Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 3(2):56-64

Mechanistic Design of Silent Asphalt Mixtures

Marinus Huurman[1+], LianTong Mo[2], and Milliyon Fekade Woldekidan[3]

Abstract: The Netherlands is a densely populated country. As a result environmental issues related to road traffic are taken very serious. This paper discusses the mechanistic design of porous asphalt surface mixtures, PA. The environmental advantages of PA are that it dramatically reduces traffic noise. A disadvantage of PA is that the presence of pores reduces the strength of the mixture which is reflected in the materials vulnerability to ravelling. And, to make matters worse, the open structure makes the material vulnerable to aging which further enhances the ravelling vulnerability. Ravelling has a negative effect on noise emission, implying that the main advantage of PA is gradually lost as the development of ravelling damage progresses throughout the service life of PA. Furthermore ravelling of PA is the main reason for PA maintenance. In this paper a mechanistic mixture design approach for PA surfacings and open graded thin surfacings is discussed. The procedure is based on meso scale material mechanics in which the in-mixture response to wheel loadings is simulated and used for further durability determination. The development of the theory summarised and the paper comes to a conclusion by validation of the procedure on the basis of full-scale ravelling tests. It is concluded that the mechanistic design of silent porous surfacing layers is feasible today and that this may well contribute to the introduction of durable and silent road surfacings on a wider scale.

***Key words**: Mechanistic mix design; Meso scale modelling; Porous asphalt; Ravelling.*

Introduction

The Netherlands is a densely populated country. As a result environmental issues related to traffic are taken very serious. Two issues are especially addressed in the Netherlands, i.e. air pollution and traffic noise.

With respect to air pollution focus is on fine dust and CO_2 emissions. The Dutch government is encouraging car owners to buy cars with limited emissions by the implementation of tax-advantages for cars with low emissions. Also tax levels on cars with high emissions were increased by a law introduced on February 1, 2008. With respect to noise hindrance the policy of the government is best reflected in the obligation to apply porous asphalt (PA) on the Dutch primary road network. At the moment close to 90% of the Dutch primary road network is surfaced with some type of noise reducing PA.

Noise reductions of 3dBA compared to dense asphalt concrete are easily achieved by application of standard types of PA. Noise reductions of 5dBA can be achieved by application of special types of PA, e.g. double layer PA where a fine 6/8 or 4/6*mm* PA is placed over a courser PA sub-layer. Elsewhere [1] it is reported that surface layers with a porosity of at least 20% result in even larger noise reductions when made more elastic by application of at least 20% rubber or other elastic products. Such poroelastic surfacings with 40% porosity may result in noise reductions up to 12dBA.

From the above it is concluded that porosity, apart from other aspects, is an important issue in noise reducing road surfacing materials. This paper discusses an elaborate fundamental research into the ravelling performance of PA and noise reducing open graded thin surfacing layers. Ravelling, the loss of stone from the road surface, is in most cases by far determinative for PA service life and directly related to PA performance and not much dependant on the structural design of the pavement. Since the introduction of PA in the Netherlands in the mid 1980s empirical research increased the service life of standard PA 0/16*mm* on slow lanes from approximately 6 years to an average of more than 10 years today. In the previous years, however, the steady growth of PA service life came to a stand still.

For this reason the DVS (Centre for Transport and Navigation of the Dutch Ministry of Transport, Public Works and Water Management) started a 5 year research into PA ravelling. As part of this research the Delft University of Technology was commissioned in 2006 to execute her plans in developing a meso scale mechanistic design tool for PA.

The (Lifetime Optimisation Tool) LOT program aims for the development of a meso scale mechanistic tool that gives in-sight into in-mixture phenomena taking place during tyre passages. Use is made of Finite Element (FE) models. The chosen approach requires information and modelling of; the PA mixture geometry, the PA mortar response, the load signals on individual surface stones, PA mortar fatigue behaviour, and finally the fatigue behaviour of the PA stone-mortar adhesive zone. To quantify the effects of aging and water subjection, the properties of aged material components and water subjected specimens are also investigated.

This paper gives a summarized overview of the LOT project and briefly discusses all mentioned modelling issues. At the end of the paper LOT is validated using full scale tests done at the STUVA (Studiengesellschaft für unterirdische Verkehrsanlagen, in English: Research Association for Underground Transportation Facilities) tests centre in Germany [2]. For more detailed information reference is made to www.vbk.tudelft.nl where most LOT reports are available

[1] Doctor, Ir., Delft University of Technology, 2600 GA Delft, the Netherlands.
[2] Doctor, Wuhan University of Technology, P.R. China & Delft University of Technology, the Netherlands.
[3] Ir., Woldekidan, Delft University of Technology, 2600 GA Delft, the Netherlands.
[+] Corresponding Author: E-mail m.huurman@tudelft.nl
Note: Submitted October 22, 2009; Revised November 28, 2009; Accepted January 14, 2010.

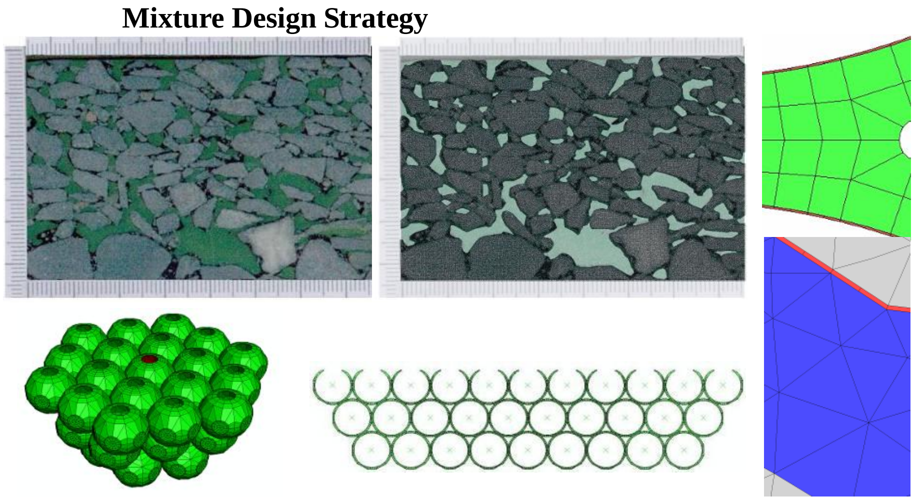

Fig. 1. Three Types of FE Models in LOT; 3D-idealized (Left Bottom), 2D-idealized (Mid Bottom), and 2D-photo Model with Original Photo (top). Impressions of Modelled Adhesive Zones in Blow-ups (Right).

on-line.

Three basic insights form the basis of the LOT mixture design strategy:

1 Pavements and pavement materials have a life expectancy that is larger than 10^5 load cycles in any realistic case. The damage that accumulates in a single load cycle is thus very small and negligible in structural response calculations for mechanistic design purposes.

2 The response of any structure depends on three pillars, i.e.; 1) structural geometry, 2) loading, and 3) material behaviour. (Boundary conditions translate into 1 or 2).

3 By respecting the three pillars phenomenological laboratory research may be brought up one level of scale by structural modelling, i.e. mixture performance follows from mixture component behaviour provided that mixture structural models are available and that insight into mixture loading exists.

On the basis of the above listed insights a simple and effective design strategy was chosen for LOT. In this strategy PA is modelled as a structure on the scale of individual stone chippings. Due to the choice of scale three material components are defined, i.e. mortar, stone, and stone-mortar adhesive zones. Insight into material component properties (mortar response and mortar and adhesive zone fatigue) is obtained by phenomenological laboratory research. Combined with insights into surface contact stresses this information is input for a PA structural model. The outputs of this model are, amongst others, in-mixture stress and strain signals. These signals, combined with knowledge of component damage development, allow the determination of PA service life. LOT is discussed in more detail elsewhere [3].

PA Structural Model

Three Models

Three types of models have been developed, i.e. 2D-idealised, 3D-idealised, and 2D-photo, see Fig. 1. Use is made of the ABAQUS FE platform and combined the models give complete insight into in-mixture phenomena. In the idealised models stone chippings are represented by perfect spheres. The 2D-idealised model is most practical and foreseen to serve as the mixture design tool in practice. By comparison of the 2D- and 3D-idealised models the effects of 2D modelling become known. Similar the effects of the idealized geometry are obtained by comparing the 2D-idealised and 2D- photo models. Adhesive zones are present in all models. These zones are 10μm thick and only visible in blow-ups, see Fig. 1.

Idealized Geometry

The most important assumptions implemented to generate the idealized structural geometry on the basis of real mixture properties are the following. The size of the perfectly round spheres that represent the stone chippings in the idealized models equals the average particle size (on basis of mass grading percentages) in the stone fraction (d > 2*mm*) of the mixture of interest. The thickness of the mortar film surrounding the spheres is determined on the basis of volumetric considerations. The distance between stone particles is determined by assuming hexagonal packing while respecting the void ratio in the represented PA mixture. Finally the geometry of the mortar film in the contact area is adjusted so that the distance between stone particles is properly reflected in the idealized models. Hereto it is assumed that mortar is squished away from the contact area to form a filled surrounding the contact area. Fig. 2 indicates that the fillet volume, V_2, is made equal to the volume of squished away mortar, V_1. The dimensions of the fillet are computed on the basis of 3D spheres.

Photo Model Geometry

The geometry of the photo models is copied from photos of real PA cross-sections. Use is made of photos of in-service PA made by the Danish Road Institute [4] and of photos of the PA mixtures in the validation tests discussed at the end of the paper [3]. For the transformation of photo to structural model first the outlines of voids and stones are defined by human action. It is not easy to distinguish between clogging dirt in the voids of in-service PA and mortar. As a result the generation of a structural model on the basis

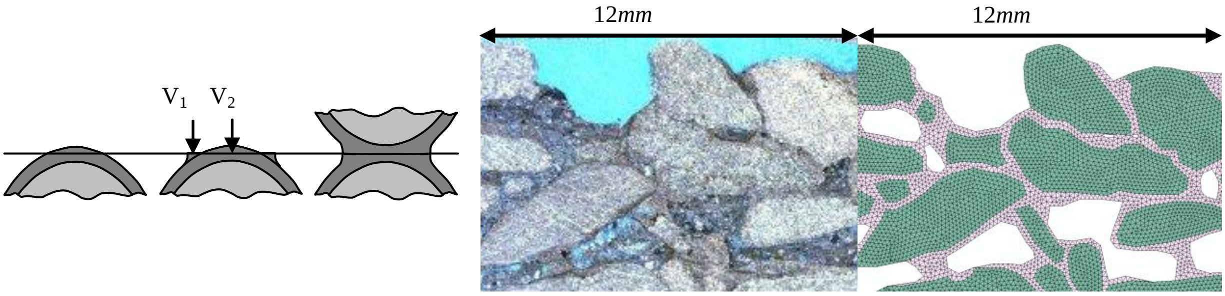

Fig. 2. Left: Fillets form Around the Contact Areas so That $V_1 = V_2$ in a 3D World. Right: Detail of Photo and Detail of Derived Model (Right).

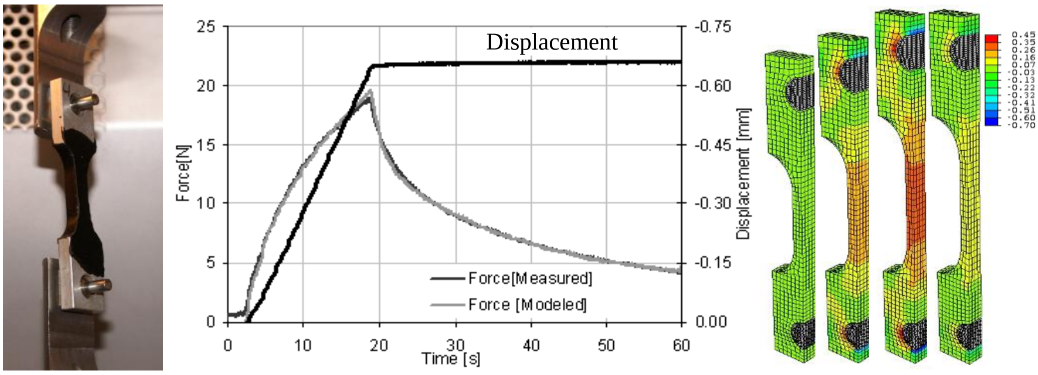

Fig. 3. DTT Relaxation Test, Results, and Back Calculation and Model of the Test.

of a photo of in-service PA is not 100% objective. This is illustrated in Fig. 2 which gives a detail of a typical photo model and related photo of in-service PA.

Material Component Behaviour

Involved Materials

The LOT laboratory test program considered mortar consisting of; Cariphalte XS SBS (Styrene-Butadiene-Styrene) modified bitumen, Wigro 60 limestone filler with 25wt% hydrated lime and sand < 0.5*mm*. Two types of stone were considered; a hard Sandstone and Greywacke. The four PA mixtures involved in the full-scale validation test, discussed later in this article, are produced using the exact same raw materials as tested. To obtain insight into the effects of aging Short Term Aged, STA (1½ *hrs* in oven at mixing temperature) and Long Term Aged, LTA (1000*hrs* protocol involving air, UV (UltraViolet Light), temperature, and moisture [5]) materials were tested. The effects of water ingress were tested by submerging specimens to water under vacuum for 1*hr*. All specimens are on a scale that equals the scale of their PA application, i.e. relevant specimen dimensions vary from approximately 3 to 6*mm*.

Paper size does not allow to discus the test program in detail, reference is made to [3, 6]. Hereafter an overview of the test program is discussed.

Mortar Response

In LOT a 2-term Prony series constitutive model is used to model mortar response.

$$E(t) = E_0 \cdot \left(1 - \alpha_1 \cdot \left(1 - \exp\left(\frac{-t}{t_1}\right)\right) - \alpha_2 \cdot \left(1 - \exp\left(\frac{-t}{t_2}\right)\right)\right) \quad (1)$$

Where:
$E(t)$ = Time dependant stiffness (*MPa*),
E_0 = Instantaneous stiffness (*MPa*),
α_1, α_2 = stiffness reduction parameters,
t = time (*s*), and
t_1, t_2= time constants (*s*).

The five stiffness parameters (E_0, α_1, α_2, t_1, and t_2) can be determined accurately by utilization of a relaxation Direct Tension Test (DTT). Such tests are done on bone shaped mortar specimens, see Fig. 3. In total 125 DTTs were done (56 STA, 17 water subjected STA, and 52 LTA) at temperatures ranging from -10 to 20℃. The elongation rate varied from 0.001 to 300*mm/min*. The bone shaped specimen sitting between the end caps is 20*mm* high. Specimens have a cross section of 6 × 6mm^2 over the central 10*mm*.

Fig. 3 gives typical DTT relaxation test data. The figure indicates that the 2-term Prony series model is very capable in describing the response. It is noted that a FE model of the DTT is used to help interpret the measured data. This model takes the test geometry into account, so that the measured response can be related solely to material behaviour. To generalize the DTT relaxation test data a total of 10 frequency sweep tests were done on STA, STA water subjected, LTA, and LTA water subjected specimens. Three types of frequency sweep tests were done; 6× Dynamic Shear Rheometer, DSR G* test, 2× Dynamic Material Analyzer, DMA dual cantilever E* test, and 2× Dynamic Material Analyzer, DMA uniaxial E* test. For the DSR G* and DMA uniaxial E* measurements use was made 20*mm* high mortar columns with a 6*mm* diameter. This test was specially designed for LOT. An impression of the involved tests is given in Fig. 4.

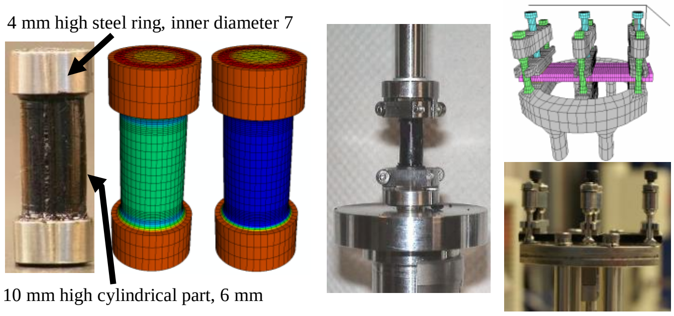

Fig. 4. From Left to Right; Specimens for DSR G* and DMA Uniaxial E* Testing, FE Modelling of DMA Uniaxial E* Tests, Specimen Mounted in DSR and DMA Dual Cantilever E* Test Model and Photo.

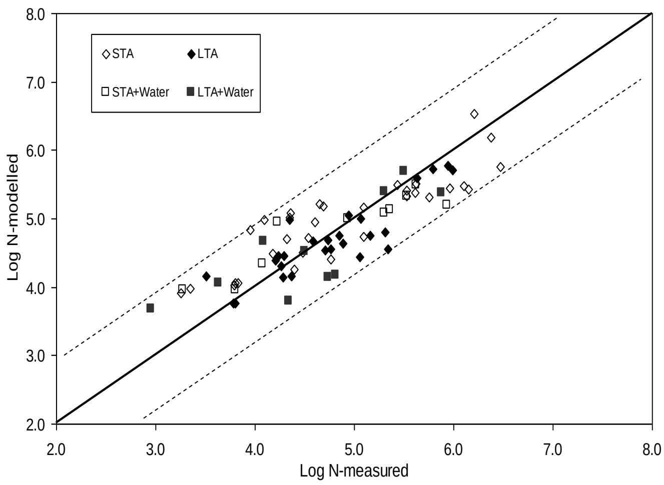

Fig. 5. Indication of Fit between Measured Data and the Dissipated Energy Fatigue Model.

Fig. 4 indicates that FE models are again used to compensate for geometrical issues so allowing relating the measured response to material behaviour solemnly. Combined the tests resulted in the following:

- The VE (ViscoElastic) 2-term Prony series parameters of STA, STA water subjected, LTA, and LTA water subjected mortar are known over a wide range of temperatures and frequencies. This allows for PA mixture simulations on meso scale, i.e. LOT simulations.
- Water subjection has no significant effect on mortar response behaviour.
- The response behaviour of mortar changes due to aging.

For a more detailed discussion of the mortar response measurements and parameter determination reference is made to [6, 7].

Adhesive Zone Response

An estimate of the 10 µm thick adhesive zone stiffness is made by consideration of the mortar E* and G* measured in frequency sweep tests (see section 4.2) by application of Eqs. (2) and (3):

$$k_n = E^*/0.01mm \text{ and } k_s = G^*/0.01mm \quad (2,3)$$

Where:
k_n = adhesive zone normal stiffness(MPa/mm) and
k_s = shear stiffness(MPa/mm).

Mortar Fatigue

DSR mortar fatigue tests have been done on mortar column specimens shown in Fig. 4. In total 78 DSR shear fatigue tests were performed on STA, STA water subjected, LTA, and LTA water subjected specimens. Tests were performed at 10 and 40Hz at temperatures of 0 and 10°C in torque controlled mode. In the fatigue tests the specimens are subjected to oscillatory torque while measuring both rotational deformation and phase lag. Failure is indicated by a smooth but sudden increase of both deformation and phase lag.

The fatigue data was best described by a model that relates the mortar fatigue life to the energy dissipated in the initial cycles. The model is given by Eq. (4). To allow regression on the total data set the model parameters n and W_0 are linearly related to temperature.

$$N_f = (W_0/W_{initial})^n \quad (4)$$

Where:
n = material constant,
W_0 = reference energy (MPa), and
$W_{initial}$ = Dissipated energy per cycle in initial phase (MPa).

The obtained fit of the model is visualized in Fig. 5, indicating a good fit. The mortar fatigue tests resulted in the following:

- The fatigue properties of STA, STA water subjected, LTA, and LTA water subjected mortar are known at relevant temperatures. This allows for the determination of the service life of mortar bridges on the basis of in-mixture stress signals, i.e. interpretation of LOT simulation results.
- The fatigue behaviour of STA mortar differs strongly from the behaviour of LTA mortar.
- A much smaller difference is observed between water subjected specimens and specimens that were not subjected to water.

Reference is made to [6, 8, 9] for more detailed information about testing and parameter determination.

Adhesive Zone Damage

Initial adhesive zone damage tests were developed at the Wuhan University of Technology [10, 11] and further optimized during the LOT project. A good impression of the damage development in the stone-bitumen adhesive zone is obtained by performing destructive force controlled DSR and DMA tests on specimens that consist of two stone columns “glued” together by a thin bitumen film, see Fig. 6.

To obtain specimens stone boulders of are sawn into slices with a thickness of approximately 10mm (see Fig. 7(a)). Sand-blasting of the slices using a fixed protocol guarantees that stone morphology of specimens does not vary too much. After sandblasting stone columns are drilled from the slices (see Fig. 7(b)). The stone columns are then cleaned in boiling distilled water for 15 minutes and dried in an oven at a temperature of 105°C for half an hour. Finally the DSR is applied for gluing two columns together at a

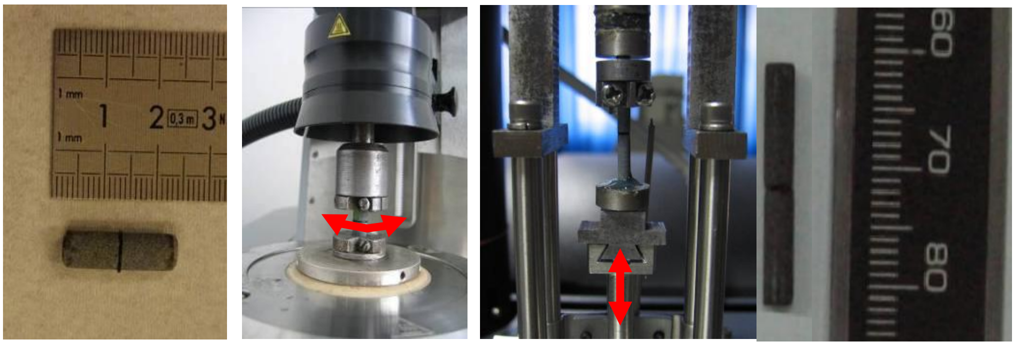

Fig. 6. Stone Column Specimens for DSR (Left) and DMA (Right). Specimens Mounted in Machines and Indication of Loading DSR (Mid Left), DMA (Mid Right).

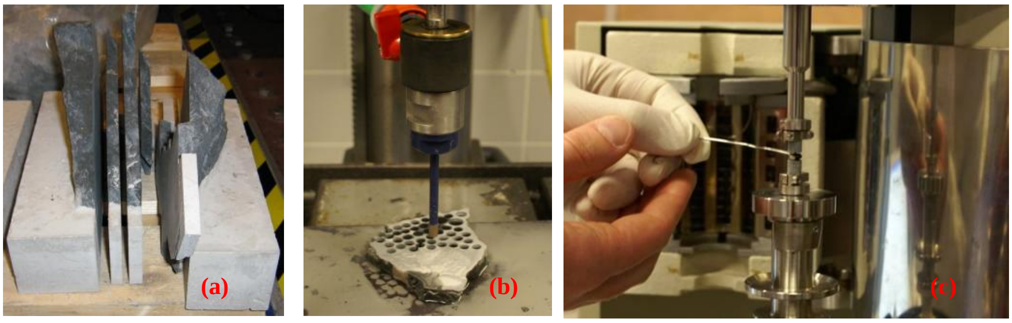

Fig. 7. Impressions of Specimen Preparation (a) Sawed Boulder Slices, (b) Drilling Cores, and (c) Gluing two Columns into a Single Specimen Using the DSR.

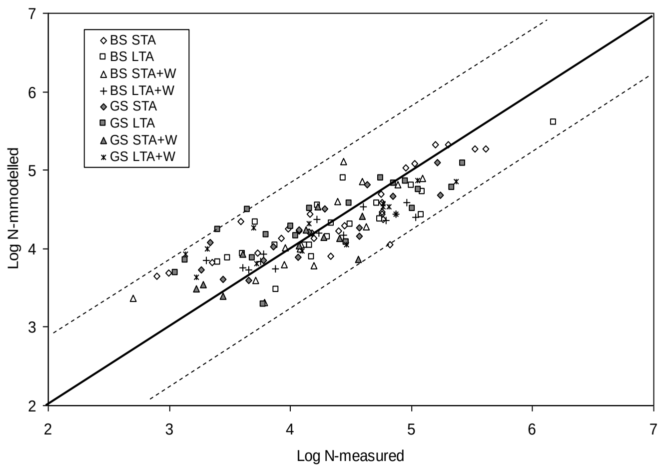

Fig. 8. Impression of the Adhesive Zone Damage Model; Combined DSR Dynamic, DMA Dynamic, and DMA Static Data.

temperature of 175°C (see Fig. 7(c)). The DSR is set to obtain specimens with a 15μm bitumen film between the glued columns. More details on the preparation of stone columns can be found elsewhere [6].

Tests are done on STA, LTA, STA water subjected, and LTA water subjected specimens. Two types of stone are involved, Sandstone and Greywacke. A total of 95 destructive DSR tests are executed. In these tests a sinusoidal torque with a frequency of 10*Hz* is applied to the specimen. In the DMA two types of tests are performed. In total 55 dynamic DMA tests were performed in which a 10*Hz* haversine tension signal is applied. Also 16 static DMA tests were performed. In these later tests a constant tensile stress is applied to the stone columns.

Each of the tests was prolonged until fracture of the stone column specimens. Results of the tests were described by the equations below. Complete failure is indicated when D reaches the value of 1. Tests were done at temperatures ranging from -10 to 20°C. To allow regression on the total data set the model parameters ϕ, n_0, and W_0 are linearly related to temperature.

$$\dot{D} = \left(\frac{\sigma_{et}}{\sigma_0}\right)^{n_0} \text{ for } \sigma_{et} > 0\text{ , } \dot{D} = 0 \text{ for } \sigma_{et} \le 0 \text{ with } \sigma_{et} = \sigma_n + \tau/\tan\phi \quad (5)$$

Where:

$\dot{D}$ = Rate of damage accumulation (1/*s*),

σ_{et} = equivalent tensile stress, i.e. tensile stress in the case of zero shear (*MPa*),

σ_n = adhesive zone normal stress (*MPa*),

τ = adhesive zone shear stress (*MPa*),

ϕ = riction angle (degr.),

n_0 = model parameter, and

σ_0 = reference stress (*MPa*).

Fig. 8 gives a visual impression of the obtained model fit. The adhesive zone damage tests resulted in the following:

- The damage properties of STA, STA water subjected, LTA, and LTA water subjected adhesive zones are known for relevant temperatures for both Sandstone and Greywacke. This allows for the determination of the service life of adhesive zones on the basis of in-mixture stress signals, i.e. interpretation of LOT simulation results.
- With aging the fatigue strength performance of adhesive zones improves.

Water subjection reduces the strength of adhesive zones, however,

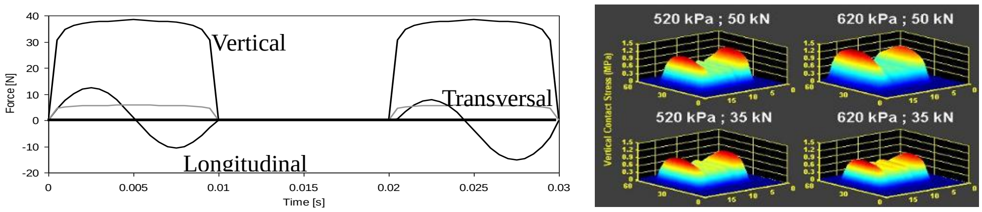

Fig. 9. Example of Applied Load Signals (left) and Measurements by de Beer [16] (Right).

Fig. 10. Left to Right; Test Slab Construction Using Regular Road Building Equipment, Retrieval of Test Slabs, and View on STUVA's APT.

Table 1. Top Layer Mixture Composition.

Mixture	A	B	C	D
Aggregate	Greywacke	Greywacke	Sandstone	Sandstone
Bitumen Content, %	6.3	5.2	6.6	5.4
Void Content (Desired/Achieved), %/%	20/24.9	26/27.4	20/21.6	26/25.0

effects remain limited.

Reference is made to [6, 8, 9] for more detailed information about testing and parameter determination.

Stone Behaviour

In LOT stone chippings are modelled rigidly, no damage can develop in the modelled stones.

PA Surface Load Model

The PA surface load model was first developed to load meso scale models of surfacing seals [12-15]. The model is based on contact pressure measurement data reported in literature [16, 17]. On the basis of these measurements force signals for individual surface stones are derived, see Fig. 9. As shown, surface stones are loaded by vertical, transversal, and longitudinal forces during a tyre passage. Close observation of Fig. 9 indicates a difference in the longitudinal load signal introduced by the first and second tyre. This is because the first wheel is free rolling, while the second wheel is driven.

Validation of LOT

Full Scale Test

Validation tests should be as realistic as possible and take place in a controlled environment. The circular Accelerated Pavement Test, APT, at STUVA in Cologne, Germany [2, 18] fulfilled all demands for LOT validation. It is an indoor APT allowing for a constant and controlled pavement temperature of 10℃. It has a circular track, allowing a realistic speed of 80*km/h* and introducing some additional shear so enhancing the development of ravelling. The APT machine allows for the application of real loads, i.e. a 50*kN* wheel load applied via a Goodyear 425/65R22.5 G286A 165KL TL super singe tyre inflated to 850*kPa*.

STUVA's APT has a 10*m* diameter, i.e. the test section has a total length of about 31.5*m*. The test section consists of 16 parallelograms. Ordinary road building equipment was used to construct the test sections, see Fig. 10. Four double layer PA mixtures were tested. In all cases the lower layer consisted of PA 11/16*mm* with a void content of 18.8 and 4.2% bitumen. Variations were in the PA 4/8*mm* top layer, see Table 1. All involved mixtures were produced using the material components (raw materials) involved in the laboratory test program discussed earlier.

To eliminate dynamical effects the founding base of the APT was levelled with great care in advance of the test. Simulations by the University of Eindhoven indicated that tyre load fluctuations due to dynamical effects remained within limits [19].

Results and Validation

A total of 700,000 wheel load applications have been applied to the four mixtures during the APT. Laser texture measurements by the German Bundesanstalt für Strassenwesen (BASt) gave detailed pictures of the surface texture, see Fig. 11. From these measurements the "Integral der Differenzen" or integral of differences can be computed [18] which is an objective measure for ravelling damage.

Ravelling damage was also assessed by detailed inspection of the PA surface at the STUVA APT by a certified Dutch visual inspector. The results of this visual inspection were expressed in a score. Fig. 11

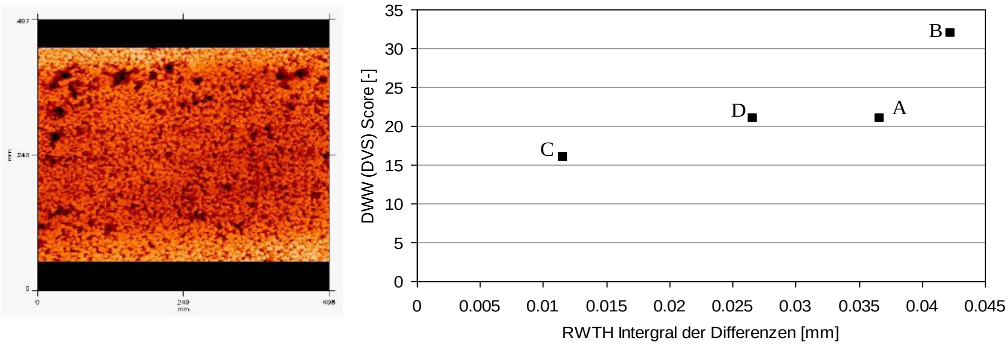

Fig. 11. Laser Texture Measurement by BASt and Comparison between Ravelling Damage as Per Texture Measurement (Horizontal Axis) and as Per Visual Inspection (Vertical Axis), Letters Indicate the Mixtures.

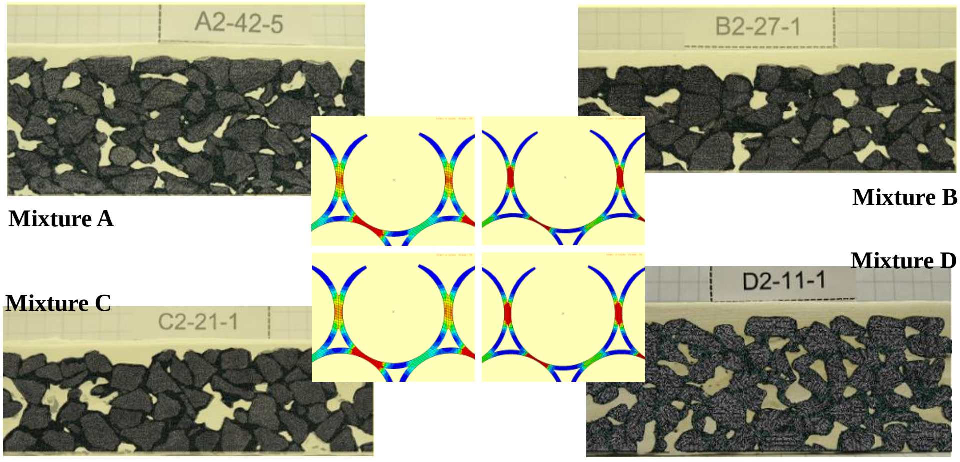

Fig. 12. Impression of the Geometry of the 2D-idealised Models Generated to Validate LOT on the Basis of the STUVA APT Test (Centre) and Photo Models of the in Situ Mixtures (Out Side).

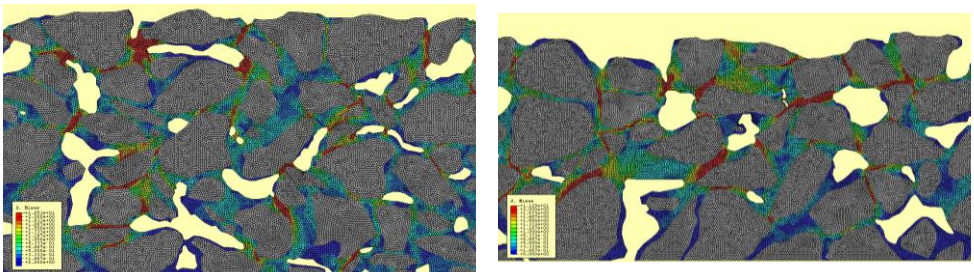

Fig. 13. Impression of LOT Photo Model Simulation Results for Mixture A (left) and B (Right). Both Plots Consider the Centre Part of Available Models Only, Colours Give an Indication of Stress.

gives an impression of the similarity between ravelling damage assessed per texture measurement and per visual inspection.

The surface load applied by the 50kN wheels that travel the circular track in the STUVA APT is complex. From other research [19] it is known that an increased shear stress in the order of 0.3MPa is generated as a result of the circular wheel path. An additional shear surface loading was therefore applied in the validation calculations. The material component properties applied in the validation simulations followed directly from the discussed laboratory research.

LOT was firstly validated on the basis of 2D-idealised models generated on the basis of mixture design inputs. The results of this validation were so promising that it was decided to extend the project. Four tested parallelograms were brought to the Delft University of Technology for two purposes. The first was to verify that the mortar in the tested mixtures is indeed the same as the mortar in the LOT laboratory research. Hereto additional laboratory tests were done on mortar retrieved from the slabs. Secondly the slabs were used to construct 2D photo models of the in situ mixtures tested in Germany.

It was shown that the mortar in the validation test has the same mechanical behaviour as the mortar in the LOT laboratory research. And, photo models of the in situ mixtures were made. Fig. 12 gives an impression of these photo models. Close observation of Fig. 12 shows that the photo models are plotted over the photo’s used to generate them.

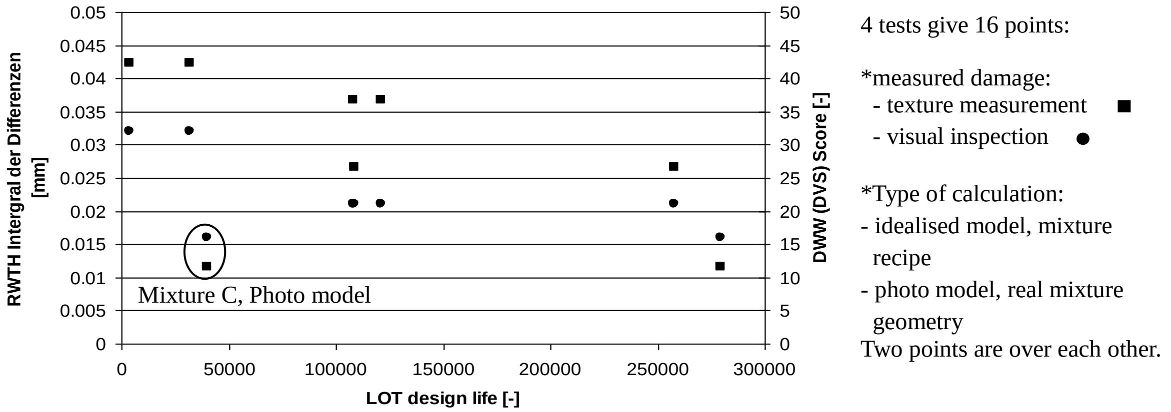

Fig. 14.. Graphical Impression of the Validation Results.

The smaller plots in the centre of Fig. 12 give an impression of in-mixture stresses under the passage of a STUVA wheel load as determined by simulation with 2D idealised models. Fig. 13 gives similar insights obtained by application of 2D photo models.

The in-mixture signals of stress and strain determined for both mortar bridges and adhesive zones can be translated into life expectancy by application of the mortar fatigue and adhesive zone damage models discussed earlier. The damage observed in the STUVA may be compared to the obtained theoretical life expectancy to validate LOT. A visual impression of validation results is given in Fig. 14. This figure gives the LOT determined life expectancy on the horizontal axis plotted against ravelling damage in the STUVA tests on the vertical axes. Circular markers are used for damage determined via visual inspection and plotted against the right vertical axis. Damage determined from laser texture scans is plotted against the left vertical axis by rectangular markers. It is noted that the figure indicates the results of validation on the basis of the 2D idealized models as per mixture design and validation on the basis of the photo models of the in situ mixtures.

In a perfect world ravelling damage determined by visual inspection would be fully equivalent to damage detected by texture measurements, so that the circular markers would fall over the rectangular markers. Furthermore the more damage accumulated during the APT test the shorter the mixture’s service life. Combined this would lead to data points sitting on the diagonal from the upper left to lower right corner of Fig. 14.

As shown by Fig. 14 most data points are fairly close to the described diagonal, indicating the validity of LOT. This is especially true when one appreciates the difference between visual inspection and texture measurements. As indicated, however, results obtained by the photo model of mixture C do not follow the general trend. The reason for this is unknown; however the most obvious explanation is that a weak spot in mixture C was used to come to the mixture C photo model.

Conclusions

The following conclusions have been drawn on the basis of the LOT project.

* It is possible to make use of meso scale mechanics to get insight into asphalt concrete mixture behaviour and performance.
* Tests required to obtain the mechanical properties of various mixture components are feasible and available.
* Insight into the tyre surface loading with ample detail is available from other research and literature.
* LOT model predictions are in good agreement with observed PA performance, indicating that the chosen approach is not only feasible but also in good agreement with material performance in the field.
* The Accelerated Pavement Test at STUVA was an excellent way to validate LOT.
* In the STUVA APT non mechanical effects such as the effects of water subjection, chemical attack, aging, etc. are absent. The development of ravelling in that test thus indicates that ravelling may be introduced by the sole effects of repeated mechanical action, i.e. fatigue.
* Meso scale mechanics will enable performance based design of composite road building materials in the near future. It is shown that a meso scale mechanistic mixture design approach gives insight into in-mixture phenomena taking place during tyre passages. On the basis of these insights the structure of, and raw materials used in a mixture may be optimized to obtain better performance, i.e. mechanistic performance based mixture design.
* Combined the above indicates that the mechanistic design of silent porous surfacing layers is feasible today. This may contribute to the introduction of durable and silent road surfacings on a wider scale.

Acknowledgement

The DVS is acknowledged for funding the project and for their trust in involved researchers. Wuhan University of Technology, Eindhoven University of Technology, STUVA, Heijmans, BASt, ISAC, and RWTH Aachen are acknowledged for their kind cooperation with the Delft University of Technology.

References

1. Sandberg, U. and Esjmont, J.A., (2002).T*yre/Road Noise Reference Book*, Informex, SE-59040 Kisa, Sweden.
2. Hinthem, P. van, (2007). LOT-Rundlaufanlage, Construction and Transport of Asphalt Plates (In Dutch: Vervaardiging en Transport Psfaltproefplaten), *Report Number 060125*, Heijmans Infrastructuur B.V., the Netherlands.
3. Huurman, M., (2008). Lifetime Optimisation Tool, LOT, *Main Report, Report 7-07-170-1*, Delft University of Technology, the Netherlands.
4. Nielsen, C., (2006). Ravelling of Porous Pavements, Experimental Procedures, *Report*, Danish Road Institute, Hedehusene, Denmark.
5. Hagos, E.T., (2008). The Effect of Aging on Binder Properties of Porous Asphalt Concrete, *PhD Dissertations*, Delft University of Technology, the Netherlands.
6. Khedoe, R. and Moraal, J., (2007). Sample Preparation and Laboratory Testing for the LOT Research Program, *Report 7-07-170-4*, Laboratory of Road and Railway Engineering, Delft University of Technology, the Netherlands.
7. Huurman, M. and Woldekidan, M., (2007). LOT, Mortar Response; Measurements, Test Interpretation and Determination of Model Parameters, *Report 7-07-170-3*, Laboratory of Road and Railway Engineering, Delft University of Technology, the Netherlands.
8. Huurman, M. and Mo, L., (2007). Lifetime Optimisation Tool, Fatigue in Mortar and Adhesive Zones; Measurements, Test Interpretation and Determination of Model Parameters, *Report 7-07-170-2*, Laboratory of Road and Railway Engineering, Delft University of Technology, the Netherlands.
9. Mo, L.T., (2010). Damage Development in the Adhesive Zone and Mortar of Porous Asphalt Concrete, *PhD Dissertation*, Delft University of Technology, the Netherlands.
10. Mo, L.T., Wu, S., Huurman, M., Molenaar, A., and Cao, T., (2006). Damage Accumulation Model for Monotonic and Dynamic Shear Fracture of Asphalt-Stone Adhesion, *Theoretical and Applied Fracture Mechanics*, 46(2), pp. 140-147.
11. Mo, L.T., Huurman, M., Wu, S., and Molenaar, A., (2007). Finite-Element Analysis and Experimental Study on Tensile Fatigue Behaviour of Bitumen-Stone Adhesion, *Fatigue & Fracture of Engineering Materials and Structures*, 30(9), pp. 823-831.
12. Huurman, M., Scarpas, T., Kasbergen, C., and Milne, T., (2003). Development of a Structural FEM for Road Surfacing Seals, *International Conference on Computational & Experimental Engineering & Sciences (ICCES'03)*, Corfu, Greece, CD-ROM.
13. Huurman, M., Ven, M. van de, and Kasbergen, C., (2004). Material Modelling on Aggregate Scale? Road to the Future (in Dutch: Materiaalmodellering op Korrelniveau? Weg naar de toekomst), *CROW wegbouwkundige Werkdagen*, Ede, the Netherlands, CD-ROM.
14. Milne, T., Huurman, M., Kasbergen, C., and Scarpas, A., (2004). Prototype Behavioural FEM Model for Road Surfacing Seals, *International Conference on Computational & Experimental Engineering & Sciences (ICCES'04)*, Madeira, Portugal, CD-ROM.
15. Milne, T., (2004). Towards a Performance Related Seal Design Method, *PhD Dissertation*, University of Stellenbosch, South Africa.
16. Beer, M. de, Fisher, C., and Jooste, F., (1997). Determination of Pneumatic Tyre/Pavement Interface Contact Stresses under Moving Loads and Some Effects on Pavements with Thin Asphalt Surfacing Layers, *8th International Conference on Asphalt Pavements*, Vol. 1, pp. 179-227, ISAP, Seattle, USA.
17. Groenendijk, J., (1998). Accelerated Testing and Surface Cracking of Asphaltic Concrete Pavements, *PhD Dissertation*, Delft University of Technology, the Netherlands.
18. ISAC, Institut für Straßenwesen Aachen, (2007). *RWTH Rheinisch Westfälische Hochschule Aachen*, *Lifetime Optimisation Tool (LOT),* Schlussbericht, (in German), Aachen, Germany.
19. Lopez, A. and Stehen, R., (2007). Prediction of Tyre/Road Contact Stress Distributions, *Report DCT 2007.106*, Dynamics and Control Group, Eindhoven University of Technology, Eindhoven , the Netherlands.