Pre-Conference Workshop: New approaches to address pavement failure more realistically in asphaltic pavement design methods

Design and management approaches addressing asphalt pavement performance

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Background

Predicting asphalt pavement performance

• Key element in pavement design
  • minimum layer thicknesses to support loading in function of material properties
  • ranking of materials
  • estimation of residual value

• Key element in pavement management
  • life-cycle-analysis
    • residual value
    • maintenance intervals
    • budgetary needs

(rehabilitation costs)

(time (years))
maintenance strategies

rehabilitation costs

(time (years))
maintenance strategies
(a) Mechanical Empirical Pavement Design (MEPD)

- German pavement design guide
  
  \textit{RDO Asphalt 09 “Richtlinien für die rechnerische Dimensionierung des Oberbaus von Verkehrsflächen mit Asphaltdeckschicht”}

- basic, traditional pavement design approach as in many other countries
Multilayer Elastic Theory

- layered elastic model
  - homogeneous, isotropic, linear elastic
  - infinite horizontal layer extension
  - infinite vertical subgrade extension
  - stick or slip layer interfaces

- limited number of input data
  - layer thicknesses
  - material properties (elastic modulus, Poisson ratio, layer friction)
  - force (magnitude of wheel load) and load geometry (tire patch load)

- materials are not stressed beyond their elastic ranges
  - suitable for short-term loading at low to moderate (?) temperatures

• simple model applicable for high numbers of load repetitions
• E. g., German design guide:
  11 load classes for consideration of truck traffic
  13 characteristic temperature distributions
  = 143 loading cases for design analysis (advantage: short calculation time)
German pavement design guide

Dominant deterioration mechanism considered

- **material fatigue** is crucial design criterion to avoid structural failure
- Wöhler curves are derived from laboratory fatigue testing
- linear summation of the damaging effects of individual loads (**Miner**)

Fatigue law:

\[ N_f = k_1 \cdot \left( \frac{1}{\varepsilon_0} \right)^{k_2} \]

**Miner rule** (linear accumulation of incremental damage):

\[ C = \sum \left( \frac{N_{voh}}{N_{fail}} \cdot p \right) \leq 1 \]

Predicting asphalt pavement performance

- **statistic variation**
- coupling of time increments
- **time increment**
- **traffic model**: axle loads, number of heavy axles
- **climate model**: layer temperatures, subgrade saturation
- **pavement model**: geometry, layer thickness, material properties
- **response model**: stress & strain
- **damage model**: damage increment \( \Delta D \)
cumulative damage \( \Sigma(\Delta D) \)
- **predicted performance**: expected life-time
Stress analysis in time increments

- time-accurate superposition of traffic & temperature

![Time-variation curve of 10 t axle loads](image1)

- time-variation curves of pavement temperatures [°C]

![Time-variation curve of pavement temperatures](image2)

- time-variation curve of strain [\(\mu\varepsilon\)] in 25 cm

![Time-variation curve of strain](image3)

→ superposition and analysis of damage in time increments

Regional climate model (REMO)

- 10 km grid, hourly resolution in time
- 112 climate parameters per box
- hourly time variation curves for air temperature, global radiation, wind speed, humidity

Nesting techniques:
Regional climate model (REMO)

Climate Stations
(DWD, 2012)

Pavement temperature distribution

climate data: meteorological observations at climate station

heat transfer at pavement surface

energy balance law

\[ Q_{\text{net}} = (1 - \alpha) G + \varepsilon_a F T_{\text{air}}^4 - \varepsilon_b F T_{\text{surf}}^4 - \lambda \frac{\Delta T}{d} + \alpha_k (T_{\text{air}} - T_{\text{surf}}) = 0 \]

heat flux within pavement layers

Fourier heat balance law

\[ C \frac{\partial T}{\partial t} = -\text{div} \ q \quad T(x, t=0) = T_e(x) \]
\[ q = -k \ \text{grad} \ T \quad q_n = \alpha (T - T_e) \]

\[ \text{C...vol. heat capacity} \]
\[ \text{q...heat flux vector} \]
\[ \text{k...heat conduction coeff.} \]
\[ \alpha...heat transfer coeff. \]
\[ T_e...ambient temperature \]

[Krebs & Böllinger, 1981; Wistuba, 2002; Villaret et al., 2007]
Pavement temperature distribution

Temperature [°C]

0 5 10 15 20 25 30 35

Depth [cm]

22 to 03 h
04 to 09 h
10 to 12 h
13 to 18 h
19 to 21 h

Pavement temperature distribution

Temperature [°C]

0 5 10 15 20 25 30 35

Material-specific Temperature-Stiffness-Function

E-Modulus [MPa]

asphalt wearing course
asphalt binder course
asphalt base course

M Wistuba | 13

M Wistuba | 14
Extended analysis? → additional incremental damage for limited number of critical load cases
**Longitudinal low temperature top down cracking**

- **Question:** can low-temp. stress be explained from LE calculation?
  - due to a negative temperature gradient (drop in temperature) and
  - low stress relaxation at low temperature

![Diagram](image)

**Arand 1995**

- **(A) in wheel path**
  - thermal stress
  - traffic induced stress

- **(B) beside wheel path**
  - total stress

(A2 Pack 2007, Foto: Wistuba)
Longitudinal low temperature top down cracking

Thermal stress at surface 1 m beside wheel track

- Winter
- Sommer
- Winter

Temperature [°C] vs. Time [h]

- Straßenoberflächentemperatur
- Abkühlrate pro Stunde

- AC 11 D N

Spannung [MPa] vs. Time [h]

Low temperature stress at surface

Traffic induced stress at surface

Total stress at surface
Longitudinal low temperature top down cracking

- can not be explained from LE calculation of low-temperature stress (only in very rare cases and for extremely hard bitumens). Generally, this type of crack is supposed to be driven by other crack mechanisms (shear at moderate and high temperatures?)


Predicting asphalt pavement performance

Molenaar, Keynote MCD 2016 Nantes
Predicting asphalt pavement performance

Molenaar, Keynote MCD 2016 Nantes

Conclusion on top down cracking

- Complex contact pressure distributions with high peak stresses will result in high tensile strains at pavement surface
- Surface/top down cracking is likely to occur because of these high tensile strains
- Top down cracking will be dominant in thicker asphalt pavements
- Hardening of surface layer will aggravate problem
- Durable, high fatigue and permanent deformation resistant mixtures will solve much of the problem

8th RILEM International Conference on Mechanisms of Cracking and Debonding in Pavements (MCD2016)
Linear visco-elastic bitumen behavior

Domains of asphalt mix behaviour
Associated phenomena

- Linear viscoelasticity
- Non linearity
- Fatigue
- Healing
- Thixotropy
- Crack propagation
- Permanent deformation
- Brittle failure
- Viscoplastic flow
- Thermo-mechanical coupling
- transfer to 3D

Fracture mechanics

- Low temperature cracking represents a serious distress for asphalt pavements in cold regions. Crack failure properties of asphalt mixture are crucial for design.
- They are used as input in the Thermal Cracking model which is part of the current Mechanistic Empirical Pavement Design Guide acc. to AASHTO 2008.
- Fracture strength properties of asphalt mixture can be successfully predicted from SCB fracture testing without performing IDT tests at low temperature.

See paper N° 66860 (Cannone Falchetto, Moon & Wistuba: Numerical correlation between low temperature SCB fracture and IDT strength of asphalt mixture using FEM analysis)
Continuum Damage Theory

- Characteristic curve representing the evolution of internal damage $D$ in the mixture in function of pseudo strain energy $W^R$ and of a material property $\alpha$

\[
\dot{D} = \left( - \frac{\partial W^R}{\partial D} \right)^\alpha
\]

\[
N_f = k_1 \cdot \left( \frac{1}{\varepsilon_0} \right)^{k_2}
\]

$k_2 = 2\alpha$ (Lee et al., 2003; Kim et al. 2006)

Evolution of damage (internal micro-cracks)

[Di Benedetto]
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Fatigue life based on maximum tensile strain?

We take into account the major principal (tensile) strain. What are we doing with the intermediate and minor principal strain? Are we ignoring them?
Predicting asphalt pavement performance

 STATISTIC VARIATION

 TRAFFIC MODEL
 axle loads, number of heavy axles

 CLIMATE MODEL
 layer temperatures, subgrade saturation

 PAVEMENT MODEL
 geometry, layer thickness, material properties

 RESPONSE MODEL
 stress & strain

 DAMAGE MODEL
 damage increment $\Delta D$
cumulative damage $\Sigma(\Delta D)$

 PREDICTED PERFORMANCE
 expected life-time

 RHEOLOGY: linear visco-elasticity: $E^*$, $\phi$
 & consideration of associated phenomena

 Fracture Mech., Cont. Damage Th.
Key issues in pavement design

- (low temp./fatigue) cracking & crack propagation
- (accumulation of) permanent deformation

stiffness and evolution with time and temp.

-20°C
+55°C

interlayer bonding

fatigue

bearing capacity of subbase

Predicting asphalt pavement performance

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Pavement Design

Use of advanced models and “complex” material tests is still far away from day to day practice

Correlating “complexity” to “simplicity” is therefore important
(b) Pavement management: Empirical Perform. Function

Pavement condition parameters are measured in time intervals, and a time-correlation function is derived describing the temporal change of the condition parameter.

Empirical Performance Function (EPF)

- EPF do not incorporate structural parameters but are based on surface characteristics / defects only
  - EPF do not work for innovative materials and structures (new products, recycled materials)
- few effort has been made to incorporate a material science based approach for performance prediction in the frame of PMS
- need for analysis of pavement condition in function of incremental distress mechanism → linked with MEPD approach
Linking empirical with mechanical information

- use information obtained from material testing in the laboratory and from structural performance modeling
- calibration of empirical performance function

Holistic PMS approach: linking data obtained from empirical analysis to data obtained from mechanistic analysis
Linking empirical with mechanical performance

- ERAnet-Road-Project “InteMat4PMS” (2012)
- PROMAT project (2016)

\[
\text{Performance Indicator } PI \left[ \% \right] \quad \text{Section Calibrated EPF} \\
\text{EPF}'(N_{\text{meas},t}, PI_{\text{meas},t}) \\
\text{Non Calibrated EPF (PI(N))} \\
\text{Laboratory Calibrated EPF} \\
\text{EPF}''(N_{\text{meas},t}, PI_{\text{meas},t}, X_{f}) \\
X_{f} = \frac{N_{f,D} - N_{\text{meas},t}}{N_{f,D} - N_{\text{meas},t}} \\
\]

\[
PI''_{t+N} = PI_{\text{meas},t} + EPF''(\Delta N) = PI_{\text{meas},t} + X_{f} \cdot EPF'(\Delta N) \quad \text{where } \Delta N = N_{t} - N_{\text{meas},t}
\]

Predicting asphalt pavement performance

Concluding remarks

- need for consideration of thermo-mechanical behavior of bituminous mixtures and pavement structures
- the influence of load \textit{and temperature} on damage evolution is a key issue
- for life-cycle-analysis of pavement structures linking empirical \textit{and} mechanical information is of advantage

Thank you for your contribution!