Perpetual Asphalt Pavements: Materials, Analysis/Design, Construction, and Other Considerations

Carl L. Monismith
Pavement Research Center
University of California, Berkeley

2006 International Conference on Perpetual Pavement
Columbus, Ohio
September 13-15, 2006
Presentation Overview

- Background
  - contributions to current approach to long-life (perpetual pavement) design
- Example
  - design and construction (I-710 full depth section)
- Conference sessions
  - Categories of papers
- Additional considerations/challenges
Lest We Forget

- Early examples of “Perpetual Pavements”
  - Appian Way (Via Appia), Roman construction, Italy; circa 300 B.C.
  - Warrenite Bitulithic Pavements, U.S; circa 1910 onward to 1920’s
- Emphasis on “good” construction
Perpetual Pavement

Appian Way
(Via Appia)

(Courtesy Prof. J.P. Mahoney)
Warrenite Pavement Plaque

(Courtesy James Martin)
The Modern Era
(Since the 1950's)

- Some key events contributing to current developments
  - AASHO Road Test, Ottawa, IL: NRC-HRB, 1956-1961
  - International Conference on Asphalt Pavements, University of Michigan, 1962
National Research Council/
Highway Research Board
AASHO Road Test

- **Highway Research Board**
  - Fred Burggraf; Director
  - W.N. Carey, Road Test Chief Engineer

- **National Advisory Committee**
  - K.B. Woods, Purdue Univ.: Chairman
  - W.A. Bugge, Director, Wash. Hwy Dept.: Co-Chairman
Fred Burggraf
W. N. Carey, Jr.
K.B. Woods
HRB Special Report 73

The AASHO Road Test
Proceedings of a Conference
Held May 16-18, 1962
St. Louis, Mo.

National Academy of Sciences—
National Research Council
publication 1012
International Conference on the Structural Design of Asphalt Pavements; August, 1962
University of Michigan, Ann Arbor

Key individuals

- The Asphalt Institute: J.E Buchanan, F. N. Finn
- The University of Michigan: W. S. Housel, W. K. Parr
J. E. Buchanan, President, TAI
F. N. Finn, Chairman, TAI Board of Study
W. S. Housel, Prof. of Civil Engin.
W. K. Parr
Assoc. Prof. of Civil Engin. & Secretay-Treasurer, AAPT
Mechanistic-Empirical Design: Key Impetus

- Multi-Layer Elastic Analysis
- Materials Characterization
  - Stiffness
  - Distress Characteristics
- Design Framework
Multilayer Elastic Analysis Programs

- BISTRO, BISAR (Shell)
- ELSYM (based on Chevron program; UC Berkeley, FHWA)
- PDMAP (PSAD) (NCHRP 1-10)
- JULEA (USACE, WES; used in LEDFAA)
- ALIZE (LCPC, France)
- CIRCLY (MINCAD, Australia)
Materials Characterization

- **Stiffness (stress/strain)**
  - Asphalt mixes; time of loading and temperature effects.
    - Van der Poel, Heukelom, Klomp (Shell 1950-60's)
  - Fine-grained soils, untreated aggregates; (Resilient Modulus, Mr),
    - H. B. Seed S. F. Brown,
    - G. F. Dehlen, R. G. Hicks, R. D. Barksdale
W. Heukelom
H. B. Seed
G. L. Dehlen
R. G. Hicks
R. D. Barksdale
Material Characterization

- Permanent deformation
  - Vertical compressive subgrade strain
    - G. M. Dormon (1962)
  - Vertical compressive stress, untreated materials
    - M. Thompson, H. Maree
Subgrade Strain Criteria

\[ N = A \left( \frac{1}{\varepsilon_v} \right)^b \]

\[ \log \varepsilon_v \]

\[ \log N \times 10^7 \]
M.R. Thompson
Materials Characterization

- Fatigue-asphalt concrete
  - Shell/Nottingham Univ.
    - P. S. Pell, R. N. J. Saal (1960, 1962)
  - UC Berkeley
    - C. L. Monismith, K. E. Secor (1958, 1961)

- Fracture-asphalt concrete
  - Shell, Heukelom
P.S. Pell
Fatigue Relationships at Constant Temp

\[ N = A \left( \frac{1}{\sigma_0} \right)^b \]

\[ N = C \left( \frac{1}{\varepsilon_0} \right)^d \]
Fatigue –
Strain vs. Load Applications

\[ \log \varepsilon_t = \log N \]

\[ \varepsilon_0 \]

\[ N_f \]
Fatigue Testing

- **Shell - Amsterdam**
  - W. Heukelom and A. Klomp (1960's)
  - W. van Dijk (1970's)

- **France**
  - Shell
  - LCPC
Fatigue Testing

- TRRL - UK
- CSIR - South Africa
- The Asphalt Institute, U.S.
- Others
LCPC, France & Nottingham Equipment
SHRP - Developed Equipment
Australian Beam Fatigue Apparatus (based on SHRP equipment)
Asphalt Concrete Fatigue Considerations

- Mode of Loading
  - Controlled-stress
  - Controlled-strain
- Dissipated Energy
- Temperature Effects
- Cumulative Damage
- Shift Factor
- Endurance Limit
Cumulative Damage

- Linear sum of cycle ratios
  - Suggested by K. Peattie (Shell, 1960)
  - Load effects, J. Deacon (1965)
  - Temperature effects, Pell, Taylor, MacElvaney (circa 1970)
Fatigue - Endurance Limit

$\log e_f$ vs. $\log N$

$70 \times 10^{-6}$

$60 \times 10^{-6}$

$\sim 10^8$
Shift Factor, SF

- Factor to relate laboratory test data to field performance (usually some specific amount of wheel path surface cracking; e.g. > 45%, ≤10%)
Fatigue Relationships – M-E Design

- NCHRP I-10B (F. Finn)

\[
\log_{10} N(\geq 45\%) = 16.086 - 3.291 \log_{10} \left( \frac{\varepsilon_t}{10^{-6}} \right) - 0.854 \log_{10} \left( \frac{S_{\text{mix}}}{10^3} \right)
\]

\( \varepsilon_t = \text{tensile strain, in./in.} \times 10^{-6} \)

\( S_{\text{mix}} = \text{mix stiffness, psi} \)

\[
\log_{10} N(\geq 45\%) = 1.4 \left[ \log_{10} N(\leq 10\%) \right]
\]
Fatigue Relationships – M-E Design

- The Asphalt Institute

\[
\log_{10} N(\geq 45\%) = C
\]

where \( C = 10^M \)

\[
M = 4.84 \left( \frac{V_{asp}}{V_{air} + V_{asp}} - 0.69 \right)
\]
Fatigue Relationships – M-E Design

- Shell International

\[ N = SF \left( K_{1\sigma} \right) \alpha^S \left( \frac{1}{\varepsilon_t} \right)^5 \left( \frac{1}{E^*} \right)^{K_3} \]

\[ K_{1\sigma} = f \left( \text{mix volumetrics, } PI_{\text{asp}} \right) \]

\[ \alpha = f \left( t_{AC} \right) \]

\[ K_3 = f \left( t_{AC} \right) \]
Perpetual Pavement — Design Concepts

<table>
<thead>
<tr>
<th>Max Tensile Strain</th>
<th>Flexible Fatigue Resistant Material 3 - 4”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Foundation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone of High Compression</th>
<th>High Modulus Rut Resistant Material 4.5 - 6”</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1/2 – 3 inches of SMA, OGFC or Superpave</td>
<td></td>
</tr>
</tbody>
</table>

- 4” to 6”
Design Example:
Full-depth Section,
I-710 Freeway Rehabilitation
Design Approach

- **Materials selection, mix design**
  - Use of SHRP developed RSST-CH (vs. Stabilometer)
- **Structural section design**
  - Perpetual pavement example
  - SHRP developed fatigue test
- **Contractor required to supply results of same mix tests for proposed mix**
Mix Design - Rutting

Input

\[ N_{\text{supply}} \]

Performance test

\[ N_{\text{demand}} \]

Traffic

\[ N_{\text{supply}} \geq M \times N_{\text{demand}} \]

No

Yes
Simple Shear Test
Simple Shear Test Results

Permanent Shear Strain

RSST Repetitions

5 %
\( N_{\text{demand}} \)

- Design ESALs - first five years
  - \( 30 \times 10^6 \) ESALs
- \( N_{\text{demand}} = 660,000 \)
  \[ M \times \text{Design ESALs} \times TCF \times SF \]
  - \( M = 5 \)
  - \( TCF = 0.116 \)
  - \( SF = 0.04 \)

____________________

*Mix with PBa-6a* binder
Design Binder Content

Asphalt content (percent by weight of aggregate)

Temperature = 50°C

- PBA 6A
- AR 8000

- 1,000,000 repetitions
- 100,000 repetitions
- 10,000 repetitions
- 1,000 repetitions

- Asphalt content (percent by weight of aggregate)

N @ γ_p = 5%

660,000 repetitions
146,000 repetitions
Applications of RSST-CH
Applications of RSST-CH

- **Mix design**

![Graph showing rut depth versus HVS load applications for different mix designs.](Image)

- 38-mm ARHM-GG
- 62-mm ARHM-GG
- 75-mm DGAC AR-4000
- 76-mm PBA-6A
Rut Depth Estimation

- Use of Shear Stress and Strain
- Compound Loading: Time hardening
Pavement Representation

Asphalt Concrete
\[ E_{AC}, \nu_{AC} \]

Base
\[ E_{base}, \nu_{base} \]

Subgrade
\[ E_{sub}, \nu_{sub} \]

\[ 50 \text{ mm (2 in)} \]

\[ \tau, \gamma^e \]
Inelastic Strains in Asphalt Concrete

- Under simple loading (effect of shearing stress, elastic shearing strain and load repetitions)
  \[ \gamma^i = a \exp(b \tau) \gamma^e n^c \]

- Under compound loading
  \[ a_j = a \exp(b \tau_j) \gamma^e_j \]
  \[ \gamma^i_1 = a_1 [\Delta n_1]^c \]
  \[ \gamma^i_j = a_j \left[ \gamma^i_{j-1}/a_j \right]^{(1/c)} + \Delta n_j]^c \]
Compound Loading - Time Hardening

Inelastic strain - n relationship for larger load

Inelastic strain - n relationship for smaller load
Surface Rutting Due to Shear within Asphalt Concrete

- \( rd = K \cdot \gamma_{ij} \), where \( K = \text{shift factor} \)
- \( K = f \left( \text{HMA layer thickness} \right) \)
Surface rutting due to deformation of unbound materials

- The Asphalt Institute subgrade strain criterion for 0.5-inch surface rutting
  \[ N = 1.05 \cdot 10^{-9} \cdot \varepsilon^{-4.484} \]

- With time hardening, \( r_d = d n^e \)
  \[ d = f / [1.05 \cdot 10^{-9} \cdot \varepsilon^{-4.484}]^e \]
  \[ r_{d1} = d [\Delta n_1]^e \]
  \[ r_{dj} = d_j [ (r_{d_{j-1}}/d_j)^{(1/e)} + \Delta n_j]^e \]

  *(for Asphalt Institute criterion, \( f = 0.5 \) inches)*
Structural Pavement Design Considerations

- Asphalt
- Concrete
- Base
- Subgrade
Input

- Structural section (full-depth)
- Traffic (200 million ESALs)
- Environment (T = 20°C)
- Trial mixes & pavement sections
- Mix fatigue data
Input

- Reliability (M=5)
- $f(\text{traffic estimate & testing variability})$
- Performance criterion
  - wheel path cracking $\leq 10\%$
Final Design

AR-OGFC

PBA-6A (4.7%)

AR-8000 (4.7%)

AR-8000 (5.2%)
(rich bottom)

subgrade

6% air voids

25 mm

75

150

75

6%

3%
Conference Sessions, Categories of Papers

- Materials
- Analysis/Design
- Test sections, Instrumentation
- Construction
- Maintenance
- Life Cycle Costs
Materials

- Subgrade soil stiffness
- HMA characteristics
  - Aging
  - Fatigue response
  - Anisotropic behavior
- HMA mix type selection
Analysis/Design

- Design Experience
  - Europe
  - Canada
  - U.S.: Ohio, Kansas, Oregon, Pennsylvania
  - Pakistan
  - Afghanistan
  - China
Analysis/Design

- Analysis
  - VECDFE pavement analyses
  - Multismart3D
  - Multi-body dynamic modeling
  - Evaluation of HMA endurance limit
Test Sections, Instrumentation

- Test Sections
  - Canada
  - U.S.: Ohio, Kansas, Oregon, China

- Instrumentation
  - Seasonal monitoring
  - Strain gages
Construction, Maintenance, Life Cycle Costs

- **Construction**
  - Afghanistan
- **Maintenance**
  - UK
  - Other European (ELLPAG)
- Life cycle costs
Additional Emphasis

- Construction
- Maintenance - long term
- Performance-Based Specifications - QC/QA considerations
- Truck pavement interaction; dynamic loading effects vs. smoothness (e.g., dedicated truck lanes)
- Linking pavement design/materials/construction data with pavement management systems
Construction

- Urban vs. rural freeway rehabilitation
  - Construction alternatives (e.g. CA4PRS)
  - Construction management
- Construction quality requirements
- Quality assurance
Maintenance

- Materials
- Environment
- Construction
- Traffic
Performance-Based Specifications

- Construction control
  - More testing?
- QC/QA
  - PWL vs. performance-based requirements (pay factors)
Asphalt content influence on rutting

As-constructed average asphalt content (%) vs. Simulated ESALs to 10% rutting (15mm or more rut depth) expressed as fraction of target ESALs.

As-constructed standard deviation of asphalt content (%): 0.114, 0.19, 0.266.
Asphalt content influence on pavement fatigue performance

Asphalt content influence on pavement fatigue performance

Estimated fatigue life (multiple of target ESALs at 90% reliability)

As-constructed average asphalt content (%)

As-constructed standard deviation of asphalt content (%)

0.114
0.190
0.266
Air-void content influence on mix rutting

Simulated ESALs to 10% rutting (15 mm or more rut depth) expressed as multiple of target ESALs

As-constructed average air-void content (%)

As-constructed standard deviation of air void content (%)

0.65
1.12
1.60

As-constructed average air-void content (%)

Simulated ESALs to 10% rutting (15 mm or more rut depth) expressed as multiple of target ESALs
Air-void content influence on pavement fatigue performance

As-constructed average air-void content (%)

Estimated fatigue life (multiple of target ESALs at 90% reliability)

As-constructed standard deviation of air-void content (%)

0.65

1.12

1.60
<table>
<thead>
<tr>
<th>Performance Characteristics</th>
<th>Asphalt content</th>
<th>Air void content</th>
<th>$\frac{P_{200}}{t_{AC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutting</td>
<td>+ 0.5%</td>
<td>+2.0%</td>
<td>- 1%</td>
</tr>
<tr>
<td></td>
<td>RP = 0.29</td>
<td>RP = 0.75</td>
<td>RP = 0.75</td>
</tr>
<tr>
<td>Fatigue</td>
<td>+ 0.5%</td>
<td>+2.0%</td>
<td>- 0.2 in.</td>
</tr>
<tr>
<td></td>
<td>RP = 1.07</td>
<td>RP = 0.49</td>
<td>RP = 0.84</td>
</tr>
</tbody>
</table>
Linking pavement design/materials/construction data to pavement management systems
Concept for Linking Databases

Electronic PMS Data Base

Electronic Materials & Construction Data Base

Electronic Performance Analysis Data Base

Pavement Design

Traffic Information

Climate & Environment

PERFORMANCE ANALYSIS FOR VARIOUS CONDITIONS
Linking Databases, Examples

- WSDOT
  - WebWSPMS
- MDDOT
  - HMA construction data to PMS (AAPT, 2003)
Truck pavement interaction

- Pavement smoothness/roughness
  effects of dynamic loading on:
    - Pavement damage
    - Truck damage
    - Goods damage
    - Fuel consumption, tire wear, etc.

★ WesTrack experience
Summary

- Many useful developments since about 1960 to assist in design and construction of perpetual pavements
- Stringent construction practices required
- Skilled engineers, technicians, and construction personnel required
- Excellent records and tracking of performance essential
Acknowledgement

The author thanks the California Department of Transportation, which sponsored some of the work reported herein; and he also expresses his appreciation to the UC Berkeley PRC Staff for their many contributions.

The materials presented are those assembled by the author and do not necessarily represent the views of the sponsor.