Combining Practice and Theory for the Preservation of Pavement Networks

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Key Aspects in Preservation of Pavement Networks

• Properly designed
• Properly constructed

• Not only important for new constructions but also for maintenance activities
Often heard statements

• The quality of the road is determined by the quality of the contractor

• Quality implies:
  - experience
  - skills
  - dedication

• Do we really need fancy research to get better roads? WE NEED GOOD CONTRACTORS!
Contractor is very important!
Poor construction gives short life!

(newly laid binder course on airport runway)
Applying theory doesn’t necessarily result in a long life pavement
One of my former bosses once said “pavement construction is all about logistics”
Logistics

“Get the right stuff in the right amount at the right time at the right place”

- WHAT (material and quantity)
- RIGHT (composition, temperature)
- WHEN (time)
- WHERE (location)
Objective of our preservation activities

• Maximize performance
• Minimize costs
• Maximize performance / cost ratio

• “Costs”:
  - construction
  - maintenance
  - user
  - environment (air/soil pollution, noise)
Why is theory needed?

- To understand the reasons why pavements behave “good” or “poor”
- To quantify the effects of “good” and “poor” performance
  - pay factors
  - bonus – malus
- Development of products for enhancing performance (use of modified bitumen)
- Development of better structures
Two examples of how theory was of enormous help to practice and where practice and theory were closely working together

1\textsuperscript{st} one: PMA for Schiphol Airport Amsterdam

2\textsuperscript{nd} one: Extending Lifetime Porous Asphalt Concrete
Use of PMA at Schiphol Airport
Amsterdam (late 1980’s)
Traditional Structure

27 cm traditional asphalt

60 cm lean concrete

20 cm sand

Clay subgrade CBR = 2%
Problem to be solved

• Shrinkage cracks developing in lean concrete base will propagate through asphalt top layer
• Wide crack openings in winter, some buckling in summer, loose material gave rise to FOD damage
• Crack spacing 10 – 45 m
• Crack width 10 – 25 mm
<table>
<thead>
<tr>
<th>Traditional Structure</th>
<th>Newly Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 cm traditional asphalt</td>
<td>20 cm PM asphalt</td>
</tr>
<tr>
<td>60 cm lean concrete</td>
<td>60 cm lean concrete</td>
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<tr>
<td>20 cm sand</td>
<td>20 cm sand</td>
</tr>
<tr>
<td>Clay subgrade CBR = 2%</td>
<td>Clay subgrade CBR = 2%</td>
</tr>
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</table>
Proposed solution

• Let us use PM asphalt
• Cut joints in lean concrete base to limit amount of movements at cracks

Project was a cooperation between Schiphol Airport, NACO consultants, main contractor and Delft University of Technology
Big Question

• Which type of PMB to be used?

• 3 PMB’s
• 5 bitumen contents
• 2 mixture types

• Too many variables and too less time to do sophisticated tests
• Use simple tests that also can be used for QA/QC purposes
Crack growth

The stresses at the tip of the crack are characterized by the stress intensity factor $K$

$$K = f(\sigma, \sqrt{c})$$

$\sigma = $ tensile stress

$c = $ crack length

Crack growth per load cycle $dc/dN = A K^n$

$A, n = $ material parameters
Crack growth parameters $A$ and $n$
both should have a low value

- Crack growth law: $\frac{dc}{dN} = AK^n$
- $A = f(S_{mix}, m, \sigma_t, \Gamma)$
- $\sigma_t$ = tensile strength, $S_{mix}$ = mixture stiffness
- $\Gamma$ = fracture energy
- $n = f(2/m$ and void content$)$
- $m$ = slope of master curve for stiffness
Approach

• Because PMA layer is thinner, K will be higher in PMA structure than in reference structure
• So $A_{PMA}$ and $n_{PMA}$ should be lower than $A_{ref}$ and $n_{ref}$ (remember $dc/dN = AK^n$ and $N = h_{asphalt} / \{dc/dN\}$)
• $n$ values don’t change too much so we should focus on reducing the A value
• Required $A_{PMA} / A_{ref}$ could be calculated
• By comparing the properties of the reference asphalt with those of different PMA mixtures, PMB to be used could be selected
Repeated load IT test to obtain $S_{\text{mix}}$, “m” and “n”
Indirect tension test was selected to determine $\sigma_t$ and $\Gamma$.
SBS A was selected
Conclusions

• Application of theoretical, fundamental principles allowed a proper selection of the PMB to be made
• Furthermore “simple” specs could be derived based on this work
• Theory also allowed to qualify and quantify consequences of not meeting specs
Porous Asphalt Concrete Wearing Course

- Extensively used in NL for noise reducing purposes
- Gap graded mixture $\phi_{\text{max}} = 11$ mm
- At least 20% voids
- Bitumen content $\approx 4.2\%$ by mass
- Reduction splash and spray
Problems with PAC

• Low bitumen content ($\approx 3.5\%$) in top part of layer due to “gravity drainage”
• Hardening of the binder due to aging making it brittle
• Variability in composition of mixture as laid (especially bitumen and void content)
Variability in void content
Result is (premature) raveling even resulting in potholes.

Too high noise production, wind screen damage, driving comfort.
Questions to be answered

- What are the key factors affecting performance?
- What measures to be taken to improve performance?
1st Approach

• Follow performance of large number of PAC sections in time
• Data were collected during a 10 year period
• Data analyses using AI tools
  - artificial neural networks
  - genetic polynomial input selection
  - regression trees
  - rough sets etc

Project was a cooperation between Ministry of Transport and Delft University of Technology
Most important factors affecting amount of raveling 5 and 8 years after construction

**After 5 years**
1. bitumen content
2. 2/3 traffic and cold days

**After 8 years**
1. voids content
2. 2 cold days
3. 3 bitumen content
Influence of void content on amount of raveling 8 years after construction

From AI analysis of SHRP-NL data base
Influence of bitumen content on amount of raveling 8 years after construction

From AI analysis of SHRP-NL data base
Conclusions

• We learned a lot such as large influence of winter conditions ("cold days")

• Practical experience was supported by research findings and now we were able to quantify effects

• Costly and time consuming exercise

• We learned about “the past” but not so much about what we should do in “the future”
**2nd Approach:** tackle the problem from a theoretical point of view

- Test properties of components (bitumen/mortar/aggregates)
  - stiffness
  - fatigue
- Model porous asphalt concrete layer
- Determine effects of:
  - bitumen type and amount
  - void content
  - aggregate type

Project was a cooperation between Ministry of Transport, Delft University of Technology, Aachen University and a main contractor
DSR testing on mortar and adhesive zone

DSR                        mortar column

CT scan

adhesive zone test setup
Some test results

Stiffness

Fatigue
Stresses in the bituminous mortar of PAC due to rolling wheel load
Some findings from theory

• Bestone (sandstone from Norway) gives better performance than Greywacke
• SBS modified bitumen gives better performance than pen 70/100 bitumen
• Don’t use stiff hard binders with low relaxation capacity
• Bitumen content certainly not lower than 4% by mass
• Too high void contents should be avoided (design void content ≈ 20%)
• Test water resistance of mortar (bitumen + all fines < 0.4 mm)
Conclusions

• Theory matched practice

• Testing – modelling allows consequences of changes and variations in mixture composition to be analyzed in a fast and effective way

• It also allows to analyze effects of pmb’s, aggregate type etc

• *Big Dutch contractors are using this approach to qualify and quantify their risks when bidding for large DBFM contracts*
Too large variability in layer properties and thickness is one of the main reasons for poor performance.

Variability is very often caused by construction issues.

Some examples will be shown.
Data were collected by means of GPS on finisher and rollers and by using infra-red technology.
Compaction model for PAC
(based on measurements)

Void content = f (compaction temperature, compaction effort, some mix variables)

Temperature and compaction effort are the most important ones

Compaction effort = \( n \frac{P}{L D^2} \)

- \( n \) = number of roller passes
- \( P \) = load on drum [kN]
- \( L \) = length of drum [m]
- \( D \) = diameter of drum [m]
Compaction and Temperature PAC
Effect of Compaction and Temperature on quality PAC
Most likely location of premature raveling

Roller passes for Thursday Lane 1

20 Roller passes; 18% voids

4 Roller passes 28% voids
Other examples of construction induced variability
Variable paver speed will not result in good product

Normally, speed of asphalt finisher = 3.5 – 4.9 m/min
A standing finisher implies that logistics need to be improved because some asphalt mix cannot be compacted well because of cooling down

Variable finisher speed implies variable compaction by vibrating beam
## Arrival and dumping times

### Truck logistics analysis
9 Feb 2016

Queuing order & waiting time

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<th>Dump time</th>
<th>Departure time</th>
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### Diagram

- **Arrival time**
- **Dump time**
- **Departure time**

**3 hrs!**

**Arrival and dumping times**
Observations

• Too often our pavements show premature damage.
• This is caused by a too high variability in the quality of the product (= the road structure) that is delivered.
• This high variability is mostly because not paying enough attention to details during construction.
• And because of poor logistics.
• The effect of this is the same as having one rotten apple in a basket of good apples.
“Damage” progresses from one poor spot

Pavement damage initiation and progression is like rotting apples in a basket: one bad apple will spoil the rest. There is an average “rot life” of an apple but there is also “rot propagation” from poor ones to good ones.
Reducing variability pays off

Probability of failure reduces when:

- Strength increases = e.g. use of polymer modification
- Stress decreases = e.g. thicker pavement

Both options cost $$$
or VARIABILITY DECREASES = better workmanship
Influence of probability of failure on maintenance costs

% of failed sections

- Existing performance
  - First failures after 4 years
  - First failures after 7 years

- Proposed performance

Time [yrs]

- 4
- 7
- 9
- 11
- 13
- 16

Tijuana, B.C., del 4 al 16 de octubre de 2018
Reducing variability pays off! It results in costs savings and reduction delay hours

<table>
<thead>
<tr>
<th></th>
<th>10% of sections has failed after [years]</th>
<th>50% of sections has failed after [years]</th>
<th>90% of sections has failed after [years]</th>
<th>Maintenance costs</th>
<th>Delay hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently</td>
<td>7</td>
<td>11</td>
<td>16</td>
<td>1</td>
<td>1</td>
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<tr>
<td>In case of reduced variability</td>
<td>9</td>
<td>13</td>
<td>16</td>
<td>0.8</td>
<td>0.9</td>
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</tbody>
</table>

Less fuel, less pollution
Reducing variability is easily said; but not easily done

- Working at night to reduce delays
- Short time slots (e.g. 21:00 pm – 5:00 am)
- Traffic MUST travel the section after 5:00 am
- Bad weather during available construction hours
- Contract clauses
  - bonus when work completed early
  - penalty when work is completed too late
- In such cases one will avoid the penalty and will go for the bonus
- Far too short warrantee period
Bold statement which unfortunately seems to be valid

a too short warrantee period will lead to sloppy work and results in a higher variability in quality AND lower average quality

In the Netherlands warrantee clauses in DC projects
7 years on wearing course
20 years on structural life
Unfortunately variability is already a result of our specifications.

In our specs we cannot pinpoint values but have to set/accept a certain range

An example will be shown how this affects fatigue performance
Each specification allows certain variability in composition.

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<thead>
<tr>
<th></th>
<th>Min.</th>
<th>Desired</th>
<th>Max.</th>
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<tr>
<td>Aggregate on sieve</td>
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<td></td>
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<tr>
<td>C31.5</td>
<td>0</td>
<td>0</td>
<td>1</td>
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<tr>
<td>2 mm</td>
<td>52</td>
<td>57</td>
<td>62</td>
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<tr>
<td>63 μm</td>
<td>93</td>
<td>94</td>
<td>95</td>
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<tr>
<td>Binder content $m_b$</td>
<td>4</td>
<td>-</td>
<td>5</td>
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<tr>
<td>at 100% aggregate</td>
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<tr>
<td>Voids</td>
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<td>Penetration 25°C</td>
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<td>(0.1 mm)</td>
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<tr>
<td>Penetration index</td>
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<td>-</td>
<td>+1</td>
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This allowed variation in mass spec affects volumetric composition

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<tr>
<th>Mat.</th>
<th>Composition</th>
<th>Binder</th>
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<tr>
<td></td>
<td>$m_b$ (%m/m)</td>
<td>$V_{\text{gravel}}$ (%V/V)</td>
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<tr>
<td>(A)</td>
<td>4.5</td>
<td>83.9</td>
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<tr>
<td>(B)</td>
<td>4.0</td>
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<td>(E)</td>
<td>5.0</td>
<td>84.6</td>
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Volumetric composition dictates mechanical properties
Variation in fatigue life due to allowed variation in composition

Rich mixture
\[ V_a = 3\%, V_b = 12.4\% \]

Average composition
\[ V_a = 5\%, V_b = 11.1\% \]

Leans mixture
\[ V_a = 7\%, V_b = 9.7\% \]
Pay factors

Theory can help in qualifying and quantifying penalties when specs are not met.

Example of how mixture characteristics and pavement life are affected by:

- insufficient compaction
- overheating of the mixture during production
Effects of mix composition on mix properties

<table>
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<th>As designed</th>
<th>Too less compaction</th>
<th>Overheated</th>
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<td><strong>Design temperature [°C]</strong></td>
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<td>30</td>
<td>30</td>
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<tr>
<td><strong>Penetration</strong></td>
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<td>15</td>
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<td><strong>Tr&amp;B [°C]</strong></td>
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<td>65</td>
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<tr>
<td><strong>PI</strong></td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.5</td>
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<td><strong>Volume percentage of bitumen [%]</strong></td>
<td>10</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td><strong>Volume percentage of aggregates [%]</strong></td>
<td>85</td>
<td>83</td>
<td>85</td>
</tr>
<tr>
<td><strong>Void content [%]</strong></td>
<td>5</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td><strong>Stiffness of the bitumen Sbit [MPa]</strong></td>
<td>14.6</td>
<td>14.6</td>
<td>42.3</td>
</tr>
<tr>
<td><strong>Stiffness of the mixture Smix [MPa]</strong></td>
<td>3180 (1)</td>
<td>2760 (0.87)</td>
<td>6290 (1.98)</td>
</tr>
<tr>
<td><strong>Fatigue life at 200 µm/m</strong></td>
<td>2.050.000 (1)</td>
<td>1.660.000 (0.81)</td>
<td>628.000 (0.31)</td>
</tr>
</tbody>
</table>

Stiffness and fatigue values estimated using the SHELL program BANDS
Effect of mix composition on fatigue life of pavement structure

50 kN
800 kPa

$E = \text{variable}$
$h = 200 \text{ mm}$

$E = 300 \text{ MPa}$
$h = 300 \text{ mm}$

$E = 100 \text{ MPa}$

<table>
<thead>
<tr>
<th></th>
<th>As designed</th>
<th>Too less compaction</th>
<th>Overheated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>4.018</td>
<td>4.401</td>
<td>4.341</td>
</tr>
<tr>
<td>$\log k_1$</td>
<td>-9.533</td>
<td>-11.058</td>
<td>-11.744</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>174 * $10^{-6}$</td>
<td>188 * $10^{-6}$</td>
<td>115 * $10^{-6}$</td>
</tr>
<tr>
<td>$N$</td>
<td>373250</td>
<td>218272</td>
<td>243781</td>
</tr>
<tr>
<td>$N/N_{\text{design}}$</td>
<td>1</td>
<td>0.58</td>
<td>0.65</td>
</tr>
</tbody>
</table>

$N = \log k_1 - n \log \varepsilon$
By means of such analyses we can determine the variability in fatigue cracking performance of the pavement as a result of the variability allowed in the specs and variations induced during construction (temperature / compaction) and we can arrive to realistic pay factors (e.g. additional asphalt thickness needed)
Dutch approach in avoiding poor performance

- Pavements are designed with a certain reliability level.
- For this reason “characteristic” values are used in design analyses for input parameters like Stiffness and Fatigue Resistance of the asphalt mixture.
- These are the so-called 85% values (so less than 15% of the measured values are lower than the “characteristic” value).
How are these characteristic values obtained?

- In Europe CE marking of mixtures is used
- In NL marking is based on results “fundamental” testing
  - mixture stiffness (4p bending) 6 classes
  - fatigue resistance (4p bending) 8 classes
  - rutting resistance (triaxial) 7 classes
  - water resistivity (indirect tension) 2 classes
- Each contractor has to classify all mixes produced by him!
- Therefore average and standard deviation of input values (85% values) for design are known
- Characteristic value is used in performance related specification
Conclusions

• Application of fundamental theory is absolutely needed for getting better materials and structures and to preserve our costly pavement networks
• Theory is needed for setting realistic specifications and pay factors
• Good/skilled contractors are absolutely needed to build long life pavements
• Good cooperation between theory and practice is needed (cross fertilization) to obtain better products
• Unfortunately this cooperation is not always there
CONTRACTORS, CONCESSIONAIRES and UNIVERSITIES SHOULD WORK CLOSELY TOGETHER IN PRESERVING OUR PAVEMENT NETWORKS
¡Muchas gracias!

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