Erosion-Based Design for PCC Pavements

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Jointed Concrete Pavement Components

- Traffic Model
- Wheel Load Stress Model
- Subbase Drainage Model
- Subbase Erosion Model
- Slab/Subbase Interface Model
JCP Erosion Related Distress
Subbase Erosion Model/Capability & Components

The three main elements of erosion:

- Rate of Erosion of the base/subbase
- Existence of Moisture under the slab
- Traffic

Properties - Lab
Model - Tested Properties
Performance - Field
Faulting and Erosion Damage

\[ \% E = \frac{f_i}{f_\infty} = e^{-\left(\frac{\rho}{D_i}\right)^\beta} \]

- \( f_i \) – faulting in time
- \( f_\infty \) – ultimate faulting

Components

- Slab/Base Interface Model
  - Slab Set
  - C & W Behavior
  - Friction
- Joint Infiltration Model
- Joint Sealant Bond Model
- Calibration & Assessment
  - Lab
  - Field

\[ D = \sum \frac{N_i}{N_f} \times (\% \text{Wet Days}) \]

\[ D_{i-m} = D_{i-h} \]
Erosion (between layers)
- Shear Stress
- Load Transfer (Vert & Hoz)
Damage Stress Ratio

Ultimate # Loads ($N_f$): Shear Stress Ratio ($r$)

$$N_f = 10^{k_1 + k_2 r}$$

$$r = \frac{\tau}{f_e} + (J_2)^m (\alpha I_1 + K)^n$$

Mechanical Wear:

1) Shear Stress ($\tau$)
2) Shear Strength ($f_e$): Bound & Unbound Materials

Bulk Consolidation:

1) Bulk Stress ($I_1$)
2) Bulk Shear ($J_2$)
Interlayer Strength Model

\[ f_e = \sigma_v \mu_e = x_b \left[ f_b \right] = \left[ x_b \cdot \cos^2 \phi \cdot \left( (1 - \text{prob}(\sigma_n > 0)) \cdot f_\tau + (1 - \text{prob}(g_n > 0)) \cdot f_F \right) \right] \]

\[ x_b = \frac{h_e - h_u}{h_b - h_u} = 1 - \%E = b + m \mu_e \]

\[ h_{e-p} = \frac{h_{e-u}}{2} \left( 1 - x_e \right) + \left( x_e \right) h_{e-b} \]

Degree of Bond

\( (\text{prob}(\sigma_n > 0)) \) - Risk of Bond Failure; Set
\( (1 - \text{prob}(g_n > 0)) \) - Chance of Contact; C & W Behavior

\( f_b \) - Bond Strength
\( f_\tau \) - Cohesive Strength
\( f_F \) - Frictional Strength
Drops on:

- Joints (Approach Slab and Leave Slab)
- Center of the Slab
- Edges and Corners

\[ x_b = \frac{h_e - h_u}{h_b - h_u} = 1 - \%E = b + m\mu_e \]
Erosion Results – %E

Comp Section

\[ y = 0.0304x - 0.443 \]

\[ R^2 = 0.3475 \]

\[ \mu_e \]

\[ \chi_b \]

% Erosion

% Erosion

Eqv Thickness

0.00% 5.00% 10.00% 15.00% 20.00% 25.00%

0.00 5.00 10.00 15.00 20.00 25.00

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50

0.00 5.00 10.00 15.00 20.00 25.00

1-Jan-90 1-Jan-92 1-Jan-94 1-Jan-96 1-Jan-98 1-Jan-00 1-Jan-02 1-Jan-04 1-Jan-06 1-Jan-08 1-Jan-10 1-Jan-12 1-Jan-14

Erosion Test and Shear Model

\[ f_e = x_b \left[ \cos^2 \phi \right] \cdot \left( f_\tau + f_F \right) \]
Displacement Results

- **Flexbase 3% Cement Treated**
- **RC 3% Cement Treated**
- **RAP-124 3% Cement Treated**
- **RAP-327 3% Cement Treated**
Layer Agnostic-Based Performance Modeling
Included to faulting model by 5 classes of erodibility based on percent of stabilizer and compressive strength

\[ FAULTMAX_i = FAULTMAX_0 + C_7 \times \sum_{j=1}^{m} DE_j \times \log(1 + C_5 \times 5.0^{EROD}) C_6 \]

\[ FAULTMAX_0 = C_{12} \times \delta_{curling} \times \left[ \log(1 + C_5 \times 5.0^{EROD}) \times \log \left( \frac{P_{200} \times WetDays}{P_5} \right) \right]^{C_6} \]

Where:
- \( FAULTMAX_i \) = maximum mean transverse joint faulting for month \( i \) in
- \( FAULTMAX_0 \) = initial maximum mean transverse joint faulting in
- \( EROD \) = base/subbase erodibility factor
- \( DE \) = differential deformation energy accumulated during month \( i \)
- \( C_{12} = C_1 + C_2 \times FR_{0.25} \)
- \( FR \) = base freezing index defined as percentage of time the top base temperature is below freezing (32 \(^\circ\)F) temperature
- \( \delta_{curling} \) = maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping
- \( P_5 \) = overburden on subgrade, lb
- \( P_{200} \) = percent subgrade material passing #200 sieve
- \( WetDays \) = average annual number of wet days (greater than 0.1 in rainfall)
Calibration

$$\% E = \frac{f}{f_{\infty}} = e^{-\left(\frac{\rho}{D}\right)^\beta}$$

Faulting ($f$) vs. Traffic ($N$)
Isolate Two Unknowns: $\beta$ and $\ln(f_\infty)$

\[
\% E = \frac{f}{f_\infty} = e^{-\left(\frac{\rho}{D}\right)^\beta}
\]

\[
\ln(f) = \ln(f_\infty) - \left(\frac{\rho}{D}\right)^\beta
\]

Taking the derivation with respect to $N_e$:

\[
\frac{1}{f} \cdot \frac{\partial f}{\partial N_e} = -\frac{\beta}{N_e} \ln\left(\frac{f}{f_\infty}\right)
\]

\[
\frac{\partial f}{\partial N_e} = -f \frac{\beta}{N_e} \ln(f) + f \frac{\beta}{N_e} \ln(f_\infty)
\]

\[
y = b + mx
\]
Find \( (N_{\infty}) \) and Damage Parameters

\[
\%_0 E = \frac{f}{f_{\infty}} = e^{-\left(\frac{\rho}{D}\right)^\beta}
\]

\[
\ln(-\ln(%_0 E)) = \beta_e \ln\left(\rho_e\right) - \beta_e \ln(D)
\]
Ridgeway, H., *Infiltration Of Water Through The Pavement Surface*

\[ q_i = I_c \left( \frac{N_c}{W_p} + \frac{W_c}{W_p C_s} \right) + k_p \]

Where

- \( q_i \): Infiltration rate per unit area, \( \text{ft}^3/\text{day}/\text{ft}^2 \)
- \( I_c \): Joint infiltration rate, \( \text{ft}^3/\text{day}/\text{ft} \)
- \( N_c \): Number of longitudinal Joints
- \( W_p \): Width of pavement lane subjected to infiltration (ft)
- \( W_c \): Length of transverse joints (ft)
- \( C_s \): Joint Spacing (ft)
- \( K_p \): Concrete infiltration rate, \( \text{ft}^3/\text{day}/\text{ft}^2 \)
Joint Infiltration Model

\[ I_i = \frac{2}{3} C_d \sqrt{2g} \left( \sqrt{H} \right)^3 \]

where

- \( I_i \) = Infiltration rate per unit area, \( \text{ft}^3/\text{s}/\text{ft} \)
- \( C_d \) = Calibrated drag or infiltration coefficient redefined as:
  \[ C_d = \frac{I_{im}}{\frac{2}{3} \sqrt{2g} H_{avg}^{3/2}} \]
- \( g \) = Acceleration due to gravity, \( \text{ft}/\text{s}^2 \)
- \( H \) = Pressure head over the joint, (ft)
- \( I_{im} \) = Measured infiltration rate per unit area, \( \text{ft}^3/\text{s}/\text{ft} \)
Drag Coefficient

\[ C_d = \frac{I_{im}}{2\sqrt{3/2}} \frac{w}{H} + c \ln(Fr) + d \left( \frac{w}{H} \right)^2 + e\left( \ln(Fr) \right)^2 + f \frac{w}{H} \ln(Fr) \]

where

- \( w \) = joint opening, (ft)
- \( H \) = Depth of sheet flow (ft)
- \( Fr \) = Froude Number = \( \frac{v^2}{gL} \) (6)
- \( v \) = Velocity of flow, (ft/s)
- \( g \) = Acceleration due to gravity – 32.174 ft/s^2
- \( L \) = Characteristic length, i.e. H (ft)
- \( a, b, c, d, e, f \) = Calibration coefficients (see Table 1)
Infiltration Model – Input (C_d & H)

\[ I_i = \frac{2}{3} C_d \sqrt{2g \left( \sqrt{H} \right)^3} \]

\[ H = \left( \frac{q_r n}{1.486 \cdot \frac{1}{\sqrt{s}}} \right)^{\frac{3}{5}} \]

where

\[ q_r = \text{Volume of runoff (sheet flow) per unit length (ft}^3/\text{t/ft)} \]

\[ n = \text{Manning’s } n \ (\text{t/ft}^{1/3}) \]

\[ s = \text{Slope of the drainage surface} \]
Number of Wet Days

\[ NWD = P\%_0 \times 365 \]

\[ P = f(P_1, P_2) \]

\( P \) is an adjustment factor that contains three factors:

P1: Probability of the Rain (\( \# \) of rainfalls / 365)

P2: Probability of wet subbase = \( \text{prob}\{(x) > 0 \} \)

1. Rainfall
2. Joint Sealant
3. Sub-base drainage
\[ I_i = \frac{2}{3} F_c C_d \sqrt{2g} \left( \sqrt{H} \right)^3 \]

\[ Q = k h_c \times 1.92 h_b^{-0.403} \]

\[ m = I_i - q_s; \]

\[ \text{Var}\{x\} = \text{Var}\{I_i\} + \text{Var}\{q_s\} \]

Flow Capacity vs Expected Inflow
Investigate Bond Strength: Dirtiness

*Current study (Bhardwaj 2018)

Investigate bond strength: Moisture

Measuring Dielectric Constant (DC) → Percometer quantify moisture level

Moisture determinations (Kim 2018)
Joint Sealant Adhesive Failure

Adhesive failure probability at joint sealant

- Improvement of configuration design
- Stress at interface
- Bond strength
- Proper joint preparation
- Failure

Well bonded vs Low quality bonding
Joint Sealant Behavior

- **Program:** Abaqus
- **Input material property**
  - Tensile strength test data set for a sealant
  - Hyper-elastic behavior model: Mooney-Rivlin model
  - Bond strength test data set

**Shape Factor (SF) = W/D**

where

- \( W \) = Sealant width
- \( D \) = Sealant edge thickness

**Degree of Curvature (DoC) =**

\[
2 \times \frac{D'}{W} \times SF = 2 \frac{D'}{D}
\]

where

- \( D' \) = Sealant center thickness
- \( SF \) = Shape factor = \( W/D \)

Stress analysis result for changing effect of the SF

Stress analysis result for changing effect of the DoC
Traffic Model

\[ r_l = \sqrt{\frac{P_l}{p\pi}} \]

\[ \sum_{k=1}^{3} \%AT_k = 100\% \]

\[ \%SA = \%AT_{SA} \cdot \%Trucks \]

\[ \%TA = \%AT_{TA} \cdot \%Trucks \]

\[ \%Trid = \%AT_{Trid} \cdot \%Trucks \]

\[ %F_{jk\ell} = a + b \frac{1}{\ln(r_{jk\ell})} + c \frac{1}{r_{jk\ell}} \text{ for } r_{jk\ell} > r_L \]

\[ %F_{jk\ell} = \left( \frac{r_{jk\ell} - r_{min}}{r_L - r_{min}} \right) \cdot %F_L \text{ for } r_{jk\ell} \leq r_L \]
Traffic Model

\[ ADTT = ADT \cdot LDF \cdot \%Trucks \]

\[ ESAL_i = ADTT \cdot \sum_{l=1}^{39} \sum_{k=1}^{3} \sum_{j=1}^{10} \left( \%F_{jkl+1} - \%F_{jkl} \right) \cdot \%AT_{kl} \cdot EAF_{kl} \cdot ELF_{kl} \cdot SD_{l} \cdot EWF \cdot GF \cdot 365 \]

where

- \( TC_i \) = Truck Category [AASHTOWare, 2] (i = 1 to 17 AASHTO; 1 to 4 ACI; or custom)
- \( VC_j \) = Vehicle Classification [1] (j = 10)
- \( \%AT_k \) = %Axle Type (k = 3) (see Table 1)
- \( NA_{jk} \) = #Axle/Vehicle Classification (see Table 1)
- \( EAF_k \) = Equivalent Axle Factor (Table 3)
- \( \%F_{jkl} \) = % Load Distribution Table (l = 39)
- \( ELF_{l} \) = Equivalent Load Factor wrt SA (Table 3)
- \( SD_{l} \) = Seasonal Distribution (l = 4)
- \( EWF \) = Equivalent Wander Factor (Table 3)
- \( LDF \) = Lane Distribution Factor
- \( GF = \frac{\left(\frac{1}{1+r}\right)^n - 1}{r} \) (non-linear); =n(1+r) linear
Erosion Process In Design

- Damages the Slab/Subbase Interface
- Lowers Friction
- Reduces Composite Slab Thickness
- Reduces k-Value
- Increases Stress
  - Bending Stress
  - Shear: Loss of LT
### Wheel Load Model

<table>
<thead>
<tr>
<th>Stress Type</th>
<th>Crack Type</th>
<th>Pavement Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Jointed</strong></td>
</tr>
<tr>
<td>SLB</td>
<td>Bottom up; typically mid-slab</td>
<td>Erosion reduces bond in the mid-slab region</td>
</tr>
<tr>
<td>SLT</td>
<td>Top down; typically at the quarter point</td>
<td>Occurs in slabs subject to slab lift-off</td>
</tr>
<tr>
<td>STB</td>
<td>Bottom up; typically in the wheel path</td>
<td>Erosion reduces bond in the wheel path</td>
</tr>
<tr>
<td>STT</td>
<td>Top down; typically between the wheel paths</td>
<td></td>
</tr>
</tbody>
</table>

\[
%\text{Cracking} = \frac{100}{1 + C_4 D^{C_5}}
\]

\[
\log(N_f) = C_1 \left(\frac{1}{r}\right)^{C_2}
\]
Faulting and Erosion Damage

\[ D = D_{i-m} \]

\[ \%E = \left( x_b \frac{\partial \delta_t}{\partial X} \right) \left( \frac{E_p}{2(1+v)} \right) \left( \frac{1}{\psi} \right) \]

\[ r_{i-m} = (x_b) \frac{\partial \delta_t}{\partial X} \frac{E_p}{2(1+v)} \left( \frac{1}{\psi} \right) \]

\[ D = D_{i-h} + D_{i-h} \]

\[ -12n \cdot V \left[ x_s S - r \cos \theta \right] \]
Design components consist of three (3) main layouts:

- Model Tree Layout
- Properties and Settings Layout
- Plot and Log Layout
Properties and settings layout

Project Name

INPUT
- Cement concrete
- Base
- Subgrade
- Traffic 1
- Climate 1
- Pavement type
- Structure 1

MATERIAL MODEL
- ANALYSIS
- RESULTS

Name: Cement concrete
Type Info: Portland Cement Concrete MIX

Custom mixture

User Defined

Mixture Properties:
- PCC Elastic modulus, 28 days (psi): 4.40E+06
- PCC Poisson's ratio: 0.15
- PCC Coefficient of thermal expansion (1/°F): 5.50E-06
- PCC Compressive strength, 28 days (psi): 10000
- PCC Modulus of rupture, 90 days (psi): 750
- PCC Modulus of rupture, 28 days (psi): 675
- PCC Top of Slab Strength Reduction Factor: 0.8
- PCC Tensile strength, 28 days (psi): 473
- PCC Ultimate drying shrinkage (in/in): 600E-6
- PCC Thermal diffusivity (ft^2/day): 1.22
- Cement content (lb/yd^3): 600
Plotting - Faulting

Faulting vs Design Life

- Name: RESULTS
- Type Info: Result
- Select Data: Erosion - Faulting
- Range:
  - Starting year: 1
  - Ending year: 20
- Plot Data

Design life (years)
Faulting
Erosion is a result of pavement type, traffic, base type, and drainage/joint seal design
  - Sealant Installation affects erosion life
- Subbase shear strength is a key to erosion resistance
- Field evaluation reveals that slab corners and edges are critical erosion areas
- Erosion affects slab stresses and joint faulting
- Erosion modeling in design must be fully integrated
THANK YOU