Module 2-3

PERFORMANCE PREDICTION MODELS FOR AC PAVEMENTS

Performance (distress) prediction models can be used to check designs generated by one or more flexible pavement design procedures.

Pavement responses determined in previous module are used as inputs.

Models relate theory to real life performance of pavements.

Available Models

- Fatigue Cracking Models
- Rutting Models
- Thermal Cracking Models

These are the 3 types of models covered in this module.

They relate structural responses to distress development, with applied loads as an input.

These models are an integral part of mechanistic-empirical design, but are also the weak link.

Fatigue Cracking

- Result of excessive strain at the bottom of a stiff layer, such as the surface or other stabilized layers
- Most models consider the strain at the bottom of the AC layer and relate strain to number of loads to initiate cracking

Strain is usually used for AC pavements.

Often deal in units of microstrain
  - .000500 = <u>500</u> x 1E-6

Fatigue Cracking (Cont)

- **Models developed from both field and laboratory tests.**
- **Strain varies with traffic loadings and climates, and these should be considered.**

Laboratory and field results differ.

- Fatigue test (3rd-point loading) - loaded upward.
- Laboratory loads are applied over a much shorter period of time than in the field.

Miner's Theory

- **Structural fatigue damage is cumulative**
- **Pavement's fatigue life is finite**
- **"Life" can be defined by the number of allowable loads until failure**

$$\text{Fatigue Damage} = \Sigma \frac{n_i}{N}$$

Originally developed for fatigue testing of aircraft wings. Many load configurations and magnitudes must be taken into account:

- n = number of actual load applications of a given magnitude
- N = number of allowable load applications of a given magnitude to failure

Concept is that for a load of any given magnitude, there is a number of loads that will cause failure. FD is the ratio of the number of those loads that have already been applied to the number of allowable loads.

What does a fatigue damage value of 0.36 mean ?

1.00 ?

2.25 ?

A value of 1.0 means fatigue damage has occurred. This would be seen as a crack in the pavement.

Values much less than 1.0 suggest no damage.

Values much greater than 1.0 suggests many cracks are occurring.

FD = 1.0 is not failure, just onset of cracking.

Because of variability, when FD is 1 there will not always be a crack.

Determining N

- Fatigue testing of AC beams in third-point loading
- Indirect tensile tests
- Testing in situ slabs
- Testing with constant stress or constant strain

Loads applied are cyclical with a rest state.

Load should be picked where between 1000 and 1,000,000 apps will cause failure.

A number of specimens are needed.

Tests are performed at a range of temperatures.

Determining N

- Calculate extreme fiber tensile strain
- Count applied loads to failure
- Plot strain against cycles to failure on log-log plot
- A straight line is represented by equations of the form:

$$N_f = f_1 (\varepsilon_t)^{-f_2}$$

$$\log N = a + b \log (\varepsilon_t)$$

Many equations have been developed from field data or lab testing. Equations based on laboratory data must be adjusted for field conditions.

Some models also use the AC elastic modulus.

Relationship between N_{lab} and N_{act}

- Typically $N_{act} >> N_{lab}$
  - ► Wheel load wander
  - ► Longer rest periods
- Asphalt Institute uses f_1 of 18.4

What else might explain these differences between filed and laboratory values?

Fatigue Damage Models

- Asphalt Institute
- Shell
- PDMAP (Finn et al.)
- Michigan State University
- Transport Road and Research Lab (UK)
- Belgian Road Research Center
- Illinois Department of Transportation

Many organizations have developed equations for predicting fatigue damage.

Different models yield a wide range of results for a given set of inputs.

Asphalt Institute

$$N_f = 0.00432\, C\, (\varepsilon_t)^{-3.291}\, (E)^{-0.854}$$

Standard Mix:

- ► 5 % air void volume
- ► 11 % asphalt volume
- ► Lab-to-field factor = 18.4

$$N_f = 0.0796\, (\varepsilon_t)^{-3.291}\, (E)^{-0.854}$$

Failure = 20 % cracking

For the standard mix, using the lab-to-field factor of 18.4, the model reduces to the bottom equation.

This equation was used to develop the design charts in the AI's thickness design procedure (Module 2-1).

Shell

$$N_f = 0.0685\, (\varepsilon_t)^{-5.671}\, (E)^{-2.363}$$

Also have equations for constant stress and constant strain tests

A nomograph was developed in order to solve the constant stress and constant strain test equations.

This is shown in Figure 2-3.4 (page 2-3.9).

PDMAP

For cracking over 10 % of area:

$$N_f = 15.947 - 3.291 \log\left(\frac{\varepsilon}{10^{-6}}\right) - 0.854 \log\left(\frac{E}{10^3}\right)$$

For cracking over 45 % of area:

$$N_f = 16.086 - 3.291 \log\left(\frac{\varepsilon}{10^{-6}}\right) - 0.854 \log\left(\frac{E}{10^3}\right)$$

Base on work from NCHRP.

Developed from lab fatigue curves calibrated with a "shift factor" to correlate with cracking observed at AASHO Road Test.

Two models were developed:

- One for fatigue cracking over 10% of the wheel path area.
- One for fatigue cracking over 45% of the wheel path area.

TRRL

$$N_f = 1.66 \times 10^{-10} (\varepsilon_t)^{-4.32}$$

BRRC

$$N_f = 4.92 \times 10^{-14} (\varepsilon_t)^{-4.76}$$

TRRL - AC properties were found to be negligible compared to effect of AC tensile strain.

IDOT

$$N_f = 5.0 \times 10^{-6} (\varepsilon_t)^{-3.0}$$

$$N_{18} = 4.92 \times 10^{11} (\Delta)^{-4.6}$$

Equations developed using ILLI-PAVE.

N_f is number of strain reps to failure (initiation of a fatigue crack).

N_{18} is number of 18 kip ESALs to fatigue failure.

Rutting

- **Permanent deformation of one or more layers in the pavement system**
- **Secondary causes**
  - **Plastic movement of AC in hot weather**
  - **Inadequate compaction of AC during construction**

Rutting can lead to hydroplaning and water freezing in the wheelpaths.

Rutting is a serious concern for AC pavements and must be dealt with during the design process. Ac mix design is also very important, although it is not covered in this course.

Two Approaches for Predicting Rutting

- **Minimize vertical strain on top of subgrade**
  - **Controlled through material selection**
  - **Proper mix design**
- **Consider permanent deformation in each layer**
  - **Sum layer deformations to obtain total deformation**

Limitation is that rutting predictions are based on assumed and not actual material information.

Two Categories:
- Subgrade Strain Models
- Permanent Deformation Models

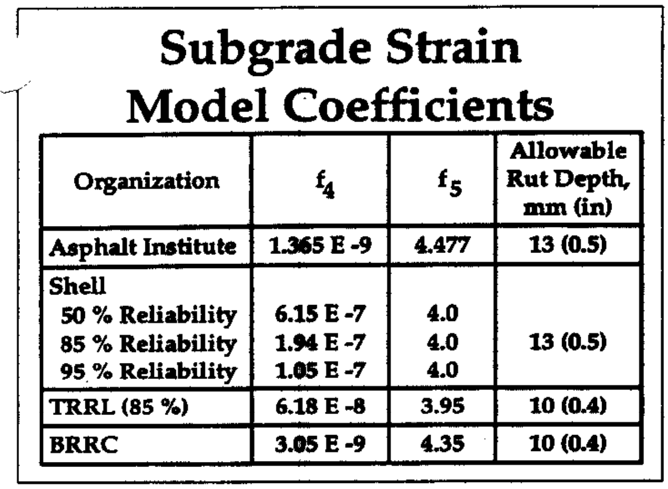
Subgrade Strain Models

$$N_f = f_4 \, (\varepsilon_v)^{-f_5}$$

- **Asphalt Institute**
- **Shell**
- **Transport and Road Research Lab (TRRL)**
- **Belgian Road Research Center (BRRC)**

Subgrade strain models control rutting by limiting the vertical compressive strain on top of the subgrade.

These models assume that rutting does not occur in the AC layer (i.e., assumes a high-quality stable AC mix is used).

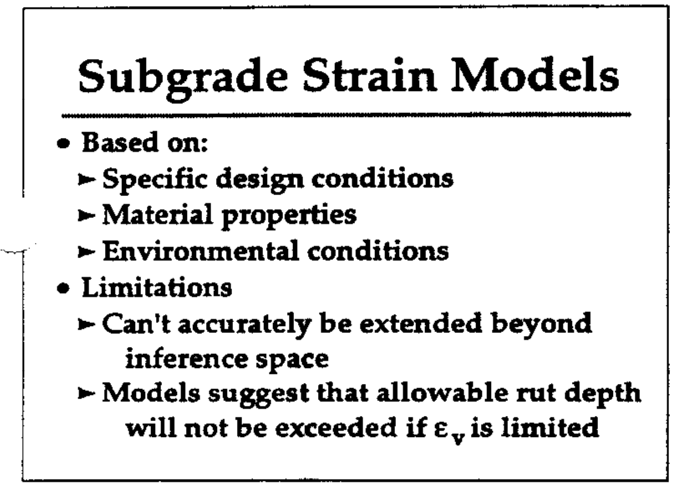


Subgrade Strain Model Coefficients

Organization	f_4	f_5	Allowable Rut Depth, mm (in)
Asphalt Institute	1.365 E -9	4.477	13 (0.5)
Shell			
50 % Reliability	6.15 E -7	4.0	13 (0.5)
85 % Reliability	1.94 E -7	4.0	
95 % Reliability	1.05 E -7	4.0	
TRRL (85 %)	6.18 E -8	3.95	10 (0.4)
BRRC	3.05 E -9	4.35	10 (0.4)

Table 2-3.3 (page 2-3.15).

Models differ only in allowable rut depth and values assigned to constants f4 and f5. These coefficients are based on data obtained from field performance at specific locations.

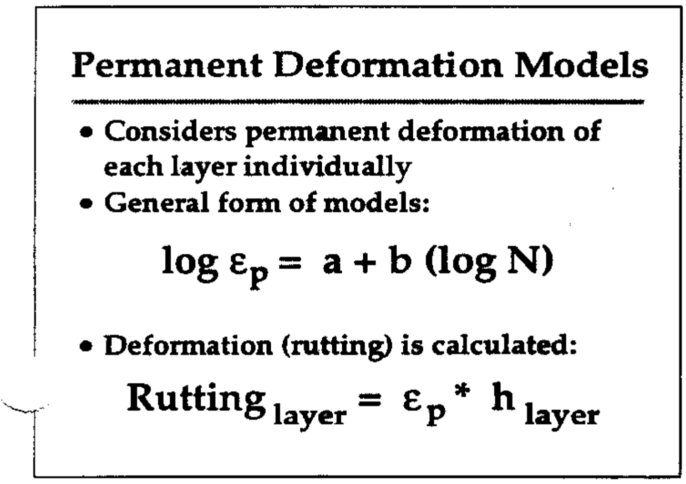


Subgrade Strain Models

- Based on:
  - ► Specific design conditions
  - ► Material properties
  - ► Environmental conditions
- Limitations
  - ► Can't accurately be extended beyond inference space
  - ► Models suggest that allowable rut depth will not be exceeded if ε_v is limited

These models are empirical in that they were developed from a specific set of conditions and can not be used to reliably estimate rutting in other circumstances.

Ideally, each agency should develop its own model based on its specific conditions, materials, climate, and construction quality.



Permanent Deformation Models

- Considers permanent deformation of each layer individually
- General form of models:

$$\log \varepsilon_p = a + b (\log N)$$

- Deformation (rutting) is calculated:

$$\text{Rutting}_{\text{layer}} = \varepsilon_p * h_{\text{layer}}$$

Evaluating AC surface rutting based on subgrade strain only may not be reasonable.

Rutting also occurs in AC, base, or subbase, especially in thicker layers.

However, these models are not effectively used; that is, the results are not well correlated.

Procedure to use for these models is described on page 2-3.17.

VESYS

- VESYS-V calculates deformation properties of each layer
- Determines structural responses to load and environment (based on CHEVRON N-layer program)
- Includes models for fatigue cracking, low-temperature cracking, and roughness

VESYS is also a pavement design method.

It was developed at MIT.

Ohio State Model

- Permanent Strain Accumulation Model (rutting rate)

$$\frac{\varepsilon_p}{N} = A\,(N)^{-m}$$

- "A" and "m" are constants based on material type and stress state

Figure 2-3.8 on page 2-3.19 shows rutting rate vs. number of axle applications.

This model considers the rutting rate of the pavement (how much rutting occurs with each load application).

Typical Constants for Cohesive Soil

Moisture	Unconfined Strength, kPa (psi)	Repeated Dev. Stress, kPa (psi)	m	A x 10^4
Optimum	159 (23)	34 (5)	0.86	12.4
		69 (10)	0.86	18.2
		103 (15)	0.86	43.7
Opt. + 4%	90 (13)	34 (5)	0.83	17.0
		69 (10)	0.83	42.5
		103 (15)	0.83	138.0

This is table 2-3.5 (page 2-3.19).

Determination of experimental constants "A" and "m" makes this model difficult to use.

"A" is quite variable and depends on the material, repeated stress rate, and environmental conditions.

"m" varies within a narrow range for cohesive soils and granular materials.

Asphalt Institute

- Considers the effect of mix design parameters on permanent AC strain
- Based on repeated load triaxial tests on 251 specimens, including rounded gravel/ crushed stone and AC-5/AC-20
- Not applicable for mixes with $V_A < 3$ % or $\sigma_d > 621$ kPa (90 psi)

This model is not applicable for mixes with less than 3 % air voids, where plastic flow dominates the behavior of the mix, or for deviator stresses greater than 621 kPa (90 psi).

Asphalt Institute (Cont)

$$\text{Log } \varepsilon_p = -14.97 + 0.408 \log N + 6.865 \log T + 1.107 \log \sigma_d - 0.117 \log V + 1.908 \log P_{eff} + 0.971 \log V_v$$

This model was developed from laboratory tests only.

It is also employed in the CAMA program, which was also developed by the Asphalt Institute.

PAVRUT (Allen and Deen)

- Rutting in AC layers
- Rutting in dense-graded aggregate layers
- Rutting in subgrade soils
- All developed from laboratory testing

$$\log \varepsilon_p = C_0 + C_1 (\log N) - C_2 (\log N)^2 + C_3 (\log N)^3$$

PAVRUT is the name of a computer program which incorporates the three Allen & Deen models.

PAVRUT also includes a traffic and temperature model.

In this approach, the amount of rutting in each layer is estimated and then summed to determine the overall rutting in the pavement.

The model is in the same form for each layer, although the coefficients do vary.

Thermal Cracking Models

- Available models
  - Finn et al.
  - Ruth, Bloy, & Avital
  - Lytton, Shanmugham, & Garrett
  - Shahin and McCollough
- Models are very complex
- Thermal cracking is best considered through material selection

Last two models take into account both low-temperature and thermal fatigue cracking.

Shahin and McCollough model has been used by several agencies with success.

Summary

- Performance prediction models exist for
  - Fatigue cracking
  - Rutting
  - Thermal cracking
- Rutting and thermal cracking can be addressed through material selection and proper mix design
- Models are somewhat empirical and have limited application without calibration

Use prediction models to insure that a design will perform adequately.

Many of the models were developed for specific materials and climatic conditions.

- May not be universally applicable
- Each agency should develop experimental constants based on their specific conditions, or else select the best match from existing models.

How do we know what answer to pick when different models give us different results?

QUESTIONS?