LOT, a meso scale mechanistic tool for Porous Asphalt mixture design; winter damage and LOT validation

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ABSTRACT: By assignment of the Centre for Transport and Navigation (DVS) of the Dutch Ministry of Transport, Public Works and Water Management the Delft University of Technology developed LOT. LOT is a Lifetime Optimisation Tool for Porous Asphalt, PA, based on meso scale structural modelling. LOT sees an asphalt mixture as a structure and computes stress and strain throughout that structure as a function of mixture component behaviour, mixture geometry, and mixture loading.

This paper discusses the validation of LOT on the basis of full scale ravelling test. Further validation is achieved by analysis of winter damage which developed in PA during the Dutch 2008/2009 winter. For this analysis LOT simulations considering Long Term Aged (LTA) PA at temperatures of -10° to +20°C were made.

The paper comes to the conclusion that meso scale mechanical models allow ravelling performance based mechanistic design of high performance PA mixtures.

KEY WORDS: Porous Asphalt concrete, Meso scale, Mechanistic mix design

1 INTRODUCTION

LOT is a mechanistic Lifetime Optimisation Tool for Porous Asphalt concrete, PA. In this paper emphasis is on validation of LOT. First, in section 2, the LOT project is briefly summarised and validation of LOT on the basis of full scale ravelling tests is discussed. Further validation of LOT was achieved by analysis of PA winter damage as developed in stretches of Dutch motorway during the 2008/2009 winter. This analysis is discussed in section 3. The paper comes to an end with section 4, Conclusions & Recommendations.

2 LOT

LOT was developed at the Delft University of Technology by assignment of the Centre for Transport and Navigation (DVS) of the Ministry of Transport, Public Works and Water Management. Paper size does not allow for a full description of LOT. Reference is made to other literatures (Huurman et al. 2009a, Huurman 2008). Here it is stated that LOT is a meso scale mechanistic tool for PA mixture design. LOT considers three pillars in explaining PA ravelling performance.

- The loads applied by passing tyres to individual stones at the road surface,
- Mixture geometry, i.e. mixture recipe,
- Material component behaviour, i.e. stone-mortar adhesive zone damage accumulation

behaviour, fatigue behaviour and response of applied mortar.

LOT makes use of Finite element modelling. Three types of models are incorporated; 2D idealised, 3D idealised and 2D photo models. Figure 1 gives an impression of these models. The models distinguish between stone, air, mortar and adhesive zones. Due to their limited thickness the adhesive zones, although present, are not visible in Figure 1.

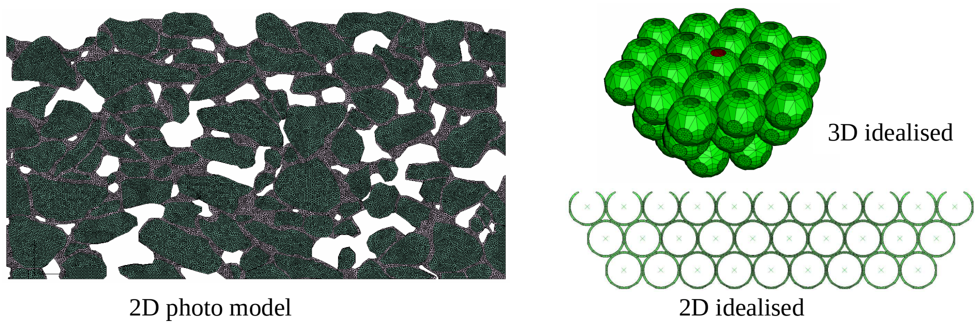

Figure 1: Three types of meso scale structural models in LOT.

During the LOT project material component properties were determined for an SBS modified mortar making use of a range of purpose designed DSR, Dynamic Shear Rheometer tests and DMA, Dynamic Material Analyser tests. Also standard DTT, Direct Tension Tests were performed. Figure 2 gives a compilation of these tests. Please note that all tests are to scale implying that relevant specimen dimensions are in the order of millimetres. Also finite element modelling was utilised to help interpret test results.

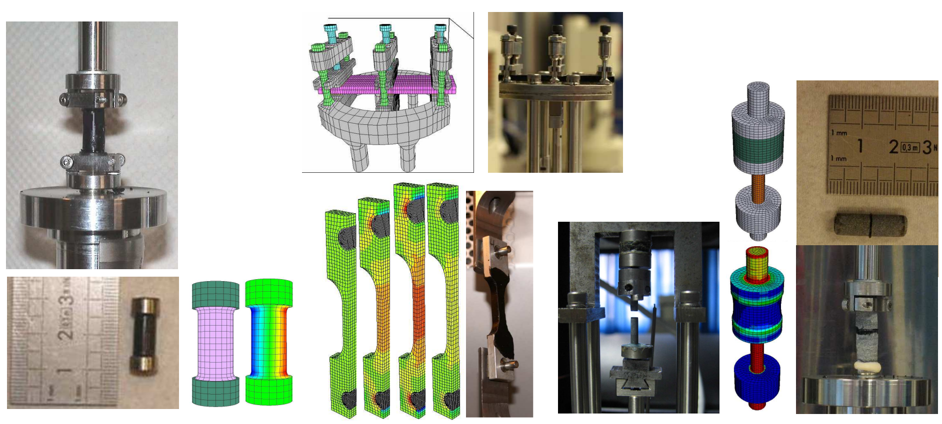

Figure 2: Compilation of various tests executed to obtain material component mechanical behaviour.

Measured material component behaviour is beyond the scope of this paper, and discussed elsewhere (Huurman, 2008). Here it is stated that LOT requires the mortar response behaviour as input, for this purpose use is made of the well known Linear Visco-Elastic Prony series model. LOT also requires insight into mortar fatigue. Hereto laboratory tests are described using a model based on dissipated energy.

$$N_f = \left(W_0 / W_{initial}\right)^n \tag{1}$$

Where n = material constant [-]; W_0 = reference energy [MPa]; $W_{initial}$ = dissipated energy per cycle in initial phase [MPa]

Finally insight into adhesive zone (where stone meets with mortar) damage accumulation is required. The following model is applied in LOT. The model parameters are determined on the basis of DSR and DMA tests on stone columns glued together by binder, see figure 2.

$$\dot{D}=\left(\frac{\sigma_{et}}{\sigma_0}\right)^{n_0} \; for\; \sigma_{et}>0, \quad \dot{D}=0 \; for\; \sigma_{et}\leq 0 \qquad with \qquad \sigma_{et}=\sigma_n+\tau/\tan\phi \tag{2}$$

Where $\dot{D}$ = rate of damage accumulation [-/s]; σ_{et} = equivalent tensile stress [MPa]; σ_n = adhesive zone normal stress [MPa]; τ = adhesive zone shear stress [MPa]; ϕ = friction angle [degr.]; n_0 = model parameter [-]; σ_0 = reference stress [MPa].

During the LOT project the properties of a single SBS modified mortar and the adhesion zone between that mortar and two types of stone, i.e. greywacke and sandstone were determined. Properties were determined after Short Term Aging and Long Term Aging. Also the effects of water subjection were determined.

At the end of the project LOT was validated by an Accelerated Pavement Test executed at the STUVA APT in Germany. Four different mixtures were involved. Figure 3 gives a compilation of that validation work.

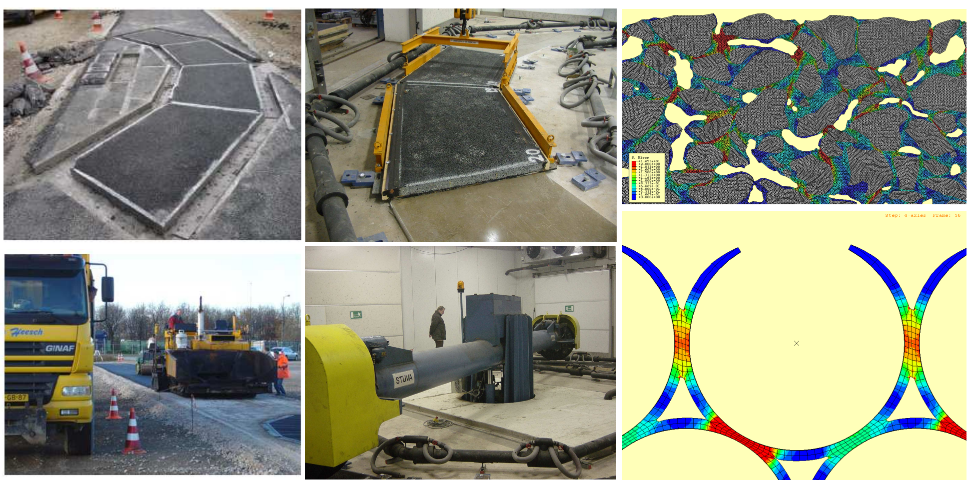

Figure 3: LOT validation work. Left: construction of test slaps, Middle: APT device and the installation of the test slaps herein, Right: LOT models used to determine the theoretical ravelling life expectancy (top: photo model, bottom: idealised model).

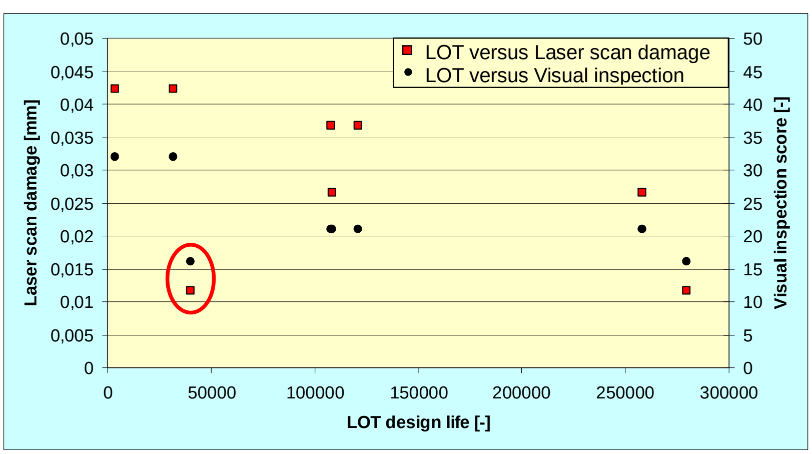

Figure 4: LOT validation. Horizontal axis: ravelling life expected by LOT, Vertical axes: ravelling damage observed in full scale APT.

Ravelling damage development during the test was assessed by visual inspection and by means of laser surface scans. The theoretical design life explained by LOT was determined by idealised models based on the mixture recipes and by photo models based on the actual structural geometry of the mixtures, see Figure 3. The validation work resulted in 16 data points plotted in Figure 4. The horizontal axis represents the theoretical life expectancy of the four involved mixtures as determined by 2D idealised and 2D photo models. The left vertical axis represents damage as per laser surface scan and the right vertical axis give damage as per detailed visual inspection.

Figure 4 shows that a short LOT explained life expectancy corresponds with much APT observed ravelling damage. Similarly a long LOT explained life expectancy corresponds with little APT observed damage. Only two data points (enclosed in a red circle) do not follow this general trend. These points follow from a 2D photo model and it is expected that the model represents a weak spot in the test section.

3 WINTER DAMAGE

3.1 The Dutch winter of 2008-2009

During the 2008-2009 winter aggressive ravelling developed at some short stretches of Dutch motorway. Traffic measures and emergency repairs, reducing network capacity, were necessary. A short national discussion about PA suitability and application followed by publication of negative articles, e.g.

- AD 13-01-09: “Hundreds of claims after frost damage”
- Autoblog 23-01-09: “Winter takes its toll: Dutch pavements damaged”
- AD 29-01-09: “News: Frost damage runs into millions”

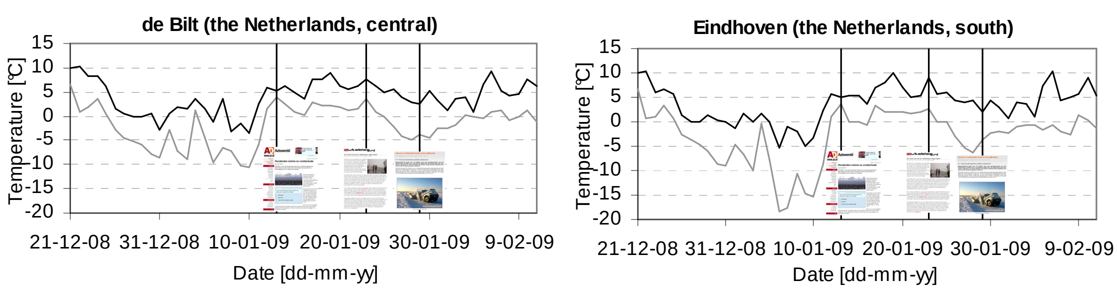

Figure 5: Daily maximum and minimum temperature in the municipality of de Bilt and Eindhoven. Vertical lines indicate the publishing dates of mentioned articles.

According to the Royal Netherlands Methodological Institute (KNMI) the 2008-2009 winter was coldest in 12 years. Figure 5 gives KNMI temperature data for two sites in the Netherlands during the period in which the described aggressive ravelling developed. Vertical lines indicate the publication date of the articles mentioned earlier.

The DVS completed an inventory of winter damage on January 22 2009 (Voskuilen, 2009). In total 55 sections were affected by winter damage. Only 2 sections did not have PA surfacing. The predominant type of damage was ravelling, however, other types of damage were also observed. The average service life of the affected sections was 11 to 12 years.

3.2 Representative case

The primary network in the Netherlands is for 90% surfaced with PA. However, the pavement structure, sub grade and even the type of PA (grading, type of bitumen, single layer or double layer) differ throughout the network. Similarly traffic conditions vary. It was decided to obtain insight into the effects of winter by consideration of a situation that is representative for the Dutch primary network. Hereafter this representative case is further defined.

A 50 kN wheel load applied by a Good Year 425R65 super single tyre is considered. The width of the wheel patch of this commercial tyre equals 330 mm. The length of the wheel patch equals 170 mm, so leading to an average contact stress of 0.891 MPa. The tyre travels at a speed of 21.25 m/s or 76.5 km/h. In the simulations it is assumed that the tyre is non driven, i.e. free rolling.

In the Netherlands the traffic load on motorways varies from approximately 30,000 to 200,000 vehicles per day in two directions. Of this traffic approximately 12.5% is commercial; on average each commercial truck introduces 1.6 times the damage introduced by a standard 100 kN axis (DVS, 1998). From this it is concluded that the slow lanes in the Netherlands are subjected to 3,000 to 20,000 equivalent 100kN axle loads per day. A value of 10,000 is used in the simulations as a practical and representative number.

From Buiter et al. (1989) it is known that lateral wander for commercial traffic on 3.5 m wide lanes has a standard deviation of 290 mm. For 330 mm wide super single tyres this leads to the existence of a 10 mm strip in the centre of the wheel path loaded by 41.9% of passing tyres. The LOT simulations consider the situation in that strip.

The simulations consider a representative Dutch asphalt pavement for motorways, see Table 1. The asphalt stiffness's listed in Table 2 follow from the Dutch design method for Asphalt pavements on motorways, DVS (1998). The unbound granular base, often a crushed concrete / crushed masonry mixture, and the sand sub base are assigned generally accepted stiffness's.

Table 1: Representative structural design of a Dutch motorway pavement.

Material	Thickness [mm]	Poisson's ratio [-]	Stiffness [MPa]			
			-10°C	0°C	+10°C	20°C
PA	50	0.35	10,475	8,625	6,000	3,750
DAC	200	0.35	20,950	17,250	12,000	7,500
Unbound base	225	0.4	400			
Sand sub base	1000	0.4	100			
Subgrade	∞	0.4	55			

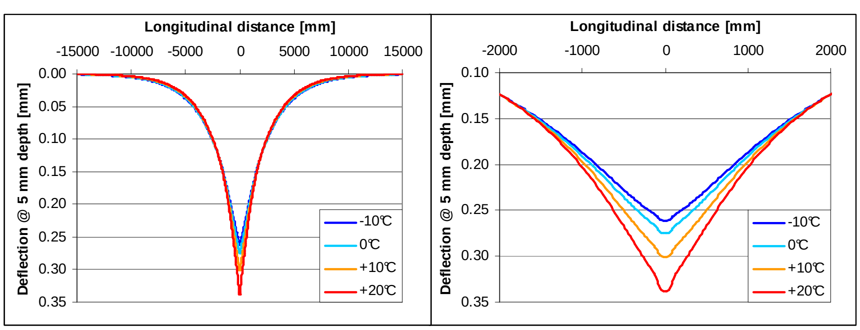

Figure 6: Deflections 5 mm below the pavement surface as a function of asphalt temperature.

For the pavement listed in Table 1 deflections were computed up to 2,000 mm away from the load centre at 5 mm and 27.5 mm depth. Use was made of WESLEA, a well known tool for Linear Elastic Multi Layer Analyses. Computations were made for temperatures of -10°C, 0°C, +10°C and +20°C. Deflections at 15,000 were considered to be nil and an exponential function was applied to describe deflections further than 2,000 mm away from the load centre. The deflections shown in Figure 6 were obtained.

The most commonly applied type of PA in the Netherlands is a PA 0/16 mm. The mixture recipe of such mixtures is obtained from the Dutch National Standard, RAW (CROW, 2005). In the simulations to be discussed use is made of the LOT idealised 2D model. Table 2 lists the main LOT inputs that determine the structural geometry of that PA 0/16 mm mixture.

Table 2: Definition of mixture geometry

Equivalent stone radius [mm]	4.8	Mineral in mortar density [kg/m3]	2650
Stone density [kg/m3]	2650	Bitumen density [kg/m3]	1020
Percentage of stone in mineral (wt %)	80%	Bitumen percentage (wt%)	4.5%
Void ratio	20%		

3.3 LOT simulations

PA at the road surface may experience three main types of mechanical loading.

- Forces introduced to the surface stones by passing tyres,
- Deformations that follows from deflection of the pavement as a whole,
- Stress that may be introduced as a result of temperature fluctuations.

In the simulations discussed here all of the above load cases are considered. For the load signals that follow from individual wheel loads reference is made to other literature (Huurman et al., 2009a and Huurman 2008). Details of the representative load are found in section 3.2.

The deflections of the pavement structure as shown in Figure 6 are translated into boundary conditions for the outer edges of the LOT model. Figure 7 gives a visual impression of this principle.

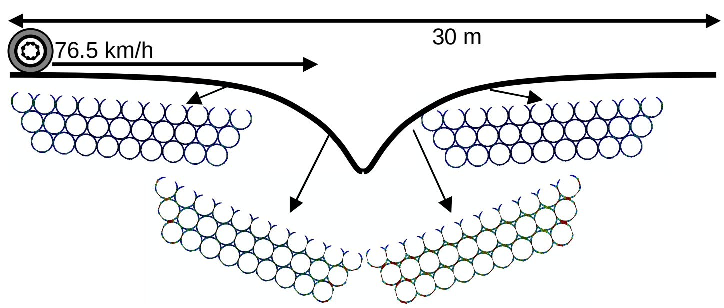

Figure 7: Deflections of the pavement structure and the effects hereof for the PA surfacing. Deformations that follow from pavement deflection are fed into the model as boundary conditions.

During the day temperatures fluctuate, see Figure 5, and the temperature of the pavement surface layer varies accordingly. As a result hereof stress may be introduced. An estimate of these stresses is made assuming sinusoidal temperature evaluation over a 24 hour period. For the calculations the linear thermal expansion coefficients for stone and mortar are set to 6.6 × 10e-6/°C and 2.5 × 10e-5/°C respectively. Calculations are made for an average daily temperature of -10°C, 0°C, 10°C and 20°C. Each calculation considered a 24 hour sinusoidal temperature signal with a 5°C amplitude. Figure 8 gives an impression of obtained results. As indicated especially the horizontal contacts are stressed. Both charts in Figure 8 refer to these horizontal contacts.

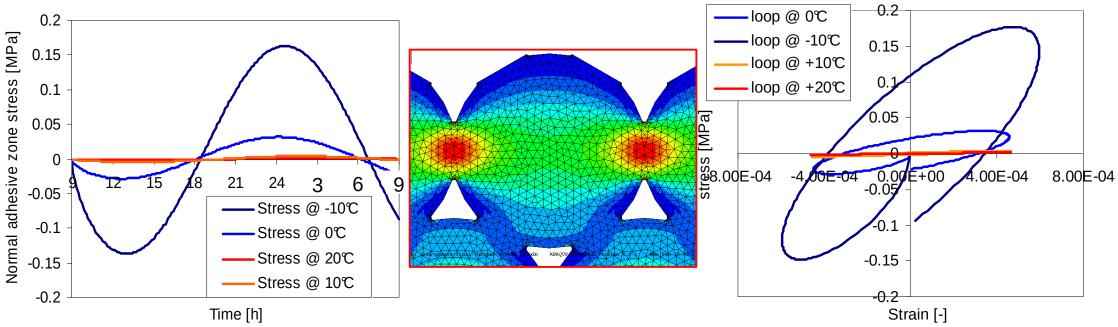

Figure 8: Obtained results for sinusoidal 10°C temperature change over a 24 hour period at average temperatures of -10, 0, +10 and +20 °C respectively. Left: adhesive zone normal stress in horizontal contacts, Right: Hysteresis loops in horizontal contacts.

3.4 LOT results

The discussed simulations result in stress and strain signals at different locations throughout the mixture as a result of wheel load passages (combined surface loading and deflection) and temperature fluctuations. Application of the damage models given in equations 1 and 2 on these signals allows for the determination of damage that accumulates in a 24 hour period. It is assumed that 85% of the 10,000 daily axle load repetitions are applied between 7:00 and 19:00 hour. During the night, 19:00 to 7:00 hour, 15% of the daily traffic load is applied.

Simulations were made for average temperatures of -10, 0, +10 and +20°C and showed that the representative PA 0/16 mm mixture is most vulnerable to failure of the adhesive zones, i.e. mortar fatigue leads to a longer ravelling design life than adhesive zone damage.

The simulations showed that the effects of temperature fluctuations over the day are limited for average temperatures of 0, +10 and +20°C. The maximum ravelling performance of the mixture is found at 0°C.

Figure 9 gives the damage accumulation in a single 24 hour day as a function of the average daily temperature and the amplitude of temperature fluctuation over that day. The figure plots the relative daily damage as compared to the daily damage introduced at 0°C. The figure clearly indicates that the ravelling performance of the mixture degrades as temperatures increase. However, as temperatures fall the mixture performance degrades much faster and aggressively, especially when temperature fluctuations of some magnitude occur.

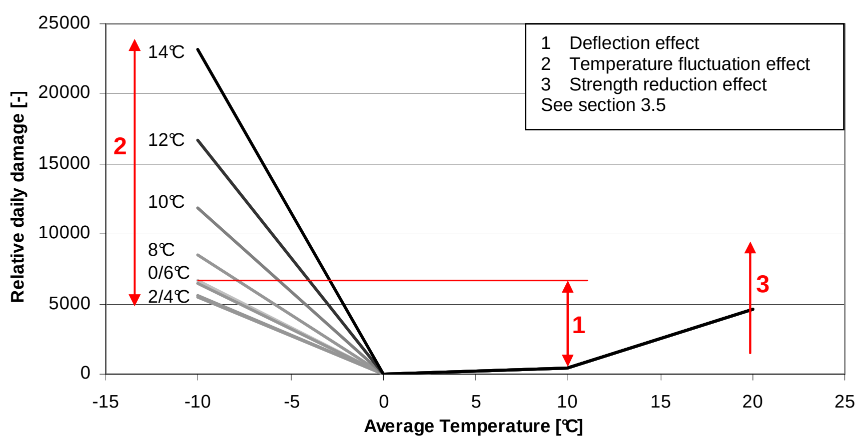

Figure 9: Relative daily damage compared to damage at 0°C, i.e. maximum mixture performance; as a function of average temperature and daily temperature fluctuation.

Figure 5 indicates the temperatures during the period in which aggressive ravelling damage developed for two locations in the Netherlands. Of course there is no direct relation between surfacing temperature and air temperature. However, it is fair to say that circumstances at locations in the Netherlands during the 2008-2009 winter can be represented by an average temperature of -10°C combined with a temperature fluctuations of more than 13°C. It is anticipated, but unknown to the authors, that more extreme circumstances developed locally due to micro climate conditions.

From Figure 9 it is learned that the accumulation of ravelling damage at $T_{average}/\delta T$ = -10°C/13°C is close to 20,000 times faster than at maximum mixture performance, i.e. 0°C. This indicates that ravelling damage accumulated during the most cold Dutch winter days may easily exceed the damage accumulated in years of less extreme conditions.

On the basis of the above it is believed that LOT explains the aggressive and extreme ravelling damage that developed at locations during the Dutch 2008-2009 winter.

3.5 Causes of winter damage

An explanation of the trends plotted in Figure 9 was found in the observation that a Porous Asphalt surfacing layer is subjected to two types of loadings.

1 Strain controlled loadings.

Due to temperature fluctuations the surfacing material wants to shrink or expand. The desired strains that are counter acted by opposite strains that result in stresses. These effects are independent of surfacing stiffness and result in a strain controlled type of loading, see Figure 8.

Secondly the pavement deflects under loading, Figures 6 and 7. These deflections depend on the structural pavement design and the traffic load. However, the contribution of the surfacing layer to structural stiffness is limited. In other words the surfacing layer cannot limit pavement deflections, even when the surfacing material becomes very stiff. As such, for the surfacing layer, pavement deflections result in a type of loading that is best described as strain controlled.

2 Force controlled loadings.

At locations where a passing tyre makes contact with the surfacing layer equilibrium between applied contact forces and surface reaction forces exists. This type of loading is thus mainly force controlled.

The relaxation behaviour of bituminous mortars degrades as temperatures decrease. For the aged SBS modified bitumen considered in this work this phenomenon resulted in a strong increase of stresses as temperatures drop to -10°C. This is best understood by consideration of the temperature dependent behaviour of adhesive zones. At some temperature the performance of these zones is maximal. With increasing and decreasing temperatures the performance degrades, see Figure 10. For the SBS modified bitumen considered here and considering the combined data for Sandstone and Greywacke the maximum adhesive zone performance is obtained at 0°C. As shown by Figure 10 adhesive zone performance at -10°C is about equal to the performance at +10°C.

However, the ravelling performance of the PA 0/16 mm mixture at +10°C is far better than at -10°C in case there are no temperature fluctuations, see red arrow #1 in Figure 9. Since temperature stresses remain absent observed differences can only follow from increasing pavement deflection stresses. At -10°C the mortar has stiffened so much that deflection stresses become of importance.

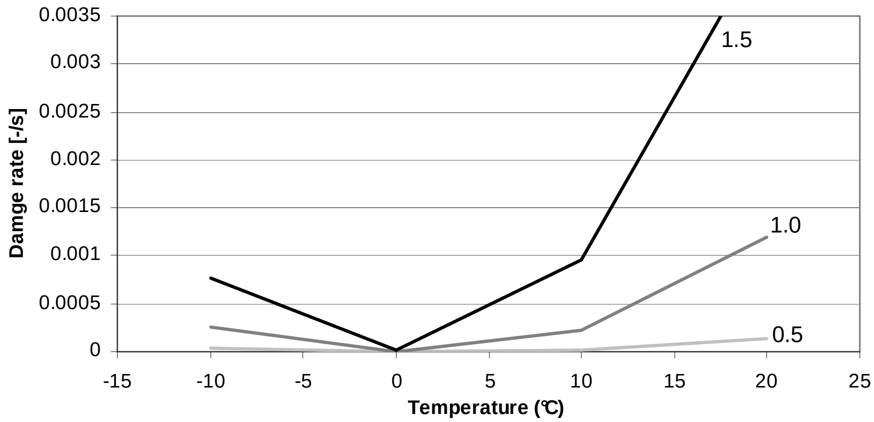

Figure 10: Adhesive zone damage rate as a function of temperature and tensile stress.

Due to the limited relaxation behaviour temperature stresses may develop at an average temperature of -10°C. Due to these stresses the damage development during periods of horizontal compressive temperature stress is reduced. However in periods of horizontal tensile temperature stress the damage accumulation is increased. Depending on the distribution of traffic over the day this results in a decrease of damage at low temperature fluctuations (damage reduction in periods of compression compensates for damage increase during periods of tension). As the temperature fluctuations are of ample magnitude only negative effects can occur (damage increase in periods of tension is of such magnitude that it cannot be compensated by damage reduction during periods of compression). See arrow #2 in Figure 9.

The relaxation behaviour at temperatures of 0°C and higher is such that temperature or deflection stresses of magnitude do not develop. At these circumstances the PA layer is solemnly subjected to the force controlled loading introduced by passing tyres. Now the strength of the material becomes important. As indicated by Figure 10 the strength of adhesive zones degrades at higher temperature so explaining the degradation of mixture ravelling performance at 20°C, see arrow #3 in Figure 9.

4 CONCLUSIONS & RECOMMENDATIONS

4.1 Conclusions

On the basis of the work discussed in this paper the following conclusions are drawn.

- LOT is a mechanistic design tool for PA mixtures,
- It was discussed that the LOT explained raffling design life for four mixtures corresponds well with damage development in a full scale ravelling test,
- It was furthermore shown that LOT explains the aggressive and extreme ravelling damage which developed during the 2008-2009 winter at locations in the Netherlands,
- The previous presents a first indication of the validity of LOT over a range of temperatures. Winter damage developed at an average temperature of -10°C while the validation tests were done at +10°C.
- It was shown that cause of winter damage is found mainly in a strong reduction of the relaxation potential of the aged mortar at low temperatures. The reduction of adhesive zone performance at low temperatures is enhancing these effects.
- It was shown that ravelling performance of PA at high temperatures degrades as a result of adhesive zone strength reduction.

4.2 Recommendations

The work discussed in this paper indicates that the performance of PA can be improved significantly when a mortar is applied that remains flexible at low temperatures, even after aging. Application of such a mortar will especially address low temperature performance.

Further improvements of PA ravelling performance may be obtained when the adhesive zone strength at high temperatures is addressed. It is expected that the benefits hereof remain limited compared to the benefits that follow from the above recommendation. This is especially so since the effects of healing, which is especially strong at high temperatures, were not considered here.

Indications are that mortars may be made more flexible at low temperatures by focussed polymer modification (e.g. ABS) or the application of pulverized rubber particles (Garcia-Morales et. Al 2006). Increasing the adhesive zone strength may be achieved by selection of highly potential combinations of stone mineral composition, bitumen and fillers.

This work showed the importance of the response behaviour of mortar in explaining the performance of asphalt concrete mixtures. It is strongly recommended to strive for better constitutive models for mortar. It is believed that the models available today (including the Prony series model used here) can be improved. Models that are stress dependent and able to accurately describe the response behaviour over a wide range of frequencies and temperatures are required for future meso scale mechanistic mixture designs.

REFERENCES

Buiter R., Cortenraad W.M.H., Eck A.C. van, Rij H. van, 1989. *Effects of transversal Distribution of Heavy Vehicles on Thickness Design of Full-Depth Asphalt Pavements*, Transportation Research Record TRR 1227, TRB, Washington, USA pp. 66-74.

CROW, 2005. *Standard Provisions RAW, manual for specifications in soil, hydraulic and pavement engineering (in Dutch: Standaard RAW Bepalingen, handboek voor bestekken in de grond-, water- en wegenbouw),* Ede, the Netherlands.

DVS, Centre for Transport and Navigation of the Dutch Ministry of Transport, Public Works and Water Management, 1998. *Pavement engineering guide, pavement design (in Dutch: Handleiding Wegenbouw, Ontwerp Verhardingen),* the Netherlands.

Garcia-Morales, M., Partal, P., Navarro, F.J., Gallegos, C., 2006. *Effect of waste polymer addition on rheology of modified bitumen*, Fuel 85, p.p. 936-943

Huurman M. 2008; *Lifetime Optimisation Tool, LOT, Main Report*, Report 7-07-170-1, Delft University of Technology, the Netherlands.

Huurman M., Mo L., Woldekidan M.F. 2009a; *Mechanistic design of silent asphalt mixtures*, Enviroad, Warsaw, Poland

Huurman M., Mo L., Woldekidan M.F. 2009b; *Porous Asphalt ravelling in cold weather conditions*, Enviroad, Warsaw, Poland

KNMI, Royal Netherlands Metrological Institute, 2009. *temperature data publicly accessible via website: knmi.nl*, de Bilt, the Netherlands.

Sandberg U., Esjmont J.A. ,2002; *Tyre/road noise reference book*, Informex, SE-59040 Kisa, Sweden

Voskuilen, J., 2009. *Personal conversations,* Centre for Transport and Navigation of the Dutch Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.