MECHANISTIC-EMPIRICAL PAVEMENT ANALYSIS AND DESIGN

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Department of Civil and Environmental Engineering
University of Wisconsin, Madison

Authors: Hani H. Titi and Emil G. Bautista
Civil Engineering and Mechanics Department
University of Wisconsin – Milwaukee

Principal Investigator: Alan J. Horowitz
Professor, Civil Engineering and Mechanics Department, University of Wisconsin – Milwaukee

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Mechanistic-Empirical Pavement Analysis and Design

INTRODUCTION
This document contains images of all slides in a course module about the theory and use of mechanistic-empirical pavement design. This presentation is available upon request to Hani Titi, hanititi@uw.edu.
Mechanistic-Empirical Pavement Analysis and Design

Educational Module
Part I – Introduction

Emil G. Bautista
Hani H. Titi

Outline

• Flexible Pavements Design Methods
• Rigid Pavements Design Methods
• Road Tests
  – Maryland and WASHO
  – AASHO
  – Long Term Pavement Performance
• Mechanistic-Empirical Pavement Design Guide (MEPDG)
  – Advantages over the AASHTO Guide
  – Basic Elements of the Design Process
Flexible Pavements Design Methods

- **Empirical Method**
- **Limiting Shear Failure Method**
- **Limiting Deflection Method**
- **Regression Method**
- **Mechanistic-Empirical Method**

### Setting Goals and Objectives

**Empirical Method**
- Subbase and pavement thickness estimated
- Without strength test
- California Bearing Ratio (CBR)
- Environmental Materials
- Loading
- Wheel loads

**Limiting Shear Failure Method**
- Determine thickness provided that shear failures will not occur
- Bearing capacity
- Pavement thickness
Flexible Pavements Design Methods

Limiting Deflection Method
- Determine thickness
- Vertical deflections will not exceed allowable limit

Example
AASHTO Method based on results of Road Tests
Applied to the conditions of the road site
Under different conditions
Needs extensive modifications

Mechanistic-Empirical Method
- Based on Mechanics of Materials
- Input: Wheel Load
- Output: Stress or Strain
- Vertical compressive strain used to control pavement deformation
- Plastic strains are proportional to elastic strains in paving materials
- Limiting the elastic strains on the subgrade will control strains on other components above the subgrade and permanent deformation on the surface
Rigid Pavements Design Methods

Rigid Pavement

Analytical Solutions → Assumes slab and subgrade are in contact

Numerical Solutions → Based on partial contact between the slab and subgrade

Goldbeck’s Formula
Westergaard’s Analysis
Pickett’s Analysis

Discrete Element Methods
Finite Element Methods

Road Tests

Maryland Road Test 1941

WASHO Road Tests (Idaho) 1953-1954

AASHO Road Tests (Ottawa, Illinois) 1958-1960

Long Term Pavement Performance 1987 - Present
Maryland and WASHO Road Tests

Maryland Road Test
- 4 different axle loadings
  - 18,000 lbs
  - 22,400 lbs
  - 32,000 lbs
  - 44,000 lbs
- Concrete pavement
  - 1.1 mile section of existing US 301
- WASHO Road Tests (Idaho)
  - 4 Loops
  - Different surfaces
  - Different base thickness
  - Loads similar to Maryland Road Test
  - Flexible pavement
  - 1 mile section

AASHO Road Tests

AASHO Road Tests (Ottawa, Illinois)
- Soil is: Uniform
  - A-6 to A-7-6
  - Representative of large portion of the USA and Canada
- Climate
  - Representative of large portion of the USA and Canada
- 6 two lane loops
- Selected thickness
- 836 test sections
- Asphalts
  - Plain
  - Reinforced
  - 100 ft. long
  - 120 ft. long
  - 240 ft. long
- Concrete
  - 120 ft. long
  - 240 ft. long
AASHO Road Tests

Variable Design Factors

Concrete
- Thickness
- Concrete slab
- Sand-gravel subbase

Asphalt
- Use or not of distributed reinforcing
- Thickness
- Asphalt surface
- Stone base
- Sand-gravel subbase
AASHO Road Tests

Present Serviceability Index

Develop to:

Measure how each test section performed

Definition

Is a numerical designation between 0 and 5 to indicate serviceability ranging from very poor to very good

Long Term Pavement Performance (LTPP)

Nearly 2,500 Test sections representing wide range of climatic and soil conditions monitored until they reach the end of design life or when recommended to be taken out of the study

LTPP

Asphalt and Concrete

United States and Canada
Long Term Pavement Performance (LTPP)

**Mission**
- To study performance data systematically all across the country
- To promote extended pavement life

**Goals**
- Collect and store performance data from a large number of in-service highways in the United States and Canada over an extended period to support analysis and product development
- Analyze these data to describe how pavements perform and explain why they perform as they do
- Translate these insights into knowledge and usable engineering products related to pavement design, construction, rehabilitation, maintenance, preservation, and management

**Objectives**
- Evaluate existing design methods
- Develop improved design methodologies and strategies for the rehabilitation of existing pavements
- Develop improved design equations for new and reconstructed pavements
- Determine the effects of loading, environment, material properties and variability, construction quality, and maintenance levels on pavements distress and performance
- Determine the effects of specific design features on pavement performance
- Establish a national long-term pavement database
Long Term Pavement Performance (LTPP)

General Pavement Study (GPS)
- In-service pavements designed and built according to good engineering practice by DOTs
- 800 sections

Specific Pavement Study (SPS)
- Designed and constructed to answer specific research questions
- 1600 sections

LTPP Test Sections

LTPP Factors

General Pavement Study
- Primary
  - Subgrade
  - Traffic
  - Temperature
  - Moisture
- Secondary
  - AC Thickness
  - AC Stiffness
  - SN of base and subgrade
  - PCC thickness
  - Joint Spacing

Specific Pavement Study
- Primary
  - Subgrade
  - Traffic
  - Temperature
  - Moisture
- Secondary
  - AC drainage
  - AC thickness
  - AC base type and thickness
  - PCC drainage
  - PCC strength and thickness
  - Lane width
  - Base type
Mechanistic-Empirical Pavement Design Guide (MEPDG)

From Design of Pavements Evolve

To Empirical

By considering Fundamental material properties

Responses to load and environment

Setting Goals and Objectives

Mechanistic-Empirical Pavement Design Guide

Develop to provide

 MEPDG

Uniform and comprehensive set of procedures for the design

Analysis and design of pavements based on Mechanistic-Empirical principles

Setting Goals and Objectives
Mechanistic-Empirical Pavement Design Guide

- **Consider**
  - Traffic
  - Climate
  - Base/Subgrade
  - Pavement Condition

- **MEPDG Steps**
  - Evaluate proposed trial design
    - User Inputs
    - Performance Criteria
    - Reliability Values

- **Design DOES NOT meet**
  - Performance Criteria at Specified Reliability
    - Revised and evaluated as necessary

**Setting Goals and Objectives**

Mechanistic-Empirical Pavement Design Guide

- **Outputs**
  - Pavement Distress
    - Rutting
    - Fatigue Cracking
    - Reflective Cracking

- **Flexible**
  - Smoothness (Ride Quality)
    - International Roughness Index (IRI)

- **Rigid**
  - NOT Layer Thickness
    - Slab Cracking
    - Joint Faulting
    - Punchouts

**Setting Goals and Objectives**
MEPDG Advantages over the AASHTO Guide

- Flexible:
  - Prediction of Performance Indicators

- Rigid:
  - Provides a tie between

Advantage of MEPDG over AASHTO

- Flexible:
  - HMA Rutting
  - Total Rutting
  - Non-Load Related Cracking (Thermal Cracking)
  - Load Related Cracking (Fatigue Cracking)
  - Reflective Cracking
  - Smoothness

- Rigid:
  - Transverse Slab Cracking
  - Mean Transverse Joint Faulting
  - CRCP Punchouts
  - Smoothness

- Provides a tie between

Basic Elements of the Design Process

- Design Process:
  - Prediction of Critical Pavement Response
    - Traffic Loading
    - Climate
  - Material Characterization
    - HMA or PCC (Surface Layer)
    - Base/subbase
    - Subgrade
  - Provides a tie between
    - Critical Pavement Response
    - Field Observed Distress
Performance Indicators Predicted by the MEPDG

Long Term Pavement Performance

Accumulation of Incremental Damage

• Time
• Truck traffic loads

References


• Federal Highway Administration (FHWA), “Getting to know the Long Term Pavement Performance Program.”
References


Mechanistic-Empirical Pavement Analysis and Design

Educational Module
Part II – Performance Indicators
Flexible Pavements

Emil G. Bautista
Hani H. Titi
Outline

• Performance Indicators Predicted by the MEPDG
  Flexible Pavements
  – Rutting
    • Hot Mix Asphalt (HMA)
    • Unbound Aggregate Base and Subbase
  – Non-Load Related Cracking
  – Load Related Cracking
    • Alligator Cracking (bottom-up)
    • Longitudinal Cracking (top-down)
  – Reflective Cracking
  – Smoothness (International Roughness Index)
Distribution of the wheel load

Wheel Load

- Hot-mix asphalt
- Base
- Subbase
- Natural soil

Rutting

Wheel load

- HMA Surface
- Base
- Subbase
- Soil
Rutting

Repeated Load Permanent Deformation Triaxial Test

HMA
Unbound Material

Accumulation of plastic deformation

Laboratory relationship
Adjusted to match
Rut depth on the field

Rutting estimated

for
Each subseason

at
Mid depth of each sublayer

Setting Goals and Objectives

Hot Mix Asphalt (HMA) Rutting

\[ \Delta p \text{(hma)} = \varepsilon_p \text{(hma)} h_{HMA} = \beta_1 r k_2 \varepsilon_r \text{(HMA)} \times 10^{k_1 r h_{HMA} k_2 r \beta_2 r T k_3 r \beta_3 r} \]

Where:
- \( \Delta_{p \text{(hma)}} \): Accumulated permanent or plastic vertical deformation in the HMA layer/sublayer, in.
- \( \varepsilon_{p \text{(hma)}} \): Accumulated permanent or plastic axial strain in the HMA layer/sublayer, in/in.
- \( \varepsilon_r \text{(HMA)} \): Resilient or elastic strain calculated by the structural response model at the mid-depth of each HMA sublayer, in/in.
- \( h_{\text{HMA}} \): Thickness of the HMA layer/sublayer, in.
- \( n \): Number of axle-load repetitions.
- \( T \): Mix or pavement temperature, °F.
- \( k_1 \): Depth confinement factor
- \( k_2 \): Global field calibration parameters (from the NCHRP 1-40 D recalibration; \( k_2 = -3.35412, k_3 = 0.4791, k_3 = 1.5606 \)).
- \( \beta_1, \beta_2, \beta_3 \): Local or mixture field calibrations constants; for the global calibration these constants were all set to 1.0.
Hot Mix Asphalt (HMA) Rutting

\[ k_2 = (C_1 + C_2D)0.328196^p \]
\[ C_1 = -0.1039(H_{HMA})^2 + 2.4868H_{HMA} - 17.342 \]
\[ C_2 = 0.0172(H_{HMA})^2 - 1.7331H_{HMA} + 27.428 \]

Where:

- \( D \) = depth below the surface, in.
- \( H_{HMA} \) = Total HMA thickness, in.

Unbound Aggregate Base and Subgrade Rutting

\[ \Delta p_{(soil)} = \beta_{s1}k_{s1}e_{r}h_{soil}\left(\frac{\epsilon_0}{\epsilon_r}\right)\exp\left(-\frac{\epsilon_0}{\epsilon_r}\right) \]

Where:

- \( \Delta p_{(soil)} \) = Permanent or plastic vertical deformation layer, in.
- \( n \) = Number of axle-load repetitions.
- \( \epsilon_0 \) = Intercepts determined from laboratory repeated load permanent deformation tests, in/in.
- \( \epsilon_r \) = Resilient strain imposed in laboratory test to obtain material properties \( \epsilon_0 \) and \( p \), in/in.
- \( \epsilon_\nu \) = Average vertical resilient or elastic strain in the layer/sublayer and calculated by the structural response model, in/in.
- \( h_{soil} \) = Thickness of the unbound layer/sublayer, in.
- \( k_{s1} \) = Global calibration coefficients; \( k_{s1} = 1.673 \) for granular materials and 1.35 for fine-grained materials.
- \( \epsilon_{s1} \) = Local calibration constant for rutting in the unbound layers; the local calibration constant was set to 1.0 for the global calibration effort.
Unbound Aggregate Base and Subgrade Rutting

\[ \log \beta = -0.61119 - 0.017638 (W_c) \]

\[ \rho = 10^9 \left( \frac{C_o}{1 - (10^9)^\beta} \right) \]

\[ C_o = \ln \left( \frac{a_1 M_r^{b_1}}{a_0 M_r^{b_2}} \right) = 0.0075 \]

Where:

- \( W_c \) = water content (%)
- \( M_r \) = Resilient modulus of the unbound layer or sublayer, psi.
- \( a_1,9 \) = Regression constants; \( a_1 = 0.15 \) and \( a_9 = 20.0 \)
- \( b_1,9 \) = Regression constants; \( b_1 = 0.0 \) and \( b_9 = 0.0 \)

Non-Load Related Transverse Cracking

Setting Goals and Objectives
Non-Load Related Transverse Cracking

Paris Law

Amount of Crack Propagation

Thermal Cooling Cycle

Assumes Relationship

Crack Depth

HMA Layer Thickness

\[ \Delta C = A (\Delta K)^n \]

Where:

\( \Delta C \) = Change in the crack depth due to a cooling cycle,
\( \Delta K \) = Change in stress intensity factor due to a cooling cycle,
\( A, n \) = Fracture parameters for the HMA mixture
Non-Load Related Transverse Cracking

\[ A = 10^{k_t \beta_t (4.389 - 2.52 \log(E_{HMA} \sigma_m))} \]

Where:
- \( \eta = 0.8 \left[ 1 + \frac{1}{n} \right] \)
- \( k_t = \) Coefficient determined through global calibration for each input level (Level 1 = 5.0, Level 2 = 1.5, and Level 3 = 3.0)
- \( E_{HMA} = \) HMA indirect tensile modulus, psi
- \( \sigma_m = \) Mixture tensile strength, psi
- \( m = \) The m-value derived from the indirect tensile creep compliance curve measured in the laboratory.
- \( \beta_t = \) Local or mixture calibration factor

\[ K = \sigma_{tip} [0.45 + 1.99(C_o)^{0.56}] \]

Where:
- \( \sigma_{tip} = \) Far-field stress from pavement response model at depth of crack tip, psi,
- \( C_o = \) Current crack length, ft.

Non-Load Related Transverse Cracking

\[ TC = \beta_{t1} N \left[ \frac{1}{\alpha_d} \log \left( \frac{C_d}{H_{HMA}} \right) \right] \]

Where:
- \( TC = \) Observed amount of thermal cracking, ft/mi,
- \( \beta_{t1} = \) Regression coefficient determined through global calibration (400),
- \( N_\sigma = \) Standard normal distribution evaluated at [z],
- \( \alpha_d = \) Standard deviation of the log of the depth of cracks in the pavement (0.769), in,
- \( C_d = \) Crack depth, in,
- \( H_{HMA} = \) Thickness of HMA layers, in.
Load Related Cracking

Wheel load

HMA surface

Base

Subbase

Soil

Fatigue Cracking

Alligator Cracking

Starts at the bottom of the HMA layer

Longitudinal Cracking

Starts at the top of the HMA layer
Load Related Cracking

Mechanistic Approach
- Stress
- Strain
- Linear Layer Elastic Analysis Procedure
- Asphalt Institute MS-1 Model

Empirical Approach
- Relates Strains to Fatigue Damage
- Caused by Traffic Loads

Prediction of Cracking
- Calibration to Real World Performance
- LTTP 82 Sections 24 states

Different Environment
- Material
- Traffic

Setting Goals and Objectives

Load Related Cracking

Induce
- Tensile and Shear Stresses
- Lead to Loss of structural integrity of bound layer (HMA layer)

Repeated Traffic Loads
- Initiate at point where Critical tensile stresses and strains occurs
- Propagate Continued action of traffic loads
- Water to seep into lower unbound layers

Setting Goals and Objectives
Load Related Cracking

- Propagation of Cracking
  - Weakens pavement structure
  - Reduces overall performance
- Increases Roughness of Pavement system
- Decrease in Pavement Serviceability
- Reducing Ride Quality

Load Related Cracking

- Asphalt Institute MS-1 Model
- Damage
- Traffic Loads
  - caused by
  - Measured fatigue cracking in the field
- Transfer Functions

Setting Goals and Objectives
Load Related Cracking

\[ N_{f-HMA} = k_f (C)(G_H) \beta_f^1 \epsilon_t^k f_1 \beta_f^2 (E_{HMA})^k f_3 \beta_f^3 \]

Where:

- \( N_{f-HMA} \): Allowable number of axle loads
- \( \epsilon_t \): Tensile strain at critical locations and calculated by the structural response model, in/in
- \( E_{HMA} \): Dynamic modulus of the HMA measured in compression, psi
- \( k_f, k_1, k_2 \): Global field calibration parameters (from the NCHRP 1-40D recalibration; \( k_1 = 0.007566 \), \( k_2 = -3.9492 \) and \( k_3 = -1.281 \))
- \( \beta_f, \beta_1, \beta_2 \): Local or mixture specific field calibration constants; for the global calibration effort, these constants were set to 1.0

Load Related Cracking

\[ C = 10^M \]

\[ M = 4.84 \left( \frac{V_{be}}{V_a + V_{be}} - 0.69 \right) \]

Where:

- \( V_{be} \): Effective asphalt content by volume, %
- \( V_a \): Percent air voids in the HMA mixture,
- \( C \): Thickness correction term, dependent on type of cracking
Load Related Cracking

Thickness correction term, dependent of type of cracking

- For bottom-up or alligator cracking:

\[ C_H = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49H_{HMA})}}} \]

- For top-down or longitudinal cracking:

\[ C_H = \frac{1}{0.01 + \frac{12.00}{1 + e^{(15.676 - 2.8186H_{HMA})}}} \]

Where:
\[ H_{HMA} = \text{Total HMA thickness, in} \]

Load Related Cracking

The incremental damage index (\( \Delta DI \)) is calculated by dividing the actual number of axle loads by the allowable number of axle loads within a specific time increment and axle-load interval for each axle type.

\[ DI = \sum (\Delta DI)_{j,m,l,p,T} = \sum \left( \frac{n}{N_{f-HMA}} \right)_{j,m,l,p,T} \]

Where:
\( n = \text{actual number of axle-load applications within a specific time period,} \)
\( j = \text{Axle-load interval,} \)
\( m = \text{Axle-load type (single, tandem, tridem, quad, or special axle configuration),} \)
\( l = \text{Truck type using the truck classification groups included in the MEPDG,} \)
\( p = \text{Month,} \)
\( T = \text{Median temperature for the five temperature or quintiles used to subdivide each month, } ^\circ F \)
Load Related Cracking

**Alligator cracking**

\[
FC_{\text{Bottom}} = \left( \frac{1}{60} \right) \left( \frac{C_4}{1 + e^{\left( C_1 C_4^2 + C_2 D_{\text{Bottom}} \right)}} \right)
\]

Where:

- \( FC_{\text{Bottom}} \) = Area of alligator cracking that initiates at the bottom of the HMA layers, % of total lane area,
- \( D_{\text{Bottom}} \) = Cumulative damage index at the bottom of the HMA layers,
- \( C_1, C_2, C_4 = \) Transfer function regression constants; \( C_4 = 6,000; C_1 = 1.00; C_2 = 1.00; C_4^* = - 2C_2 \star \)
- \( C_4^* = -2.40874 – 39.748 (1 + H_{\text{HMA}})^{-2.586} \)

Where:

- \( H_{\text{HMA}} \) = Total HMA Thickness, in

**Longitudinal cracking**

\[
FC_{\text{Top}} = 10.56 \left( \frac{C_4}{1 + e^{\left( C_1 - C_2 D_{\text{Top}} \right)}} \right)
\]

Where:

- \( FC_{\text{Top}} \) = Length of longitudinal cracks that initiate at the top of the HMA layer, ft/mi,
- \( D_{\text{Top}} \) = Cumulative damage index near the top of the HMA surface,
- \( C_1, C_2, C_4 = \) Transfer function regression constants; \( C_4 = 7.00; C_2 = 3.5 \); and \( C_4 = 1,000.00 \)
Reflective Cracking in HMA Overlays

Reflective Cracking

% Area of Cracks that propagates

As a function of time

Stabilized Layer

Existing Pavement

Joints and Cracks in Rigid Pavements

Empirical Equation

Sigmoidal Function

Reflective Cracking in HMA Overlays

\[ RC = \frac{100}{1 + e^{a(c) + bt(d)}} \]

Where:

- \( RC \) = Percent of cracks reflected
- \( t \) = Time, yr,
- \( a, b \) = Regression fitting parameters defined through calibration process,
- \( c, d \) = User-defined cracking progression parameters.

\[ a = 3.5 + 0.75 (H_{eff}) \]
\[ b = -0.688684 - 3.37302 (H_{eff})^{-0.915469} \]

Where:

- \( H_{eff} \) = HMA Overlay Thickness
Reflective Cracking in HMA Overlays

Continual Damage Accumulation

\[ DI_m = \sum_{i=1}^{m} \Delta DI_i \]

Where:
- \( DI_m \) = Damage index for month, \( m \)
- \( \Delta DI_i \) = Increment of damage index in month \( i \)

Area of fatigue damage for the underlying layer at month \( m \)

\[ CA_m = \frac{100}{1 + e^{6 - (6DI_m)}} \]

Reflective Cracking in HMA Overlays

Amount of Cracking Reflected

\[ TRA_m = \sum_{i=1}^{m} RC_t (\Delta CA_i) \]

Where:
- \( TRA_m \) = Total reflected cracking area for month \( m \), (%)
- \( RC_t \) = Percent cracking reflected for age \( t \) (in years)
- \( \Delta CA_i \) = Increment of fatigue cracking for month, \( i \)
To predict IRI, the MPEDG have embedded two equations developed from data collected within the LTPP program.

1. **New HMA Pavements and HMA Overlays of Flexible Pavements**

   \[ IRI = IRI_0 + 0.0150(SF) + 0.400(FC_{total}) + 0.0080(TC) + 40.0(RD) \]

   Where:
   - \( IRI_0 \) = Initial IRI after construction, in/mi
   - \( SF \) = Site factor
   - \( FC_{total} \) = Area of fatigue cracking (combined alligator, longitudinal, and reflection cracking in the wheel path), percent of total lane area. All load-related cracks are combined on an area basis; length of cracks is multiplied by 1 ft to convert length into an area basis,
   - \( TC \) = Length of transverse cracking (including the reflection of transverse cracks in existing HMA pavements), ft/mi
   - \( RD \) = Average rut depth, in
Smoothness (International Roughness Index)

To predict IRI the MPEDG have embedded two equations develop from data collected within the LTPP program.

2. HMA Overlays of Rigid Pavements

\[ IRI = IRI_0 + 0.00825(SF) + 0.575(F_{C_{total}}) + 0.0014(TC) + 40.8(RD) \]

Where:
- \( IRI_0 \) = Initial IRI after construction, in/mi,
- \( SF \) = Site factor
- \( F_{C_{total}} \) = Area of fatigue cracking (combined alligator, longitudinal, and reflection cracking in the wheel path), percent of total lane area. All load related cracks are combined on an area basis – length of cracks is multiply by 1 ft to convert length into an area basis,
- \( TC \) = Length of transverse cracking (including the reflection of transverse cracks in existing HMA pavements), ft/mi,
- \( RD \) = Average rut depth, in

Smoothness (International Roughness Index)

Site Factor

\[ SF = Age [0.02003(PI + 1) + 0.007947(Precip + 1) + 0.000636(FI + 1)] \]

Where:
- \( Age \) = Pavement age, year,
- \( PI \) = Percent of plasticity index of soil,
- \( FI \) = Average annual freezing index, °F days,
- \( Precip \) = Average annual precipitation or rainfall, in
References


- Federal Highway Administration (FHWA), “Getting to know the Long Term Pavement Performance Program.”

References


Mechanistic-Empirical Pavement Analysis and Design

Educational Module
Part III – Performance Indicators
Rigid Pavements

Emil G. Bautista
Hani H. Titi

Outline

• Performance Indicators Predicted by the MEPDG
  Rigid Pavements
  – Transverse Slab Cracking (Jointed Plain Concrete Pavements)
  – Mean Transverse Joint Faulting (Jointed Plain Concrete Pavements)
  – Punchouts (Continuously Reinforced Concrete Pavements)
  – Smoothness (International Roughness Index)
    • Jointed Plain Concrete Pavements
    • Continuously Reinforced Concrete Pavements
Performance Indicators Predicted by the MEPDG

Rigid Pavement

Distribution of Wheel Load on Rigid Pavement
Transverse Slab Cracking
Jointed Plain Concrete Pavement (JPCP)

Design factors and site conditions that affect JPCP structural performance

- Slab thickness
- PCC material characteristics
  - Modulus of elasticity
  - Poisson’s ratio
  - Unit weight
  - Coefficient of thermal expansion and shrinkage
- Base material characteristics
  - Thickness
  - Modulus of elasticity
  - Unit weight
- Interface condition between the PCC slab and base
- Joint Spacing
- Subgrade stiffness
- Lane-shoulder joint LTE

Setting Goals and Objectives

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Transverse Slab Cracking
Jointed Plain Concrete Pavement (JPCP)

Design factors and site conditions that affect JPCP structural performance

- Longitudinal joint lane-to-lane LTE
- Temperature distribution through the slab thickness
- Moisture distribution through the slab thickness
- Magnitude of effective permanent curl/warp
- Axle weight
- Wheel tire pressure and wheel aspect ratio
- Axle position

- Load configuration
  - Bottom-up cracking – axle type (single, tandem, tridem, and quad axles)
  - Top-down cracking – short, medium, and long wheelbase

Setting Goals and Objectives
Any given slab may crack either from bottom-up or top-down but not both.

The predicted bottom-up and top-down cracking must be determined combined because they are not particularly meaningful by themselves. This will exclude the possibility of both modes of cracking occurring on the same slab.

**Transverse Slab Cracking**

**Jointed Plain Concrete Pavement (JPCP)**

**Setting Goals and Objectives**

**Transverse Slab Cracking**

**Jointed Plain Concrete Pavement (JPCP)**

\[ DI_F = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}} \]

Where:

- **DIF** = Total fatigue damage (top-down or bottom-up)
- \( n_{i,j,k,l,m,n,o} \) = Applied number of load applications at condition \( i, j, k, l, m, n, o \)
- \( N_{i,j,k,l,m,n,o} \) = Allowable Number of load applications at condition \( i, j, k, l, m, n, o \)
- \( i \) = Age (accounts for change in PCC modulus of rupture and elasticity, slab/base contact friction, deterioration of shoulder LTE)
- \( j \) = Month (accounts for change in base elastic modulus and effective dynamic modulus of subgrade reaction)
- \( k \) = Axle type (single, tandem, and tridem for bottom-up cracking; short, medium, and long wheelbase for top-down cracking)
- \( l \) = Load level (incremental load for each axle type)
- \( m \) = Equivalent temperature difference between top and bottom PCC surfaces
- \( n \) = Traffic offset path
- \( o \) = Hourly truck traffic fraction
Transverse Slab Cracking
Jointed Plain Concrete Pavement (JPCP)

\[
\log(N_{i,j,k,l,m,n,o}) = C_1 \left( \frac{MR_i}{\sigma_{i,j,k,l,m,n,o}} \right)^{C_2}
\]

Where:
\(N_{i,j,k,l,m,n,o}\) = Allowable number of load applications at condition i, j, k, l, m, n, o
\(MR_i\) = PCC modulus of rupture at age i, psi
\(\sigma_{i,j,k,l,m,n,o}\) = Applied stress at conditions i, j, k, l, m, n, o
\(C_1\) = Calibration constant, 2.0, and
\(C_2\) = Calibration constant, 1.22

Transverse Slab Cracking
Jointed Plain Concrete Pavement (JPCP)

\[
CRK = \frac{1}{1 + (D_l)^{-1.98}}
\]

Where:
CRK = Predicted amount of bottom-up or top-down cracking (fraction), and
\(D_l\) = Fatigue damage
Transverse Slab Cracking
Jointed Plain Concrete Pavement (JPCP)

The fatigue damage calculation is a process of summing damage from each damage increment.

\[
TCRACK = (CRK_{Bottom-Up} + CRK_{Top-Down} - CRK_{Bottom-Up} \times CRK_{Top-Down})
\]

Where:

- \( TCRACK \) = Total transverse cracking (percent, all severities),
- \( CRK_{Bottom-Up} \) = Predicted amount of bottom-up transverse cracking (fraction), and
- \( CRK_{Top-Down} \) = Predicted amount of top-down transverse cracking (fraction)

Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

**Definition**
Is the difference in elevation between adjacent joints at a transverse joint measured approximately 1 ft. from the slab edge or from the right-most lane paint stripe for a widened slab.

**Potential**
Repeated heavy axle loads crossing transverse joints

**Faulting**
Repeated heavy axle loads crossing transverse joints

**Result of:**
- Excessive slab edge and corner deflections that cause erosion and pumping fines from beneath a loaded leave slab
- When a given pavement exhibits a combination of poor load transfer across a joint or crack, heavy axle loads, free moisture beneath the pavement, and erosion and pumping of the supporting base, subbase, or subgrade material from underneath the slab or treated base.

**Conditions for Faulting to occur**
- Significant differential deflections of adjacent slabs impart energy to the underlying pavement materials. The differential energy across the joint or crack is amplified by several factors, including heavy wheel loads and inadequate load transfer.
- Underlying pavements materials are erodible.
- Free water is present in the pavement structure, which leads to the saturation of the underlying materials at the slab-base or treated base-subgrade interface.
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

The relationship between the density of energy of subgrade elastic deformation, the PCC slab deflections, and the coefficient of subgrade has the following form:

\[ E = \frac{k \delta^2}{2} \]

Where:
- \( E \) = density of elastic deformation (i.e., energy of subgrade deformation of a unit subgrade surface area)
- \( \delta \) = the slab's deflection, and
- \( k \) = modulus of subgrade reaction
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

\[ DE = E_L - E_{UL} = \frac{k\delta_L^2}{2} - \frac{k\delta_{UL}^2}{2} = \frac{k}{2} (\delta_L - \delta_{UL})(\delta_L + \delta_{UL}) \]

Where:

- \( DE \) = differential energy of subgrade deformation
- \( E_L \) = energy of subgrade deformation under the loaded slab corner
- \( E_{UL} \) = energy of subgrade deformation under the unloaded slab corner
- \( \delta_L \) = corner deflection under the load slab
- \( \delta_{UL} \) = corner deflection under the unloaded slab
- \( (\delta_L - \delta_{UL}) \) = differential corner deflection between loaded and unloaded slab corner
- \( (\delta_L + \delta_{UL}) \) = free corner deflection, represents the total flexibility of the slab

Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Differential Energy Concept

\[ LTE = \frac{\delta_{UL}}{\delta_L} \times 100\% \]

\[ DE = k \left( \frac{\delta_L + \delta_{UL}}{2} \right) \left( 1 - \frac{LTE_{100}}{LTE} \right) \]

Where:

- \( LTE \) = Limiting Transverse Energy
- \( LTE_{100} \) = Limiting Transverse Energy Value
- \( DE \) = Differential Energy
- \( k \) = A constant
- \( \delta_L \) = Corner deflection under the load slab
- \( \delta_{UL} \) = Corner deflection under the unloaded slab
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Modeling of joint LTE

Combined LTE:

\[ LTE_{joint} = 100 \left[ 1 - \left(1 - \frac{LTE_{dowel}}{100}\right) \left(1 - \frac{LTE_{agg}}{100}\right) \left(1 - \frac{LTE_{base}}{100}\right) \right] \]

Where:

- \( LTE_{joint} \) = total joint LTE (%)
- \( LTE_{dowel} \) = joint LTE if dowels are the only mechanism of load transfer (%)
- \( LTE_{base} \) = joint LTE if the base is the only mechanism of load transfer (%)
- \( LTE_{agg} \) = joint LTE if aggregate interlock is the only mechanism of load transfer (%)

Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Aggregate Interlock LTE (Zollinger et al. aggregate interlock model)

The nondimensional stiffness of an aggregate joint is a function of the load shear capacity, \( S \):

\[ \log(J_{agg}) = -3.19626 + 16.09737 \times \exp \left\{ -\exp \left[ -\left( \frac{S - E}{f} \right) \right] \right\} \]

Where:

- \( J_{agg} = (Agg/kI) \) = joint stiffness of the transverse joint for current increment
- \( I \) = PCC slab radius of relative stiffness (in)
- \( f \) = constant equal to 0.38
- \( S \) = joint shear capacity
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

The joint shear capacity depends on the joint width and past damage and is defined as follows:

\[ S = 0.05 \times h_{pcc} \times e^{-0.028/jw} - \Delta s_{tot}^b \]

Where:

- \( S \) = dimensionless aggregate joint shear capacity,
- \( jw \) = joint opening [mils (0.001 in)]
- \( h_{pcc} \) = PCC slab thickness (in)
- \( \Delta s_{tot}^b \) = cumulative loss of shear capacity at the beginning of the current month equal to sum of loss of shear capacity from every axle-load application

Joint width is calculated for each month on the basis of PCC zero-stress temperature, PCC shrinkage, and PCC mean nighttime monthly temperature:

\[ jw = \max\{12,000 \times JTSpace \times \beta \times [\alpha_{pcc} \times (T_{constr} - T_{mean}) + \epsilon_{sh,mean}], 0\} \]

Where:

- \( \epsilon_{sh,mean} \) = PCC slab mean shrinkage strain
- \( \alpha_{pcc} \) = PCC coefficient of thermal expansion (in/in/°F)
- \( JTSpace \) = joint spacing (ft)
- \( \beta \) = joint open/close coefficient assumed equal to 0.85 for a stabilized base and 0.65 for an unbound granular base
- \( T_{mean} \) = mean monthly nighttime middepth temperature (°F)
- \( T_{constr} \) = PCC zero-stress temperature at set (°F) defined as the temperature at which the PCC layer exhibits zero thermal stress
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

The cumulative loss of shear at the end of the month is determined as follows:

\[
\Delta s_{tot}^b = \Delta s_{tot}^b - \sum_i n_i \Delta s_i
\]

Where:

- \(\Delta s_{tot}^b\) = cumulative loss of shear capacity at the end of the current month equal to sum of loss of shear capacity from every axle-load application
- \(n_i\) = number of applications of axle load \(i\)
- \(\Delta s_i\) = loss of shear capacity due to single application of an axle load \(i\) defined as follows:

\[
\Delta s_i = \begin{cases} 
0 & \text{if } \frac{jw}{h_{PCC}} < 0.001 \\
0.005 \times 10^{-6} \left( \frac{\tau_i}{\tau_{ref}} \right)^{5.5} & \text{if } 0.001 < \frac{jw}{h_{PCC}} < 3.8 \\
0.068 \times 10^{-6} \left( \frac{\tau_i}{\tau_{ref}} \right)^{7.5} & \text{if } \frac{jw}{h_{PCC}} > 3.8 
\end{cases}
\]

- \(\tau_i\) = shear stress on the transverse joint surface from the response model for the load group \(i\) (psi)
- \(\tau_{ref}\) = reference shear stress derived from the Portland Cement Association test results (psi)
- \(jw\) = joint opening (mils)
- \(h_{PCC}\) = PCC slab thickness (in)

*LTE reduction with time comes from the loss of shear capacity and the increase in joint opening due to shrinkage.
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Dowelled Joint Load Transfer

Ioannides and Korovesis identified the following nondimensional parameters governing dowel joint behavior:

\[ J_D = \frac{D}{DowelSpace \, kl} \]

Where:
- \( J_D \) = nondimensional stiffness of dowelled joints
- \( D \) = shear stiffness of a single dowel (lb/in)
- \( Dowel \, Space \) = space between adjacent dowels in the wheelpath (in)

Adopted model for nondimensional dowel joint stiffness:

\[ J_d = J_d^* + (J_0 - J_d^*) \exp(-DAM_{dowels}) \]

Where:
- \( J_d \) = nondimensional dowel stiffness
- \( J_0 \) = initial nondimensional dowel stiffness
- \( J_d^* \) = critical nondimensional dowel stiffness
- \( DAM_{dowels} \) = damage accumulated by a dowelled joint due to past traffic
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Initial and long term nondimensional dowel stiffnesses:

\[ J_0 = \frac{152.8 A_d}{h_{PCC}} \]

\[ \Delta_s = \begin{cases} 
118 & \text{if } \frac{A_d}{h_{PCC}} > 0.656 \\
210.0845 \frac{A_d}{h_{PCC}} - 19.8 & \text{if } 0.009615 \leq \frac{A_d}{h_{PCC}} \leq 0.656 \\
0.4 & \text{if } \frac{A_d}{h_{PCC}} < 0.009615 
\end{cases} \]

Where:

- \( J_0 \) = initial nondimensional dowel stiffness
- \( J^* \) = critical nondimensional dowel stiffness,
- \( A_d \) = area of dowel cross section
- \( h_{PCC} \) = PCC slab thickness (in)

Dowel joint damage accumulated from an individual axle repetition is determined using the following equation:

\[ \Delta DOWDAM = C_B \frac{F_j A}{d_f^*} \]

Where:

- \( \Delta DOWDAM \) = dowel damage increment from an individual axle application,
- \( f' \) = PCC compressive stress (psi)
- \( C_B \) = calibration constant
- \( F \) = effective dowel shear force induced by an axle and defined as follows:
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

\[ F = J_d \times (\delta_L - \delta_U) \times \text{DowelSpace} \]

Where:

- \( J_d \): nondimensional dowel stiffness at the time of load application
- \( \delta_L \): deflection at the corner of the loaded slab induced by the axle
- \( \delta_U \): deflection at the corner of the unloaded slab induced by the axle

Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

Base Load Transfer

The design procedure accounts for the effect by assigning a percentage of LTE of the base layer, LTE\text{base}, depending on the base layer type.

<table>
<thead>
<tr>
<th>Base Type</th>
<th>LTE\text{base} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate base</td>
<td>20</td>
</tr>
<tr>
<td>Asphalt-treated or cement-treated</td>
<td>30</td>
</tr>
<tr>
<td>Lean concrete base</td>
<td>40</td>
</tr>
</tbody>
</table>
Mean Transverse Joint Faulting
Jointed Plain Concrete Pavement (JPCP)

The mean transverse joint faulting is predicted month by month using an incremental approach.

$$ Fault_m = \sum_{i=1}^{m} \Delta Fault_i $$

$$ \Delta Fault_i = C_{34} \times (FAULTMAX_{i-1} - Fault_{i-1})^2 \times DE_i $$

Where:
- Fault_m = Mean joint faulting at the end of the month m, in.
- $$ \Delta Fault_i $$ = Incremental change (monthly) in mean transverse joint faulting during month i, in.
- FAULTMAX_i = Maximum mean transverse joint faulting, in.
- $$ DE_i $$ = Differential density of energy of subgrade deformation accumulated during month i.
Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

\[ FAULTMAX_1 = FAULTMAX_0 + C_7 \sum_{j=1}^{m} DE_j \cdot \log (1 + C_5 + 5.0^{EROD}) \]

\[ FAULTMAX_0 = C_{12} \cdot \delta_{curling} \cdot \left[ \log (1 + C_5 + 5.0^{EROD}) \cdot \log \left( \frac{P_{200} \cdot WetDays}{P_2} \right)^{C_6} \right] \]

Where:

- \(FAULTMAX_0\) = Initial maximum mean transverse joint faulting, in.,
- \(EROD\) = Base/subbase erodibility factor,
- \(\delta_{curling}\) = Maximum mean monthly slab corner upward deflection PCC due to temperature curling and moisture warping,
- \(P_2\) = 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), and
- \(C_{1,2,3,4,5,6,7}\) = Global calibration constants (\(C_1 = 1.29; C_2 = 1.1; C_3 = 0.00175; C_4 = 0.0008; C_5 = 250; C_6 = 1.2\))

Mean Transverse Joint Faulting

Jointed Plain Concrete Pavement (JPCP)

\[ C_{12} = C_1 + C_2 \cdot FR^{0.25} \]

\[ C_{34} = C_3 + C_4 \cdot FR^{0.25} \]

Where:

- \(FR\) = Base freezing index defined as percentage of time the top base temperature is below freezing (32°F) temperature
Concrete Reinforced Concrete Pavements (CRCP)

- Continuous longitudinal steel reinforcement
- Absence of intermediate transverse contraction joint
- Well-defined pattern of transverse cracks that develops within 2 years from construction
  - Typically spaced 0.6 to 1.8 m (2 to 6 ft.) apart

Design factors and site conditions that affect CRCP structural performance:

- Slab thickness
- PCC material characteristics
  - Strength
  - CTE
  - Ultimate shrinkage
- Transverse cracks as a function of pavement design parameters
- Reinforcement applications
  - Percent steel
  - Bar diameter
  - Depth of steel
- Transverse cracks width and crack load transfer during service life
- Slab supporting layers, including the possibility of erosion and loss of support along the edge
- Full spectrum of axle loading and traffic wander characteristics
- Environmental differentials through the slab thickness due to temperature change in concrete
Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Based on the prediction of several critical conditions that take place in the field:

- Development of transverse cracks
- Loss of aggregate interlock across transverse cracks
- Loss of edge support due to erosion
- Fatigue damage accumulation leading to the formation of longitudinal cracks in concrete and punchout development

Punchouts

Defined

By a settle area within a concrete slab enclosed by two closely spaced transverse cracks, a short longitudinal crack, and the edge of the pavement

Results

In the loss of ride quality and represent serious hazards that could lead to fatal road accidents
Punchouts
Concrete Reinforced Concrete Pavements (CRCP)

Mechanistic principles

To account changes in many factors:
- Material properties
- PCC strength and modulus
- Erosion base
- Seasonal climatic conditions
- Traffic loadings
- Crack load transfer
- Subgrade support

Damage accumulation
Correlated with CRCP punchouts by using extensive field data

Setting Goals and Objectives

Punchouts
Concrete Reinforced Concrete Pavements (CRCP)

Modeling of Transverse Cracks and Longitudinal Joint

Shear spring stiffness elements were used to model discontinuities at the transverse cracks and the longitudinal joint. Shear spring stiffness per unit of transverse crack length can be estimated by a equation based on Crovetti:

\[ AGG = k l \left( \frac{1}{LTE - 0.01} \right)^{-\frac{1}{0.012}} \]

Where:
AGG = vertical shear spring stiffness (lb/in/in)
LTE = load transfer efficiency (%)
k = coefficient of subgrade reaction (pci)
l = radius of relative stiffness

Setting Goals and Objectives
Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

LTE across the transverse cracks:

\[ LTE_{trans} = 100 \times \left[ 1 - \left( 1 - \frac{1}{1 + \log^{-1} \left( \frac{0.214 - 0.183 \frac{P_b}{l_i} - \log(J_{ci}) - (500P_b - 3)}{1.18} \right) } \right) \times \left( 1 - \frac{LTE_{Base}}{100} \right) \]  

Where:

- \( LTE_{trans} \) = total crack LTE due for time increment \( t \) (%)
- \( l_i \) = radius of relative stiffness computed for time increment \( i \) [mm (in)]
- \( a \) = radius of loaded area [mm (in)]
- \( P_b \) = percent of longitudinal reinforcement expressed as a fraction
- \( LTE_{Base} \) = load transfer efficiency contributed by the base layer
- \( J_{ci} \) = nondimensional aggregate interlock factor for time increment \( i \)

Nondimensional aggregate interlock factor is computed for each time increment \( i \) based on current value of shear capacity \( s \) by using the following equation:

\[ \log(J_{ci}) = a e^{-e \left( \frac{b}{s} \right)} + d e^{-e \left( \frac{c - e}{s} \right)} + g e^{-e \left( \frac{d - e}{s} \right)} + e^{e \left( \frac{g - e}{s} \right)} \]  

Where:

- \( a = -2.2 \)
- \( b = -11.26 \)
- \( c = 7.56 \)
- \( d = -28.85 \)
- \( e = 0.35 \)
- \( f = 0.38 \)
- \( g = 49.8 \)
- \( J_s \) = lane shoulder joint stiffness across (4 for tied PCC, 0.004 for all other shoulder types)
- \( S_i \) = dimensionless shear capacity for time increment \( i \)
Punchouts
Concrete Reinforced Concrete Pavements (CRCP)

Dimensionless shear capacity of the transverse cracks

\[ S_i = S_{0i} - \Delta S_{i-1} \]

Where:

- \( s_{0i} \) = initial crack shear capacity based on crack width and slab thickness for time increment \( i \)
- \( \Delta S_i \) = loss of shear capacity accumulated from all previous time increments

Loss of shear capacity at the end of a time increment:

\[ \Delta S_i = \sum_j \left[ \frac{0.005}{1 + 1 \times \left( \frac{cw_j}{h_{PCC}} \right)^{1.5}} \right] \left( \frac{n_{ij}}{10^5} \right) \left( \frac{t_{ij}}{\tau_{ref}} \right) ESR_i \]

if \( \left( \frac{cw_j}{h_{PCC}} \right) < 3.7 \)

\[ \Delta S_i = \sum_j \left[ \frac{0.068}{1 + 6 \times \left( \frac{cw_j}{h_{PCC}} - 3 \right)^{-1.5}} \right] \left( \frac{n_{ij}}{10^5} \right) \left( \frac{t_{ij}}{\tau_{ref}} \right) ESR_i \]

if \( \left( \frac{cw_j}{h_{PCC}} \right) > 3.7 \)

Where:

- \( cw_j \) = crack width for time increment \( i \) [mm (mils)]
- \( h_{PCC} \) = slab thickness [m (in)]
- \( n_{ij} \) = number of axle load applications for load level \( j \)
- \( t_{ij} \) = shear stress on the transverse crack at the corner due to load \( j \) [kPa (psi)]
- \( \tau_{ref} \) = reference shear stress derived from the Portland Cement Association test results [kPa (psi)]
- \( ESR \) = equivalent shear ratio to adjust traffic load applications for lateral traffic wander
Punchouts
Concrete Reinforced Concrete Pavements (CRCP)

Average crack width at the depth of the steel for time increment \(i\) :

\[
cw_i = L \left( \varepsilon_{shr} + \alpha_{PCC} \Delta T \right) - L \frac{C_2}{E_{PCC}} \left[ \frac{LU_mP_b}{c_1s_d b} + C_0 \left( 1 - \frac{2h_s}{h_{PCC}} \right) + \frac{L}{2} f \right]
\]

Where:
- \(L\) = crack spacing (mm)
- \(\varepsilon_{shr}\) = unrestrained concrete drying shrinkage at the steel depth
- \(\alpha_{PCC}\) = concrete coefficient of thermal expansion (CTE) \(\text{[°C}^{-1}\text{ (°F}^{-1})]\)
- \(\Delta T\) = drop in PCC temperature at the depth of the steel for time increment \(i\) \(\text{[°C (°F)]}\)
- \(c_1\) = first bond stress coefficient
- \(c_2\) = second bond stress coefficient
- \(E_{PCC}\) = concrete modulus of elasticity \(\text{[kPa (psi)]}\)
- \(U_m\) = peak bond stress \(\text{[kPa (psi)]}\)
- \(h_{PCC}\) = PCC slab thickness \(\text{[mm (in)]}\)
- \(h_s\) = depth to steel \(\text{[mm (in)]}\)
- \(f\) = subbase friction coefficient from test data or by using AASHTO recommendations
- \(C\) = Bradbury’s correction factor for slab size
- \(\sigma_0\) = Westergaard nominal environment stress factor \(\text{[kPa (psi)]}\)

Modeling of Subgrade and Edge Support:

\[
EE = AGE \times \frac{(-7.4 + 0.32P_{200} + 1.557BEROD + 0.234PRECIP)}{12}
\]

Where:
- \(EE\) = erosion extent from pavement edge (in)
- \(AGE\) = pavement age (month)
- \(P_{200}\) = percent subgrade passing the No. 200 sieve (%)
- \(PRECIP\) = mean annual precipitation (in)
- \(BEROD\) = base erodibility index (1 for LCB, 2 for CTB with 5% cement, 3 for AT and CTB with < 5% cement, 4 for granular base [GB] with 2.5% cement, and 5 for untreated GB)
Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

Modeling of Transverse Cracking:

\[ L = \frac{(f_c - f_a)}{f} + \frac{U_m P}{2} + c_1 d_b \]

Where:

- \( L \) = mean crack spacing [mm (in)]
- \( f_c \) = tensile strength of the concrete [kPa (psi)]
- \( f_a \) = maximum stress in concrete at steel level [kPa (psi)]
- \( f \) = friction coefficient
- \( U_m \) = peak bond stress [kPa (psi)]
- \( P \) = percent of longitudinal reinforcement
- \( d_b \) = reinforcing steel bar diameter [mm (in)]
- \( c_1 \) = bond-slip coefficient

Fatigue Prediction Model:

\[ D_{IP} = \sum N_{i,j} \]

For each load level in each gear configuration or axle-load spectra, the tensile stress on top of the slab is used to calculate the number of allowable load repetitions, \( N_{i,j} \), due to this load level

\[ \log(N_{i,j}) = 2.0 \times \left( \frac{M_{R_i}}{\sigma_{i,j}} \right)^{1.22} - 1 \]

Where:

- \( M_{R_i} \) = PCC modulus of rupture at age \( i \), psi
- \( \sigma_{i,j} \) = Applied stress at time increment \( j \) due to load magnitude \( j \), psi.
Punchouts

Concrete Reinforced Concrete Pavements (CRCP)

The following globally calculated model predicts CRCP punchouts as a function of accumulated fatigue damage due to top-down stresses in the transverse direction:

\[ PO = \frac{A_{PO}}{1 + \alpha_{PO} \cdot (D_{PO})^{\beta_{PO}}} \]

Where:

- \( PO \) = Total predicted number of medium and high-severity punchouts, 1/mi,
- \( D_{PO} \) = Accumulated fatigue damage (due to slab bending in the transverse direction) at the end of \( y \)th yr, and
- \( A_{PO}, \alpha_{PO}, \beta_{PO} \) = Calibration constants (195.789, 19.8947, -0.526316, respectively).

Smoothness

Jointed Plain Concrete Pavement (JPCP)

Predicted as a function of the initial as-constructed profile of the pavement and any change in the longitudinal profile over time and traffic due to distresses and foundation movements.

\[ IRI = IRI_I + C_1 \cdot CRK + C_3 \cdot SPALL + C_3 \cdot TFAULT + C_4SF \]

Where:

- \( IRI \) = Predicted IRI, in./mi,
- \( IRI_I \) = Initial smoothness measured as IRI, in./mi,
- \( CRK \) = Percent slabs with transverse cracks (all severities),
- \( SPALL \) = Percentage of joints with spalling (medium and high severities),
- \( TFAULT \) = Total joint faulting cumulated per mi, in., and
- \( C_1 = 0.8203, \quad C_2 = 0.4417, \quad C_3 = 0.4929, \quad C_4 = 25.24, \quad SF = Site factor \)
Smoothness

Jointed Plain Concrete Pavement (JPCP)

\[ SF = AGE \left(1 + 0.5556 \times FI\right) \left(1 + \frac{P_{200}}{10^{-6}}\right) \]

Where:
- AGE = Pavement age, yr,
- FI = Freezing index, °F-days, and
- \(P_{200}\) = Percent subgrade material passing No. 200 sieve

* The transverse cracking and faulting are obtained using the models described earlier.

---

Smoothness

Jointed Plain Concrete Pavement (JPCP)

\[ SPALL = \left(\frac{AGE}{AGE + 0.01}\right) \left(\frac{100}{1 + 1.005^{-12 \times (AGE + SCF)}}\right) \]

Where:
- SPALL = Percentage joints spalled (medium and high severities),
- AGE = Pavement age since construction, yr, and
- SCF = Scaling factor based on site, design, and climate related
Smoothness

Jointed Plain Concrete Pavement (JPCP)

\[
SCF = -1400 + 350 \times ACPCC \times (0.5 + PREFORM) + 3.4 f'c \times 0.4 - 0.2 (FTcycles \times AGE) + 43 H_{PCC} - 536 WC_{PCC}
\]

Where:
- \(ACPCC\) = PCC air content, %,
- \(AGE\) = Time since construction, yr,
- \(PREFORM\) = 1 if preformed sealant is present; 0 if not,
- \(f'c\) = PCC compressive strength, psi,
- \(FTcycles\) = Average annual number of freeze-thaw cycles,
- \(H_{PCC}\) = PCC slab thickness, in., and,
- \(WC_{PCC}\) = PCC w/c ratio.

Smoothness

Continuously Reinforced Concrete Pavement (CRCP)

Is the result of a combination of the initial as constructed profile of the pavement and any change in the longitudinal profile over time and traffic due to the development of distress and foundations movements.

\[
IRI = IRI_i + C_1 \times PO + C_2 \times SF
\]

Where:
- \(IRI_i\) = Initial IRI, in./mi,
- \(PO\) = Number of medium and high severity punchouts/mi,
- \(C_1 = 3.15\),
- \(C_2 = 28.35\), and
- \(SF\) = Site Factor
Smoothness

Continuously Reinforced Concrete Pavement (CRCP)

\[ SF = AGE \left( 1 + 0.556 \times FI \right) \left( 1 + P_{200} \right) \times 10^{-6} \]

Where:

- \( AGE \) = Pavement age, yr,
- \( FI \) = Freezing index, °F-days, and
- \( P_{200} \) = Percent subgrade material passing No. 200 sieve

References

- Federal Highway Administration (FHWA), “Getting to know the Long Term Pavement Performance Program.”
References


Mechanistic-Empirical Pavement Analysis and Design

Educational Module
Part IV – MEPDG Inputs

Emil G. Bautista
Hani H. Titi
Outline

- Hierarchical Design Inputs Levels
- General Project Information
  - Design and Analysis Life
  - Construction and Traffic Opening Dates
  - General Information
  - Design Types
  - Pavement Types
- Design and Performance Criteria
- Reliability Level

Outline

- Traffic Input Characterization
- Climate Effects
- Characterization of Materials
  - Subsurface Investigation
  - Laboratory and Field Test for Pavement Design
Hierarchical Design Input Levels

For
Mechanistic-Empirical Pavement Design Guide

Hierarchical Input Levels

- Little Investments
  - State agencies
  - Pavement designers

- Function
  - Input Level 1

- Flexibility
  - Input Level 2
  - Input Level 3

Important Remarks

For a given design project inputs can be obtained using a mix of levels.

No matter the input levels used, the computational algorithm for damage and distress is exactly the same.
Hierarchical Input Levels

Level 1
- Project specific
- Measured directly
- Highest level of accuracy
- Requires laboratory and field testing

Level 2
- Closest to typical procedure of earlier AASHO Guides
- Intermediate level of accuracy
- Estimated from correlations or regression equations

Level 3
- Based on best estimate or default values
- Lowest level of accuracy

General Project Information

For
Mechanistic-Empirical Pavement Design Guide
Design and Analysis Life

Initial Construction until Pavement has deteriorated

For Design Periods > 30 years

Design and Analysis Life

Durability and Material Disintegration

Surface distress Not predicted by MEPDG

Adequate material Adequate specifications

Few pavements that exceeded 30 years of performance where included in the global calibration

Construction and Traffic Opening Dates

Impact Distress predictions

Base/Subgrade pavement traffic estimated by Designer

Traffic Loading

- Layers Modulus
- Subgrade Modulus
- HMA aging
- PCC aging

Related to monthly

Climatic Inputs
General Information

Setting Goals and Objectives

Design Types

Setting Goals and Objectives

- New Pavement
- Overlay
- Restoration
Pavement Types

New Pavement
- Flexible Pavement
- Jointed Plain Concrete Pavement (JPCP)
- Continuously Reinforced Concrete Pavement (CRCP)

Overlay
- AC over AC
- AC over JPCP
- AC over CRCP
- AC over JPCP (fractured)
- AC over CRCP (fractured)
- Bonded PCC/JPCP
- Bonded PCC/CRCP
- JPCP over JPCP (unbonded)
- JPCP over CRCP (unbonded)
- CRCP over CRCP (unbonded)
- CRCP over JPCP (unbonded)
- JPCP over AC
- CRCP over AC
Pavement Types

Restoration
- JPCP Restoration

Design and Performance Criteria

For
Mechanistic-Empirical Pavement Design Guide
Selecting a Design-Performance Criteria

- Ensure Pavement Design
- Perform satisfactorily
- Over design life

Critical Limits or Thresholds
- Selected by designer
- Represents
- Agency policies

Projects exceed Performance Criterion
- Maintenance
- Rehabilitation

Recommended design-performance criteria at the end of design life for HMA and Overlays

- Alligator Cracking
  - Interstate – 10% of lane area
  - Primary – 20% of lane area
  - Secondary – 35% of lane area

- Transverse Cracking
  - Interstate – 500 ft/mi
  - Primary – 700 ft/mi
  - Secondary – 700 ft/mi

- Rut Depth
  - Interstate – 0.40 in
  - Primary – 0.50 in
  - Others (<45 mph) – 0.65 in

- International Roughness Index (IRI)
  - Interstate – 160 in/mi
  - Primary – 200 in/mi
  - Secondary – 200 in/mi
Reliability Level

For
Mechanistic-Empirical Pavement Design Guide

Design Reliability (R)

Is the probability (P) that the predicted distress will be less than the critical level over the design period.

\[ R = P \] \[ Distress \ over \ Design \ Period < Critical \ Stress \ Level \]

This means that if 10 projects are designed and constructed using a design reliability of 90% on average, on average, 1 of those projects will exceed the performance limit value at the end of the design period.
Selecting a Reliability Level

- Based on the general consequence of reaching terminal condition earlier than the design life.
- Some agencies have typically used the level of truck traffic volume as the parameter for selecting design reliability.
- It is recommended that the same reliability be used for all performance indicators.

Performance Criteria
Traffic Input and Characterization

For
Mechanistic-Empirical Pavement Design Guide

MEPDG vs AASHTO 1972, 1993

- Equivalent Single Axle Load (ESAL) as a measure of “unit damage” endured by a pavement structure relative to 18-kip loaded single axle
- Equivalency factors for each axle load and configuration
- Observational basis as inferred from the AASHO Road Test
- Lacks material response, seasonal variations in traffic volume, and economy
MEPDG vs AASHTO 1972, 1993

Wide array of design input to consider:

- Seasonal variation in truck volume and economy
- Monthly and daily variation in truck volume
- Axle load distribution of loaded axle configurations → Load Spectra Analysis
- Vehicle speed
- Tire and axle spacing, wheelbase
- Vehicle classification distributions

WIM Record Data Formatting

W 55 030010 S 1 06010100 09 0174 03 050 05 064 010 060

W – indicates weight record, in metric units (E for english units)
55 – state identification (WI)
450239 – station identification (USH 35, Cameron)
3 – direction of travel
   1-8 relative to compass rose (S South)
1 – lane of travel
   1 is outermost lane (right)
   2-n from right to left with n number of lanes
06010100 – year, month, day, hour
09 – vehicle classification
0174 – gross weight of vehicle
03 – total number of axles
050 – weight of axle A
05 – axle spacing A-B
064 – weight of axle B
010 – axle spacing B-C
060 – weight of last axle C

Specified in FHWA’s Traffic Monitoring Guide!
WIM Quality Control

**Five criterion (per AASHTO “Guidelines for Traffic Data Programs” 2009)**

1. Compare hourly totals for vehicle classes 2 and 3. Class 3 volume near or exceeding that of class 2 can indicate error
2. Consistency of traffic volume for classes 2, 3, and 9, relative to total volume. These classes should constitute the majority of traffic volume.
3. Day to day comparison of lane and directional distributions for consistency.
4. Directional distribution by vehicle class should be approximately equal (50-50).
5. AADT and vehicle class distribution to historical data. Volume changes of more than 15% for classes 2, 3, and 9 indicate inaccuracy.

Validating Vehicle Classification

**Validating Vehicle Weights**

**Three criterion (per AASHTO “Guidelines for Traffic Data Programs” 2009)**

1. Gross vehicle weight (GVW)
   - Bimodal distribution for loaded and unloaded class 9 vehicles
     - First peak: 28,000 – 32,000 lb (unloaded)
     - Second peak: 70,000 – 80,000 lb (loaded)
2. Front axle weight (FAW) to gross vehicle weight
   - <32,000 GVW → 8,500 lb FAW
   - 32,000 – 70,000 lb GVW → 9,300 lb FAW
   - >70,000 lb GVW → 10,400 FAW
3. Day to day ESALS should be consistent (no recommended)
Input Parameters From WIM

Frequency distribution of loaded axles within each vehicle class and axle type

- Only FHWA vehicle classes 4-13 considered
  - Single Axles: 3,000 lb – 40,000 lb @ 1,000 lb intervals
  - Tandem Axles: 6,000 lb – 80,000 lb @ 2,000 lb intervals
  - Tridem/Quad: 12,000 lb – 102,000 lb @ 3,000 lb intervals

Monthly axle load distribution if available

Input Parameters From WIM

- Monthly Adjustment Factors (MAF)
  \[ MAF_i = \frac{AMDTS_i}{\sum_{j=1}^{12} AMDTS_j} \]

- Hourly Adjustment Factors (HAF)
  \[ HAF_i = \frac{AHDTF_i}{\sum_{j=1}^{24} AHDTF_j} \]

- Truck Volume Adjustment Factors

- Axle Load Spectra
- Vehicle class distribution: Percentage of total traffic classified by each FHWA class 4-13
- Average axles per truck
- Average axle spacing
Traffic Inputs
Traffic Inputs – Axle Distribution

Setting Goals and Objectives

Single Axle Load Distribution Pallet in AASHTOWare Pavement ME

Tandem Axle Load Distribution Pallet in AASHTOWare Pavement ME

Tridem Axle Load Distribution Pallet in AASHTOWare Pavement ME

Quad Axle Load Distribution Pallet in AASHTOWare Pavement ME
Other Input Parameters

- **Wheelbase, Axle Spacing**: Generally standardized
- **Dual Tire Spacing**: 12 in standard/default
- **Tire Pressure**: Assumed constant for all loading conditions - \textbf{120 psi}
- **Axle-Load Wander**: 10 in standard/default
  - Lane width < 10 ft → 8” wander
  - Lane width > 12 ft → 12” wander

Lower Level Inputs

- **Level 2**: Use regional WIM data from similar roadway segments
- **Level 3**: Use default values in DARWin-ME → Based on LTPP evaluations

Functional classification of roadway (General Category)

- Principal Arterials → Interstates and Defense Routes
- Principal Arterials → Other
- Minor Arterials
- Major Collectors
- Minor Collectors
- Local Routes and Streets
Truck Traffic Classification Groups (TTC)

Derives Vehicle Classification Distribution based upon estimates of:

- % buses in traffic flow
- % multi-trailers in traffic flow
- Single trailer or single units in traffic flow

Default distributions based on estimated vehicle distribution on roadway and functionality

Truck Traffic Classification Groups

### Table

<table>
<thead>
<tr>
<th>Class</th>
<th>Vehicle Class Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>14.2</td>
</tr>
<tr>
<td>3</td>
<td>31.5</td>
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<tr>
<td>4</td>
<td>0.6</td>
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<tr>
<td>5</td>
<td>0.4</td>
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<tr>
<td>6</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Denotes recommended distribution for road category.
Climate Effects

Enhanced Integrated Climatic Model (EICM)

Internal to MEPDG and DARWin-ME software

User supplies reference elastic modulus at optimum moisture and density condition

Uses local weather station data to account for:
- Seasonal change in moisture content in subgrade and pavement layers and evaluates change in elastic moduli
- Freeze-thaw effect on reference elastic moduli and number of cycles
- Evaluates time varying temperature effect on subgrade and pavement layers
  - HMA – temperature effect on viscosity of asphalt
  - PCC – temperature gradient in PCC layer to reflect thermal expansion
Weather Data Utilized

Weather data used to reflect pavement layer responses:

- **Hourly air temperature**
  - Defines freeze-thaw periods
  - Heat balance defines convection heat transfer and long wave radiation emission
- **Hourly precipitation**
  - Estimate infiltration rate and depth, average GWT height
- **Hourly wind speed**
  - Convective heat transfer
- **Hourly sunshine (as a percentage of time in cloud cover)**
  - Surface shortwave absorptivity
- **Hourly relative humidity**
  - PCC pavements – shrinkage in concrete curing

Climate Inputs
Climate Inputs

Material Input For Use by EICM

PCC and HMA
- Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Heat Capacity, (Q) (Btu/lb. °F)

Unbound Compacted Material
- Atterberg limits
- Grain Size Distribution
- Specific Gravity, (G_s)
- Optimum Gravimetric Water Content, (w_{opt})
- Maximum unit weight of solids, (\gamma_{dmax})
- Saturated hydraulic conductivity
- Dry Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Dry Heat Capacity, (Q) (Btu/lb. °F)

Unbound Natural (Uncompacted) Material
- Atterberg limits
- Grain Size Distribution
- Specific Gravity, (G_s)
- Optimum Gravimetric Water Content, (w_{opt})
- Maximum unit weight of solids, (\gamma_{dmax})
- Saturated hydraulic conductivity
- Dry Thermal Conductivity, (K) (Btu/ft.hr.°F)
- Dry Heat Capacity, (Q) (Btu/lb. °F)
Virtual Weather Stations

Not every site has a weather station readily available.

Important Remarks

Should project site lie between stations, weather data can be interpolated to more accurately reflect weather conditions at that location.

Characterization of Materials

Foundation, Subgrade Soils, HMA and Unbound Materials
Subsurface Investigations

1. Horizontal and vertical variations in subsurface soils
2. Moisture content
3. Densities
4. Water table depth
5. Location of rock strata

The MEPDG does not predict volume change potential.

Problem soils found along a project needs to be dealt with external to the MEPDG.

Laboratory and Field tests for Pavement Design

New HMA Layers Material Properties Inputs

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Measure Property</th>
<th>Source of Data</th>
<th>Recommended Test Protocol and/or Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>New HMA (new pavement and overlay mixtures), as built properties prior to opening to truck traffic</td>
<td>Dynamic Modulus</td>
<td>X AASHTO T62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tensile Strength</td>
<td>X AASHTO T322</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Creep Compliance</td>
<td>X AASHTO T322</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson’s Ratio</td>
<td>X National test protocol unavailable. Select MEPDG default relationship</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface Shortwave</td>
<td>X National test protocol unavailable. Select MEPDG default relationship</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Absorptivity</td>
<td>X National test protocol unavailable. Select MEPDG default relationship</td>
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</tr>
<tr>
<td></td>
<td>Thermal Conductivity</td>
<td>X ASTM E 1952</td>
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</tr>
<tr>
<td></td>
<td>Heat Capacity</td>
<td>X ASTM D 2766</td>
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<tr>
<td></td>
<td>Coefficient of Thermal Contraction</td>
<td>X National test protocol unavailable. Select MEPDG default relationship</td>
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<tr>
<td></td>
<td>Effective Asphalt Content by Volume</td>
<td>X AASHTO T308</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air voids</td>
<td>X AASHTO T166</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregate Specific Gravity</td>
<td>X AASHTO T84 and T85</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gradation</td>
<td>X AASHTO T27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unit Weight</td>
<td>X AASHTO T166</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Voids Filled with Asphalt (VFA)</td>
<td>X AASHTO T209</td>
<td></td>
</tr>
</tbody>
</table>
Laboratory and Field tests for Pavement Design

Existing HMA Layers Material Properties Inputs

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Measure Property</th>
<th>Source of Data</th>
<th>Recommended Test Protocol and/or Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing HMA Mixtures, in-place properties at time of pavement evaluation</td>
<td>FWD Backcalculated Layer Modulus</td>
<td>X</td>
<td>AASHTO T 256 and ASTM D 5858</td>
</tr>
<tr>
<td></td>
<td>Poisson’s Ratio</td>
<td>X</td>
<td>National test protocol unavailable. Select MEPDG default value</td>
</tr>
<tr>
<td></td>
<td>Unit Weight</td>
<td>X</td>
<td>AASHTO T 566 (cores)</td>
</tr>
<tr>
<td></td>
<td>Asphalt Content</td>
<td>X</td>
<td>AASHTO T 164 (cores)</td>
</tr>
<tr>
<td></td>
<td>Gradation</td>
<td>X</td>
<td>AASHTO T 27 (cores or blocks)</td>
</tr>
<tr>
<td></td>
<td>Air Voids</td>
<td>X</td>
<td>AASHTO T 209 (cores)</td>
</tr>
<tr>
<td></td>
<td>Asphalt Recovery</td>
<td>X</td>
<td>AASHTO T 164 / T 370/ T 318 (cores)</td>
</tr>
</tbody>
</table>

Laboratory and Field tests for Pavement Design

Asphalt Binder Material Properties Inputs

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Measure Property</th>
<th>Source of Data</th>
<th>Recommended Test Protocol and/or Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt (new, overlay, and existing mixtures)</td>
<td>Asphalt Performance Grade (PG), or</td>
<td>X</td>
<td>AASHTO T 315</td>
</tr>
<tr>
<td></td>
<td>Asphalt Binder Complex Shear Modulus (G’) and Phase Angle (δ), or Penetration, or</td>
<td>X</td>
<td>AASHTO T 49</td>
</tr>
<tr>
<td></td>
<td>Ring and Ball Softening Point Absolute Viscosity Kinematic Viscosity Specific Gravity, or</td>
<td>X</td>
<td>AASHTO T 202 AASHTO T 201 AASHTO T 228</td>
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<tr>
<td></td>
<td>Brookfield Viscosity</td>
<td>X</td>
<td>AASHTO T 316</td>
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</table>
### Laboratory and Field tests for Pavement Design

#### Unbound Aggregate Base, Subbase, Embankment and Subgrade Material Properties Inputs

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Measured Property</th>
<th>Source of Data</th>
<th>Recommended Test Protocol and/or Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>New (lab samples) and existing (extracted materials)</td>
<td>Resilient Modulus</td>
<td>Test</td>
<td>AASHTO T 307 or NCHRP 1-28A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Estimate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poisson's ratio</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The generalized model used in MEPDG design procedure is as follows:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( M_r = \alpha \beta \left( \frac{E}{G} \right)^{\frac{k_1}{k_2}} \left( \frac{1}{\kappa} + 1 \right)^{k_3} )</td>
</tr>
<tr>
<td></td>
<td>Maximum Dry Density</td>
<td>X</td>
<td>AASHTO T 180</td>
</tr>
<tr>
<td></td>
<td>Optimum Moisture Content</td>
<td>X</td>
<td>AASHTO T 180</td>
</tr>
<tr>
<td></td>
<td>Specific Gravity</td>
<td>X</td>
<td>AASHTO T 100</td>
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<tr>
<td></td>
<td>Saturated Hydraulic</td>
<td>X</td>
<td>AASHTO T 215</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Soil Water Characteristics Curve Parameters</td>
<td>X</td>
<td>Pressure Plate (AASHTO T 109) or Filter Paper (AASHTO T 180) or Temple Cell (AASHTO T 100)</td>
</tr>
</tbody>
</table>

#### Unbound Aggregate Base, Subbase, Embankment and Subgrade Material Properties Inputs

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Measured Property</th>
<th>Source of Data</th>
<th>Recommended Test Protocol and/or Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing material to be left in place</td>
<td>FWD backcalculated modulus</td>
<td>X</td>
<td>AASHTO T 256 and ASTM D 5828</td>
</tr>
<tr>
<td></td>
<td>Poisson's ratio</td>
<td>X</td>
<td>National test protocol unavailable. Select MEPDG default value</td>
</tr>
</tbody>
</table>

### Setting Goals and Objectives
References


• Federal Highway Administration (FHWA), “Getting to know the Long Term Pavement Performance Program”.

References


