or excluding the curling stress, is used in both design and calibration processes.

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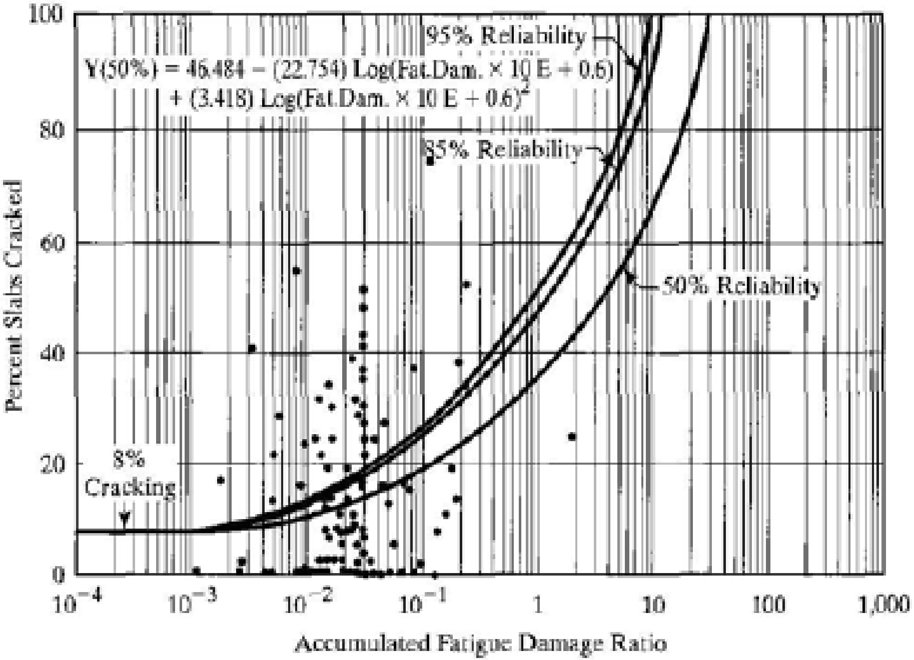
$$D_T = \sum_{i=1}^{p} \sum_{k=1}^{3} \sum_{j=1}^{m} \frac{n_{i,k,j}}{N_{i,k,j}}$$

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Curling Stress



$$D_r = \sum_{i=1}^{p}\sum_{k=1}^{3}\sum_{j=1}^{m}\frac{n_{i,k,j}}{N_{i,k,j}}$$

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Curling Stress

The performance curves shown in Figure were based on field calibration. For 50% reliability, the theoretical percent slabs cracked at a damage ratio of 1 should be 50%, but the percentage shown in the figure is only 27%. One possible cause for the discrepancy is the difficulty of determining the concrete modulus of rupture during the entire evaluation period from the initial loading to the time of evaluation. Additional research needs to be done on the best method for estimating concrete strength in existing pavements and on how the observed cracking can be correlated with the damage ratio and the probability of cracking.

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

Pumping and Erosion Models

There is an important mode of distress in addition to fatigue cracking that needs to be addressed in the design of rigid pavements. This is the pumping and erosion of material beneath and beside the slab. In fact, most of the failures in the Maryland and AASHO road tests were the result of pumping.

Factors that influence pumping and erosion include the presence of water, the rate at which water is ejected under the slab, the erodibility of the subbase material, the magnitude and number of repeated loads, and the amount of deflection. No mechanistic models currently available take all of the above factors into account. The only available model is the one developed by PCA, which is described in Section 12.2. The PCA model was based primarily on the results of the AASHO Road Test, and only the corner deflection was taken directly into consideration.

CALIBRATED MECHANISTIC DESIGN PROCEDURE

Pumping and Erosion Models

Because the subbase materials used in the AASHO Road Test are highly erodible and are currently not used by any of the highway agencies, the application of the model appears to be limited. Attempts have been made to correlate erosion with rate of water ejection, traffic loads, and pavement deflection through an energy model (Dempsey, 1983; Phu *et al.*, 1986). The thrust of this approach is to calculate the amount of energy involved in the deflection of a pavement system and establish a correlation between the total energy absorbed for given levels of traffic and erosion. These attempts have been moderately successful for specified conditions, but there are other factors affecting erodibility that have not been duly considered. Additional work is needed before these models can be incorporated into a mechanistic-based pavement design procedure.

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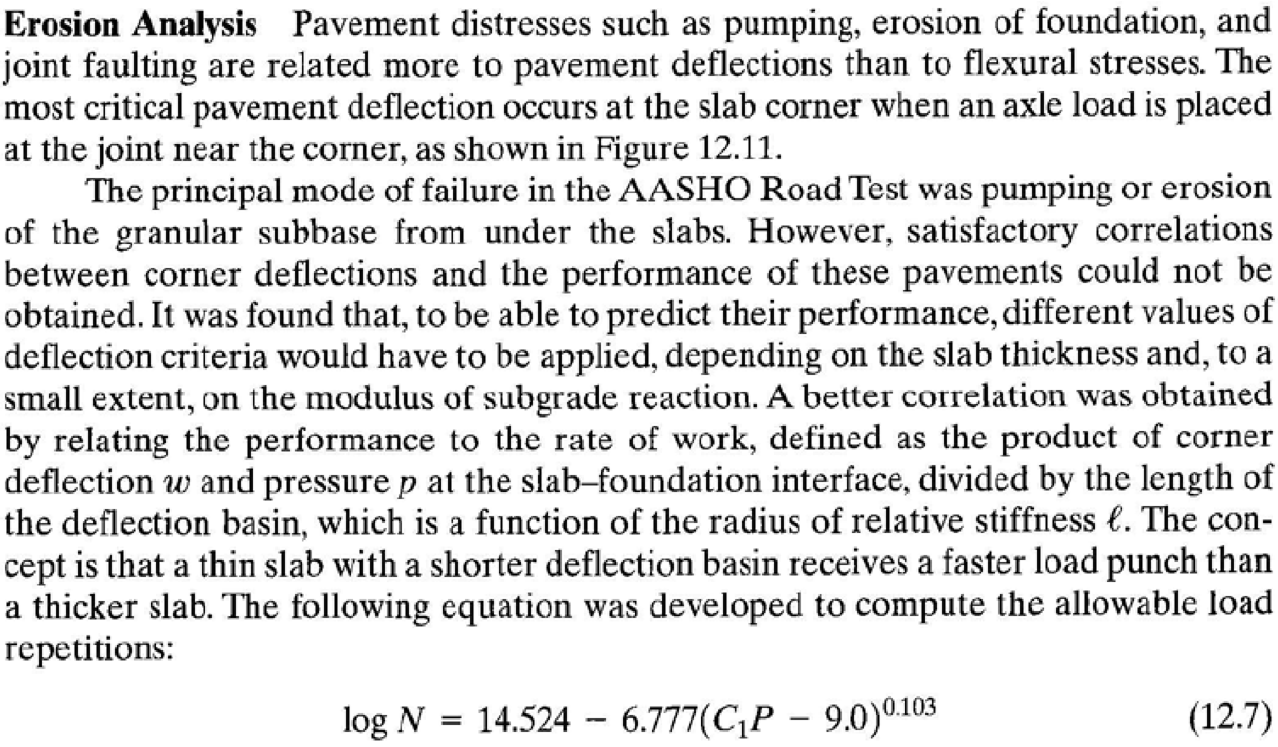
CALIBRATED MECHANISTIC DESIGN PROCEDURE

Erosion Analysis-PCA method



Erosion Analysis Pavement distresses such as pumping, erosion of foundation, and joint faulting are related more to pavement deflections than to flexural stresses. The most critical pavement deflection occurs at the slab corner when an axle load is placed at the joint near the corner, as shown in Figure 12.11.

The principal mode of failure in the AASHO Road Test was pumping or erosion of the granular subbase from under the slabs. However, satisfactory correlations between corner deflections and the performance of these pavements could not be obtained. It was found that, to be able to predict their performance, different values of deflection criteria would have to be applied, depending on the slab thickness and, to a small extent, on the modulus of subgrade reaction. A better correlation was obtained by relating the performance to the rate of work, defined as the product of corner deflection w and pressure p at the slab–foundation interface, divided by the length of the deflection basin, which is a function of the radius of relative stiffness ℓ. The concept is that a thin slab with a shorter deflection basin receives a faster load punch than a thicker slab. The following equation was developed to compute the allowable load repetitions:

$$\log N = 14.524 - 6.777(C_1P - 9.0)^{0.103} \tag{12.7}$$

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

Erosion Analysis-PCA method

$$\log N = 14.524 - 6.777(C_1 P - 9.0)^{0.103} \tag{12.7}$$

In this equation, N is the allowable number of load repetitions (based on a PSI of 3.0), C_1 is an adjustment factor (with a value of 1 for untreated subbases and 0.9 for stabilized subbases), and P is the rate of work or power, defined by

$$P = 268.7 \frac{p^2}{hk^{0.73}} \tag{12.8}$$

in which p is the pressure on the foundation under the slab corner in psi (which is equal to kw for a liquid foundation), h is the thickness of slab in inches, and k is the modulus of subgrade reaction in pci. The equation for erosion damage is

$$\text{Percent erosion damage} = 100 \sum_{i=1}^{m} \frac{C_2 n_i}{N_i} \tag{12.9}$$

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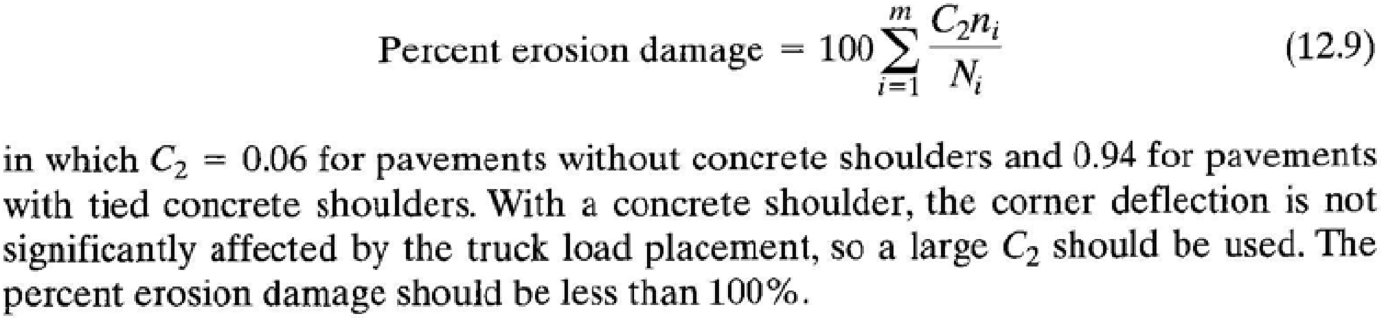
PORTLAND CEMENT ASSOCIATION METHOD

Erosion Analysis-PCA method



$$\text{Percent erosion damage} = 100 \sum_{i=1}^{m} \frac{C_2 n_i}{N_i} \tag{12.9}$$

in which $C_2 = 0.06$ for pavements without concrete shoulders and 0.94 for pavements with tied concrete shoulders. With a concrete shoulder, the corner deflection is not significantly affected by the truck load placement, so a large C_2 should be used. The percent erosion damage should be less than 100%.

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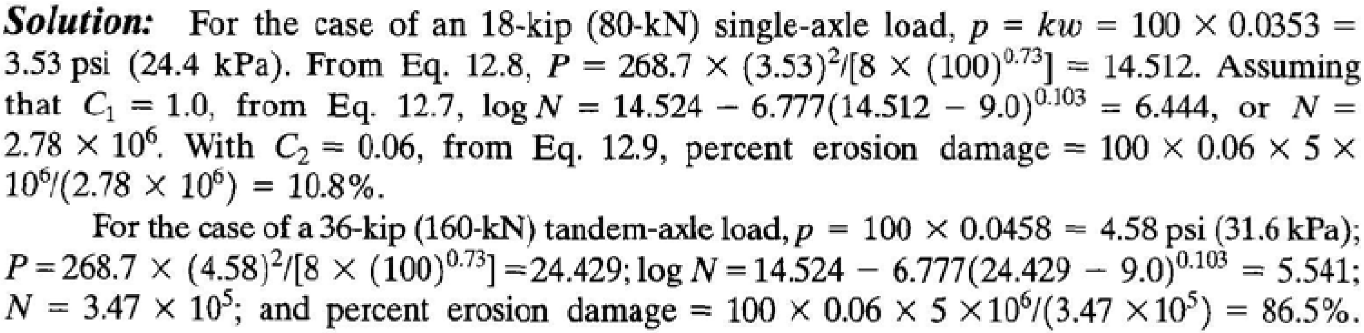
CALIBRATED MECHANISTIC DESIGN PROCEDURE

Erosion Analysis-PCA method –Numerical problem

The sensitivity analysis of corner deflection shows that, for the standard case with h = 8 in. and k = 100 pci , the corner deflection is 0.0353 in. under an 18-kip single-axle load and 0.0458 in. under a 36-kip tandem-axle load. If the predicted number of load repetitions is 5 x 10^6 , compute the percent erosion damage under the single and tandem-axle loads, respectively.



Solution: For the case of an 18-kip (80-kN) single-axle load, $p = kw = 100 \times 0.0353 = 3.53$ psi (24.4 kPa). From Eq. 12.8, $P = 268.7 \times (3.53)^2/[8 \times (100)^{0.73}] = 14.512$. Assuming that $C_1 = 1.0$, from Eq. 12.7, $\log N = 14.524 - 6.777(14.512 - 9.0)^{0.103} = 6.444$, or $N = 2.78 \times 10^6$. With $C_2 = 0.06$, from Eq. 12.9, percent erosion damage $= 100 \times 0.06 \times 5 \times 10^6/(2.78 \times 10^6) = 10.8\%$.

For the case of a 36-kip (160-kN) tandem-axle load, $p = 100 \times 0.0458 = 4.58$ psi (31.6 kPa); $P = 268.7 \times (4.58)^2/[8 \times (100)^{0.73}] = 24.429$; $\log N = 14.524 - 6.777(24.429 - 9.0)^{0.103} = 5.541$; $N = 3.47 \times 10^5$; and percent erosion damage $= 100 \times 0.06 \times 5 \times 10^6/(3.47 \times 10^5) = 86.5\%$.

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

Erosion Analysis-PCA method –Numerical problem

Problem-1: A 10-in. concrete pavement without concrete shoulders is placed on an untreated subbase having the k value 150 pci. Estimate the allowable corner deflection by the PCA erosion criterion if the pavement is subjected to 2 million applications of a given axle load. [Answer:0.0468 in.]

Same pavement as in Problem-1, but with concrete shoulders. Estimate the allowable corner deflection . [Answer: 0.0318 in.]

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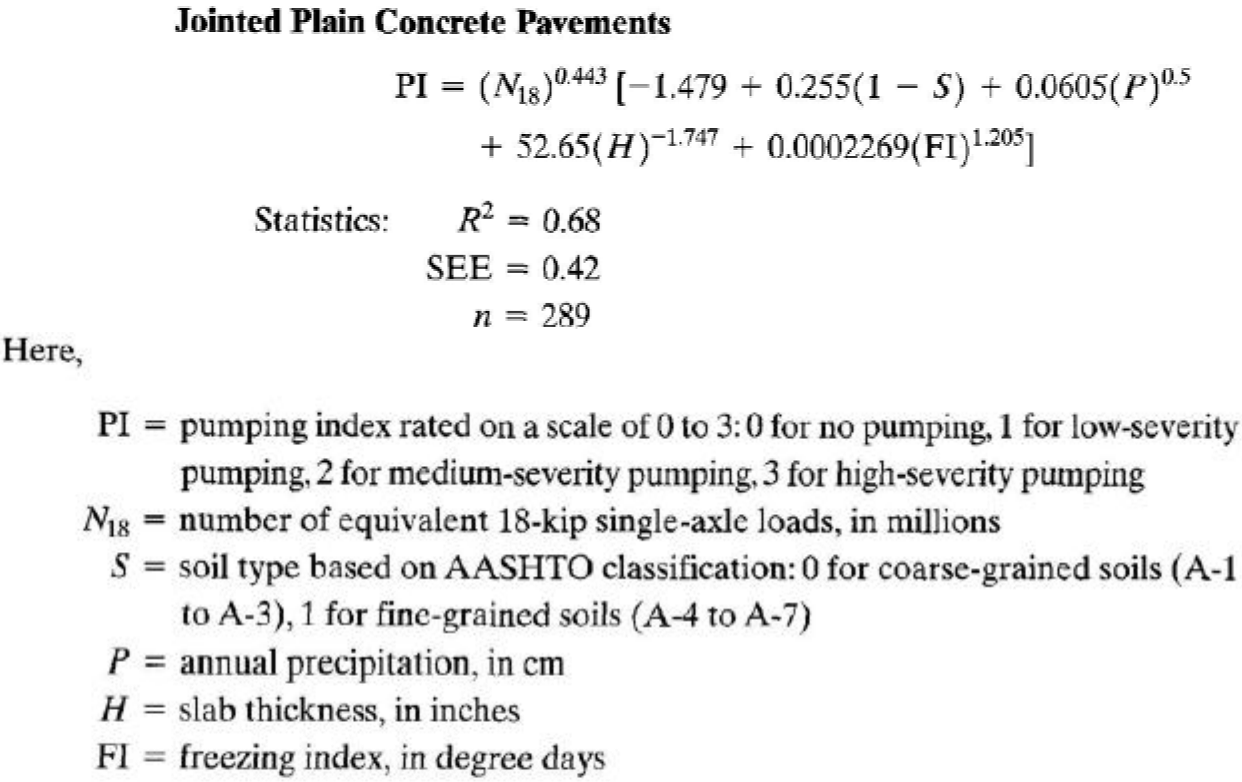
CALIBRATED MECHANISTIC DESIGN PROCEDURE

Pumping and Erosion Models



Jointed Plain Concrete Pavements

$$\mathrm{PI} = (N_{18})^{0.443}\,[-1.479 + 0.255(1 - S) + 0.0605(P)^{0.5} + 52.65(H)^{-1.747} + 0.0002269(\mathrm{FI})^{1.205}]$$

Statistics: $R^2 = 0.68$

$\mathrm{SEE} = 0.42$

$n = 289$

Here,

PI = pumping index rated on a scale of 0 to 3: 0 for no pumping, 1 for low-severity pumping, 2 for medium-severity pumping, 3 for high-severity pumping

N_{18} = number of equivalent 18-kip single-axle loads, in millions

S = soil type based on AASHTO classification: 0 for coarse-grained soils (A-1 to A-3), 1 for fine-grained soils (A-4 to A-7)

P = annual precipitation, in cm

H = slab thickness, in inches

FI = freezing index, in degree days

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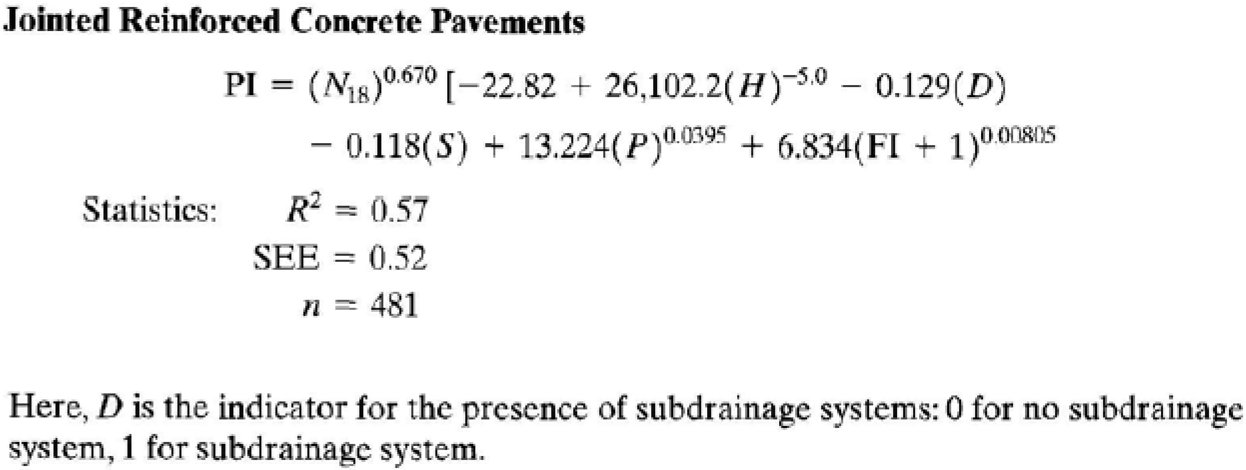
Pumping and Erosion Models



Jointed Reinforced Concrete Pavements

$$\mathrm{PI} = (N_{18})^{0.670}[-22.82 + 26{,}102.2(H)^{-5.0} - 0.129(D) - 0.118(S) + 13.224(P)^{0.0395} + 6.834(\mathrm{FI} + 1)^{0.00805}$$

Statistics:

$R^2 = 0.57$

$\mathrm{SEE} = 0.52$

$n = 481$

Here, D is the indicator for the presence of subdrainage systems: 0 for no subdrainage system, 1 for subdrainage system.

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

FAULTING MODELS

Faulting at transverse joints is a serious problem that can lead to severe roughness in jointed concrete pavements. The mechanisms of faulting distress in doweled pavements are quite different from those in undoweled pavements. Therefore, these two pavements are discussed separately.

Doweled Pavements

Faulting of doweled pavements is caused by the erosion of concrete around the dowels under repeated loading. Because the design of dowels is based on the bearing stress between dowel and concrete, it is natural to assume that faulting is due to excessive bearing stress. It was found that, if the bearing stress is kept below approximately 1500 psi (10.4 MPa), faulting can be limited to an acceptable level.

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

FAULTING MODELS-Doweled Pavements

$$F = (N_{18})^{0.5377}\,[2.2073 + 0.002171(S)^{0.4918} + 0.0003292(\mathrm{JS})^{1.0793} - 2.1397(k)^{0.01305}]$$

In this equation,

F = pavement faulting, in inches
N_{18} = number of equivalent 18-kip single-axle loads, in millions
S = maximum bearing stress, in psi
JS = transverse joint spacing, in ft
k = estimated modulus of subgrade reaction on the top of the subbase, in pci

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

FAULTING MODELS-Doweled Pavements-Numerical Problem

A doweled concrete pavement has a joint spacing of 20 ft and no tied concrete shoulders for edge support. The calculated bearing stress between dowel and concrete is 3000 psi, and the pavement is placed on a subbase with an effective modulus of subgrade reaction of 100 pci. Estimate the amount of transverse joint faulting after the pavement has been subjected to 20 million repetitions of an 18-kip equivalent single-axle load.

$$F = (N_{18})^{0.5377}\,[2.2073 + 0.002171(S)^{0.4918} + 0.0003292(\mathrm{JS})^{1.0793} - 2.1397(k)^{0.01305}]$$

In this equation,

F = pavement faulting, in inches
N_{18} = number of equivalent 18-kip single-axle loads, in millions
S = maximum bearing stress, in psi
JS = transverse joint spacing, in ft
k = estimated modulus of subgrade reaction on the top of the subbase, in pci

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CALIBRATED MECHANISTIC DESIGN PROCEDURE

FAULTING MODELS-Undoweled Pavements

To date, no mechanistic-based analyses have been attempted for undoweled pavements. The following regression equation was derived from 186 pavement sections in the COPES data base and presented in Report 1-26:

$$
\begin{aligned}
F = (N_{18})^{0.3157}[0.4531 &+ 0.3367(z)^{0.3322} - 0.5376(100w)^{-0.008437} \\
&+ 0.0009092(\mathrm{FI})^{0.5998} + 0.004654(B) - 0.03608(\mathrm{ES}) \\
&- 0.01087(S) - 0.009467(D)]
\end{aligned}
$$

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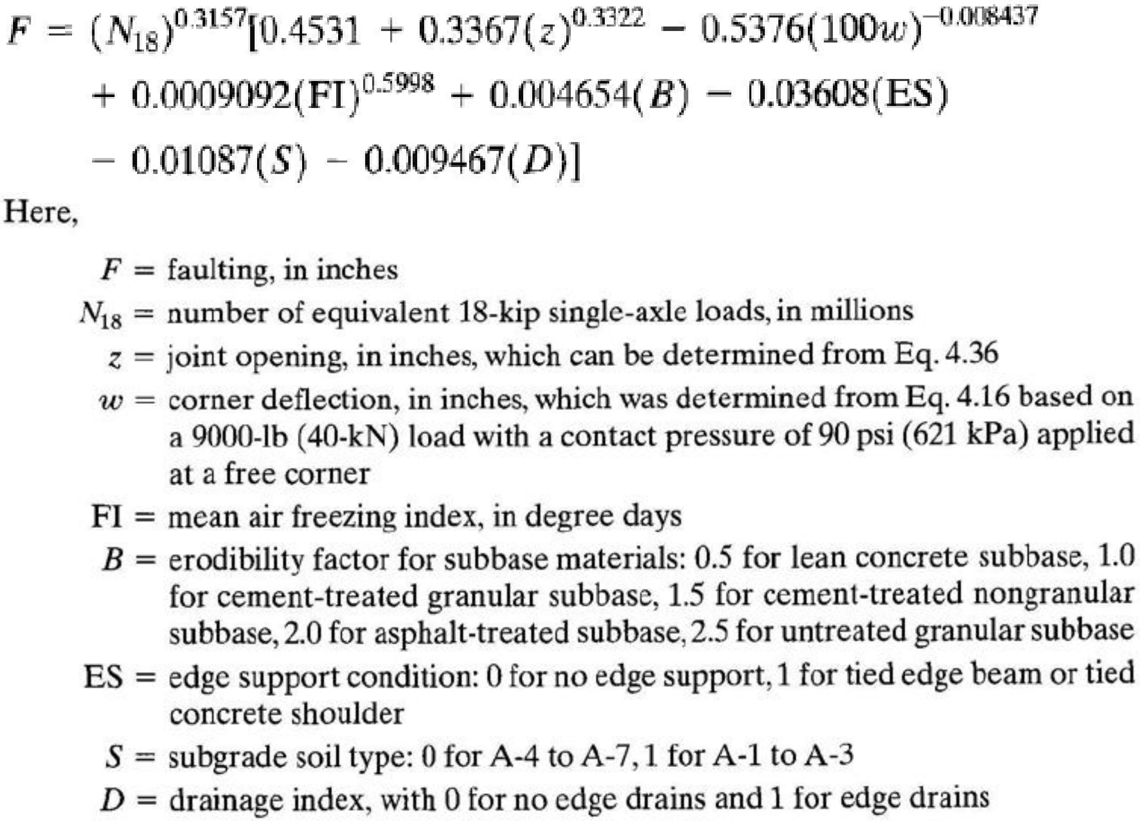
CALIBRATED MECHANISTIC DESIGN PROCEDURE

FAULTING MODELS-Undoweled Pavements



$$F = (N_{18})^{0.3157}[0.4531 + 0.3367(z)^{0.3322} - 0.5376(100w)^{-0.008437} + 0.0009092(\mathrm{FI})^{0.5998} + 0.004654(B) - 0.03608(\mathrm{ES}) - 0.01087(S) - 0.009467(D)]$$

Here,

F = faulting, in inches

N_{18} = number of equivalent 18-kip single-axle loads, in millions

z = joint opening, in inches, which can be determined from Eq. 4.36

w = corner deflection, in inches, which was determined from Eq. 4.16 based on a 9000-lb (40-kN) load with a contact pressure of 90 psi (621 kPa) applied at a free corner

FI = mean air freezing index, in degree days

B = erodibility factor for subbase materials: 0.5 for lean concrete subbase, 1.0 for cement-treated granular subbase, 1.5 for cement-treated nongranular subbase, 2.0 for asphalt-treated subbase, 2.5 for untreated granular subbase

ES = edge support condition: 0 for no edge support, 1 for tied edge beam or tied concrete shoulder

S = subgrade soil type: 0 for A-4 to A-7, 1 for A-1 to A-3

D = drainage index, with 0 for no edge drains and 1 for edge drains