# SBS Polymer Modified Base Course Mixtures for Heavy Duty Pavements

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## ABSTRACT

Polymer Modified Bitumen (PMB) is often used to improve the resistance to cracking and rutting of asphalt pavements. Although the benefits for application in top layers have been shown in many cases, PMBs are rarely used in base layers. A joint research programme was initiated between Delft University of Technology and Kraton Polymers Research to study the effects of different types of SBS modification in a base course asphalt mix. The study entails binder testing, asphalt mix testing and material modelling. Based on the binder test results, six PMBs were selected for evaluation in a base course asphalt mix. A base course mix with non-modified 40 pen bitumen was used as reference. The asphalt mix testing included monotonic uniaxial compression and tension tests. The polymer modified mixes showed a very good performance compared to the non-modified reference, particularly in the tension test. Also four point beam bending fatigue tests were carried out which supported the outcomes of the monotonic tension tests. Based on the fatigue test results an endurance strain limit for both the reference mixture as well as two polymer modified mixtures was derived. The endurance tensile strain limit for the reference mixture was 50 μm/m while for one of the polymer modified mixtures it was as high as 80 μm/m. Also the consequences of these endurance limits on thickness design are presented in the paper. The results until date have shown that polymer modification can be an effective measure to extend pavement life and to reduce life cycle costs.

**Keywords:** modified binders, polymers, mechanical properties, performance testing

## 1. INTRODUCTION

Block copolymers of the Styrene-Butadiene-Styrene type have been applied since the seventies of the past century to improve the durability of mainly asphalt top layers. Many studies and case examples have been generated which show the effect of SBS modification on the resistance to cracking (fatigue and thermal) and rutting. SBS accounts for at least 65% of the global polymer modified asphalt market.
The effects of modified base courses on the performance of the total asphalt pavement is however an area that has hardly been explored. A full-depth polymer modified pavement should bring advantages in terms of durability of the total pavement as well as the possibility to construct thinner pavements. Improving the performance of the traditionally non-modified base courses could lift the overall quality of the asphalt pavement to new levels and to an improved economy.

In order to investigate this opportunity a joint research programme has been initiated between Kraton Polymers Research and the Road and Railway Engineering. The study includes binder research, fundamental asphalt mix testing and design analyses.

## 2. BACKGROUND OF THE STUDY

After a fairly long incubation period Polymer Modified Bitumen (PMB) and Polymer Modified Asphalt Mixtures (PMA) have become one of the main solutions for the road building industry to construct more cost effective and better performing pavements. Especially in the last two decades the use of PMB has made a large impact, while its use is mainly restricted to the top layers.

Particularly for areas with heavily loaded pavements, both in terms of number and weight of the vehicles, and environmentally hostile conditions it may be worthwhile to consider full-depth polymer modified pavements. Also for so called perpetual pavements full-depth modification may provide a cost effective alternative. The study was set up to evaluate various polymer modified binders in a full-depth modified asphalt pavement in comparison with conventional structures.

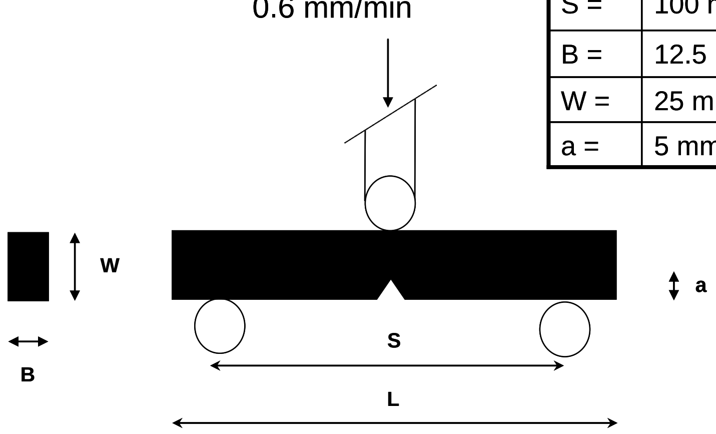
## 3. EXPERIMENTAL PROGRAMME

The study entails full depth modification of the asphalt pavement. This implies that not only the top layer(s) but also the asphalt base course should be polymer modified asphalt. In order to specifically address this part, a typical base course mix was selected. The base course mix is continuously graded asphalt with 40 pen base bitumen. First several binders with different SBS polymer grades were tested on low temperature cracking performance in a three point bending test for bituminous binders. This was done to rank the fracture toughness of these binders. Based on the outcome of this test a selection of binders was made to be used in the base course mixture to be evaluated.

The asphalt mixture testing was done using resilient modulus tests, fatigue tests and compression and tension tests, the results of which were used a.o. to develop an endurance limit for the reference as well as modified mixtures. The endurance limit is defined as the tensile strain level below which no fatigue will occur. These results were then used in a thickness design analysis to show the benefits in terms of reduced thickness that can be offered when using one of the SBS modified mixtures as investigated in this study.

### 3.1 Binder testing

The three point bending test on notched bituminous bars is a relatively new test that originally was used to test metals. In this test a notched bituminous bar is loaded with a displacement rate of 0.6 mm/min until it breaks. This is done at low temperatures; at some point the force required for breaking the bar changes dramatically. This indicates the ductile-to-brittle transition point. The dimensions are given in figure 1.




| | |
|---|---|
| L = | 120 mm |
| S = | 100 mm |
| B = | 12.5 mm |
| W = | 25 mm |
| a = | 5 mm |

Figure 1. Dimensions of the three point bending test

Different requirements can be distinguished for a PMB to be used in base course asphalt:

- A high stiffness is required to give the asphalt mixture a large load-spreading capacity. This implies that a relatively hard base bitumen should be used and hence for modification. The viscosity of the PMB should be looked at carefully when selecting SBS grade and content.
- A hard bitumen generally contains less maltenes; this means that less “solvent” is available. This should also be considered when selecting the SBS grade and content.
- The PMB should give the asphalt mixture a high resistance to cracking and permanent deformation.

Various SBS grades have been tested; from low molecular weight linear grades to high molecular weight radial grades. Also some experimental polymers specifically designed for this application have been tested.

Polymer contents of 3%, 6% and 7.5% were tested; it soon became clear that 3% SBS was not sufficient to bring the cracking performance at the desired level. This is in line with previous experiences; a continuous polymer rich phase is needed to get significantly improved resistance to cracking. This continuity of the polymer rich phase occurs generally from polymer contents of 5% and higher (depending on the polymer grade and the base bitumen). For the reasons mentioned above it was decided to apply 6% and 7.5% polymer content.

Due to this relatively high polymer content the higher molecular weight grades were no longer feasible because of workability. These grades were abandoned and focus was put on the experimental and low molecular weight grades.

### 3.2 Mixtures tested

The mixtures tested are so-called stone asphalt concrete 0/22 (maximum aggregate size 22 mm) mixtures. In the reference mixture a 40 pen binder was used. It is a standard base course mixture, designed according to the Dutch specifications. This reference mixture is called mixture 40 in the paper. The polymer modified mixtures had the same volumetric composition, with a binder content of 4.6% (w/w) and a voids content of the compacted mixture around 5%. Together with the reference mixture six SBS modifications were tested in the mixture testing program. The mixtures with SBS modified binders are coded as mixture 41, 42, 43, 45, 46 and 47.

### 3.3 Test program on the mixtures

The tests performed on the mixtures were repeated load indirect tension tests to determine the mixture stiffness in relation to temperature and loading frequency. Furthermore tension and compression tests were performed and finally 4 point bending, displacement controlled fatigue tests were performed on three mixtures [4, 5, 6, 7].

*3.3.1 Mixture stiffness*

Stiffness master curves were determined using the repeated load indirect tension tests (ITT), the four point bending beam fatigue test (4PBT, strain controlled) and ultrasone testing (UPV). Furthermore the modulus was determined from the initial part of the stress – strain curve as determined by means of the monotonic tension and compression tests ($E_t$ resp $E_c$; this modulus is a tangent modulus). Some test results are shown in table 1.

Table 1. Mixture stiffness as obtained by means of different test methods at 20 $^0$C

| | 4PBT, 8Hz, fatigue (initial) | 4PBT, 8Hz, at 50 µstrain | ITT, 8Hz, loadlevel: $^1$=800N $^2$=1000N | $E_t$ at 1 %/s | $E_t$ at 0.1 %/s | $E_c$ at 1 %/s | $E_c$ at 0.1 %/s | UPV |
|---|---|---|---|---|---|---|---|---|
| mixture | [MPa] | [MPa] | [MPa] | [MPa] | [MPa] | [MPa] | [MPa] | [MPa] |
| 599-40 (= 40) | 8871 | | 13368$^1$ 12513$^2$ | 11701 | 6473 | 7028 | 3757 | 27259 |
| 604-41 (= 41) | 10124 | 11018 | 13991$^1$ 12630$^2$ | 14468 | 6591 | 6161 | 3709 | 26485 27773 |
| 602-42 (= 42) | 10801 | | 11329$^2$ | 12660 | 5643 | 7714 | 3319 | 29014 |
| 45 | 8154 | 8502 | 10378$^2$ | 10046 | 4254 | 4029 | 2474 | 24831 |
| 48 | 9940 | 9544 | | | | | | 28501 |

Table 1 shows that the stiffness modulus seems to be dependent on the test method used. It seems that the ITT method as well as the UPV method results in very high values. Furthermore the big difference between the modulus in tension and compression ($E_t$ vs $E_c$) is remarkable.
Later on in this paper, the results 4PBT initial stiffness values obtained during the fatigue tests performed on mixtures 599-40, 604-41 and 602-42 will be used for pavement design analyses.

*3.3.2 Monotonic tension and compression tests*

In soil mechanics, the shear resistance of soils and granular materials is usually represented with the Mohr- Coulomb diagram by which the cohesion and angle of the material as a function of gradation, moisture content, degree of compaction etc can be determined. A similar approach was used to characterize the reference and modified mixtures. The difference however is that instead of triaxial tests, monotonic tension and compression tests were used to characterize the failure behaviour of the mixtures. Therefore tension and compression tests were carried out at various temperatures and loading speed in order to capture the temperature and load speed dependency of the tensile and compressive strength.

The monotonic uni-axial tests (figure 2) were done at 5°C, 20°C and 40°C. At each temperature strain rates were varied from 0.001 %/s to 1 %/s in tension and from 0.01 %/s to 5 %/s in compression to fully recognize the influence of temperature and strain rate on the material properties.
An example of the results of the tension and compression test performed on mixture 45 is given in figures 3 (tension test at 5 $^o$C) and 4 (compression test at 40 $^0$C).

It should be noted that in figure 3 the axial strains are positive and the radial strains are negative. In figure 4 the results from compressive stresses are given and the axial strains are negative and the radial strains are positive.

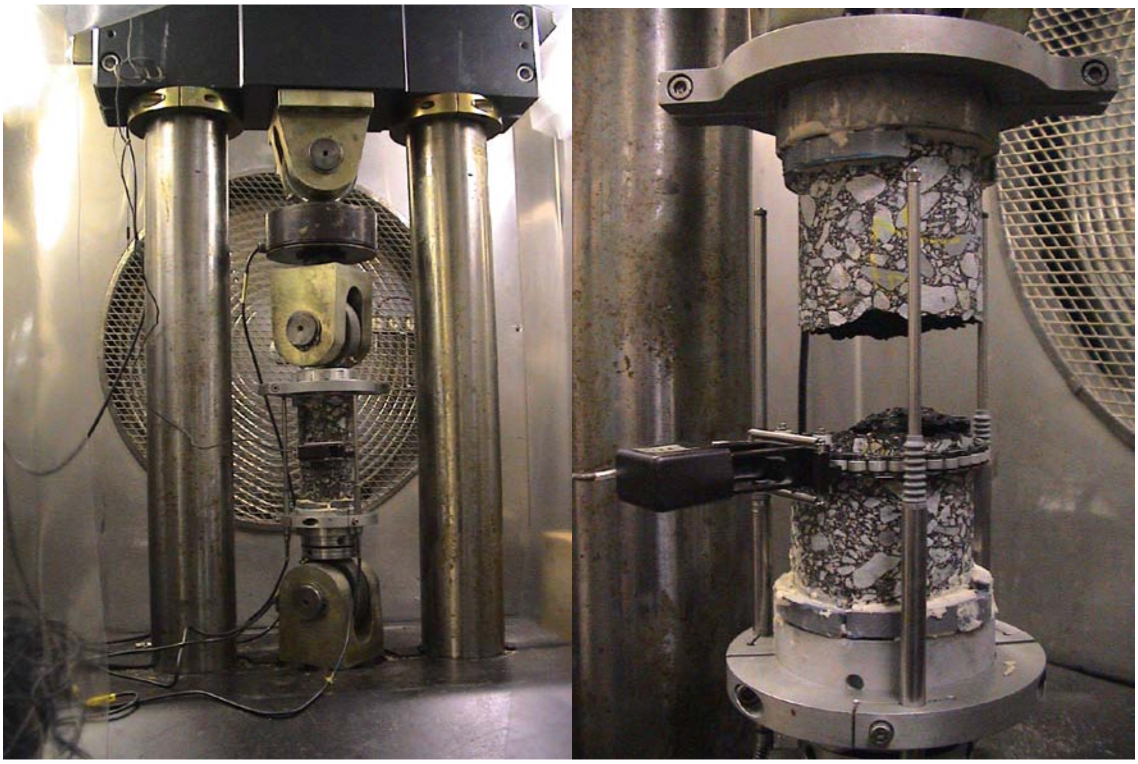


Figure 2a. Uni-axial tension test


Figure 2b. Uni-axial compression test

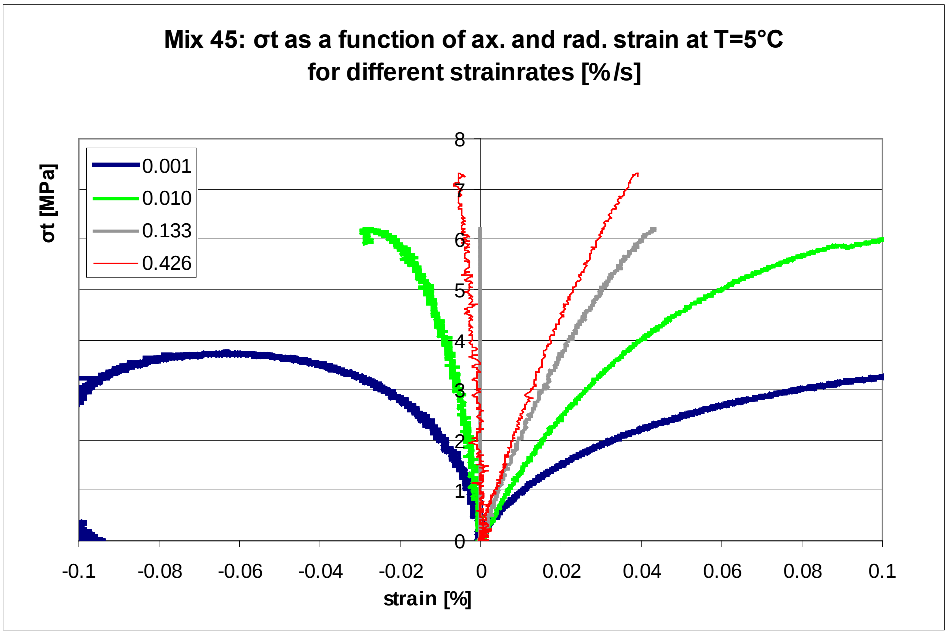



Figure 3. Tensile stress as a function of axial and radial strain at different axial strain rates for mixture 45 at T = 5°C

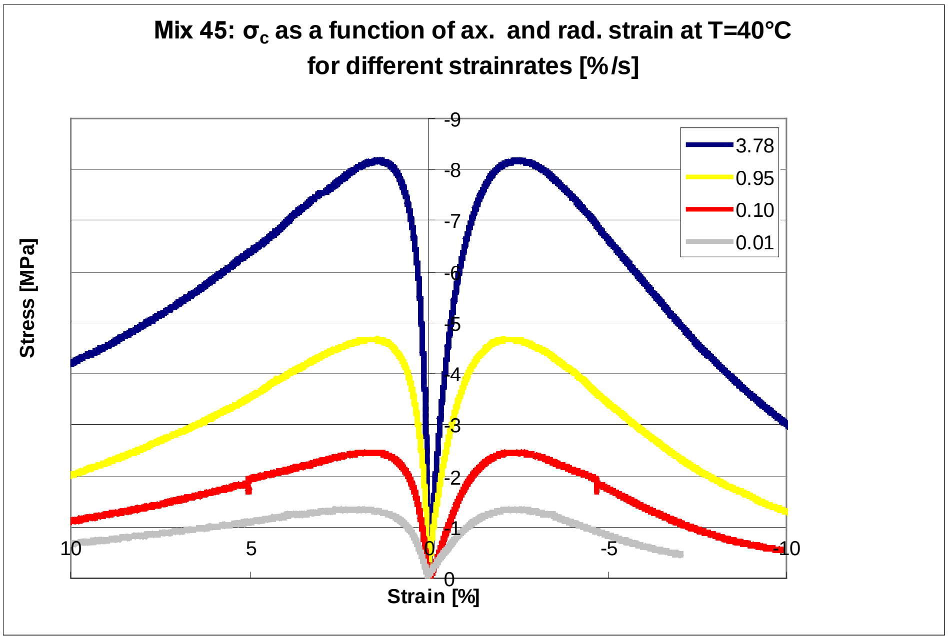



Figure 4. Compressive stress as a function of axial and radial strain at different strain levels for mixture 45 at T = 40°C

From these monotonic uni-axial tension and compression tests a number of parameters were calculated like strength, failure energy, E-moduli (tangent and secant), strain at peak, total strain and Poisson's ratio. Comparison of these properties at different temperatures and strain rates gives a good indication of the characteristics of the materials relative to each other.
Figure 5 e.g. gives a comparison of the tensile strength of the various mixtures at 40 °C while figure 6 gives such a comparison for the compressive strength at 5°C.

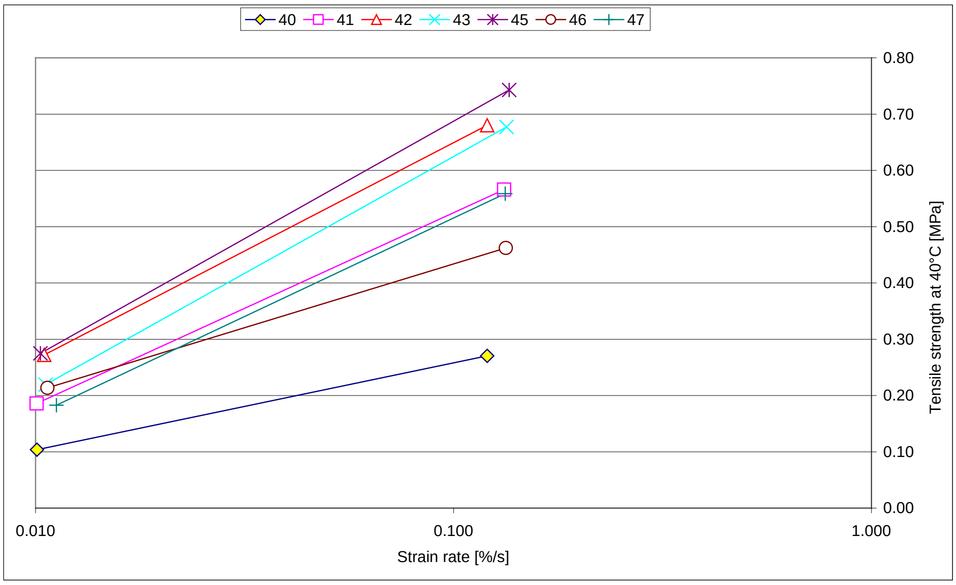



Figure 5. Tensile strength at 40°C as a function of strain rate

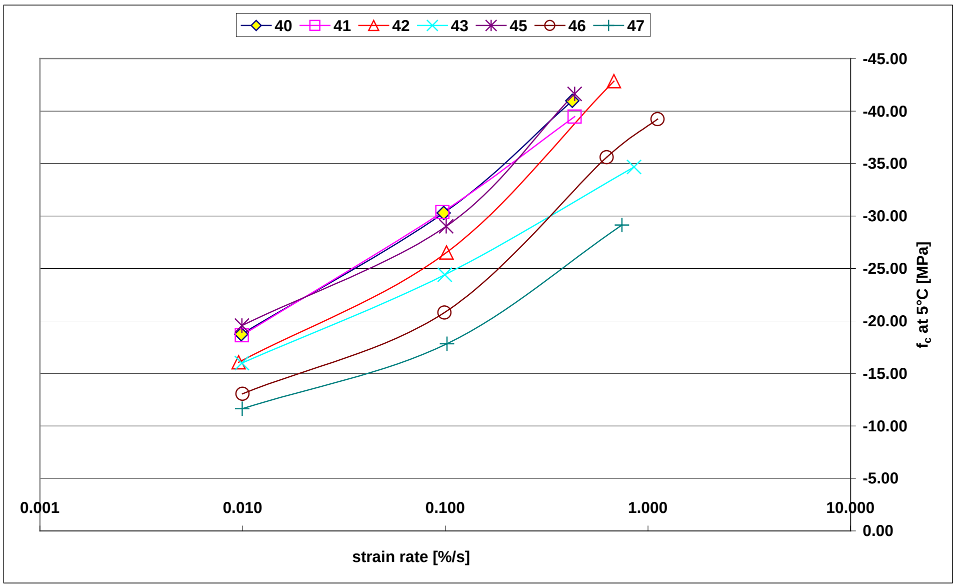



Figure 6. Compressive strength at 5°C as a function of strain rate

From figures 5 and 6 it becomes clear that it is possible that the ranking of the mixtures can change in relation to temperature and strain rate. It is clear that at 40°C the tensile strength of all SBS modified mixes is superior to the reference (40), but at 5°C the reference (40) shows higher compressive strength compared to most of the SBS modified mixtures.

If the tensile- ($f_t$) and compressive strength ($f_c$) of a material are known at a certain temperature and strain rate it is possible to estimate a failure line at these conditions by plotting these two (stress) points in the $I_1$-$\sqrt{J_2}$ plane, where $I_1$ is the first stress invariant (representing the normal stresses) and $J_2$ the second stress invariant (representing the shear stresses). In this way similar plots are obtained as the Mohr-Coulomb failure line [1, 2, 3].

Figures 7 and 8 show some of these response surfaces; they are given for a strain rate of 0.01 %/s and two extreme temperatures. The ultimate surfaces show that the modified binders improve the resistance to combinations of tensile ($I_1$ is positive) and shear stresses considerably compared to the reference, especially at higher temperatures. Figures 9 and 10 also contain the ultimate surfaces as determined for other types of asphalt mixtures and cement concrete.

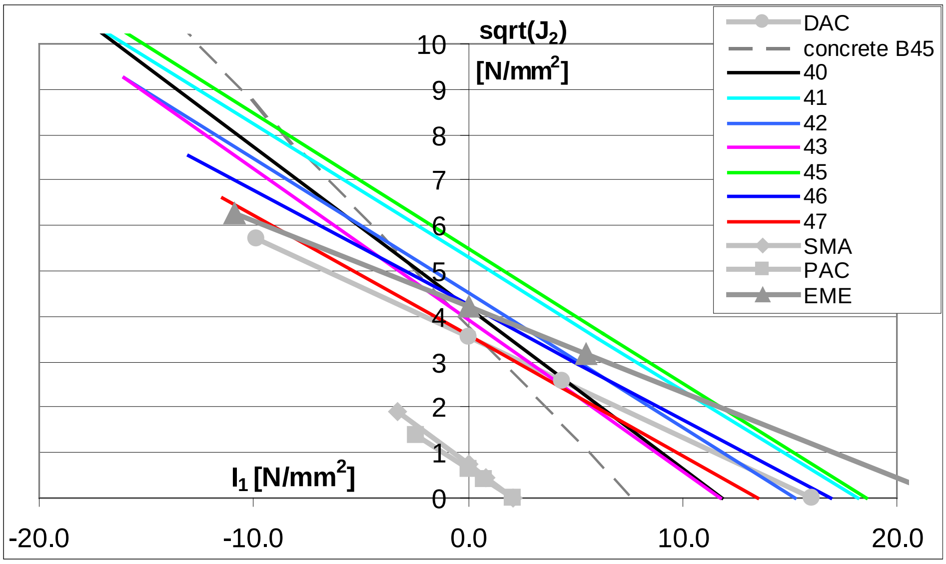



Figure 7. Ultimate slopes of the tested mixtures at T = 5ºC and strain rate = 0.01 %/s together with concrete, Dense Asphalt Concrete, Stone Mastic Asphalt, Porous Asphalt Concrete and base course mix EME (Enrobé à Module Elevé)

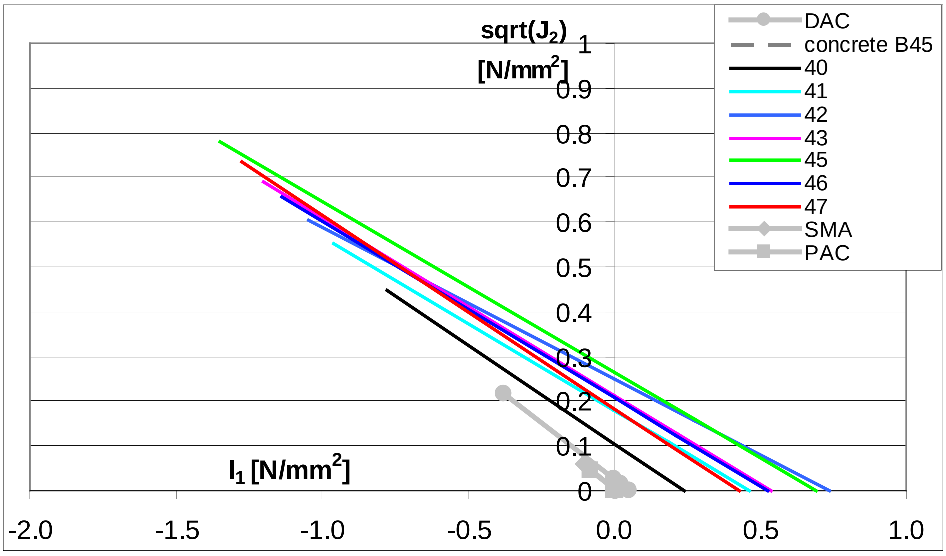



Figure 8. Ultimate slopes of the tested mixtures at T = 40ºC and strain rate = 0.01 %/s together with concrete Dense Asphalt Concrete, Stone Mastic Asphalt, Porous Asphalt Concrete and base course mix EME (Enrobé à Module Elevé)

It is recalled that:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \text{ and } J_2 = \frac{1}{2}(s_1^2 + s_2^2 + s_3^2) = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2\right]$$

Where: $\sigma_1$, $\sigma_2$, $\sigma_3$ = principle stress

*3.3.3 Fatigue testing*

On the reference mixture and 2 modified mixtures, 4 point beam bending tests were also performed. The tests were done at 20 $^o$C and a loading frequency of 8 Hz. Per mixture 8 fatigue tests at different strain levels were performed. The tests were done in the controlled displacement mode. Failure was defined as the number of load repetitions at which the mixture stiffness had reduced to 50% of its initial value. A full sinusoidal load was applied implying that the upper and lower edge of the beam were subjected to alternating tension and compression stresses.

The results are shown in figure 9. One will observe that the modified mixtures showed a superior fatigue behaviour when compared to the reference mixture.

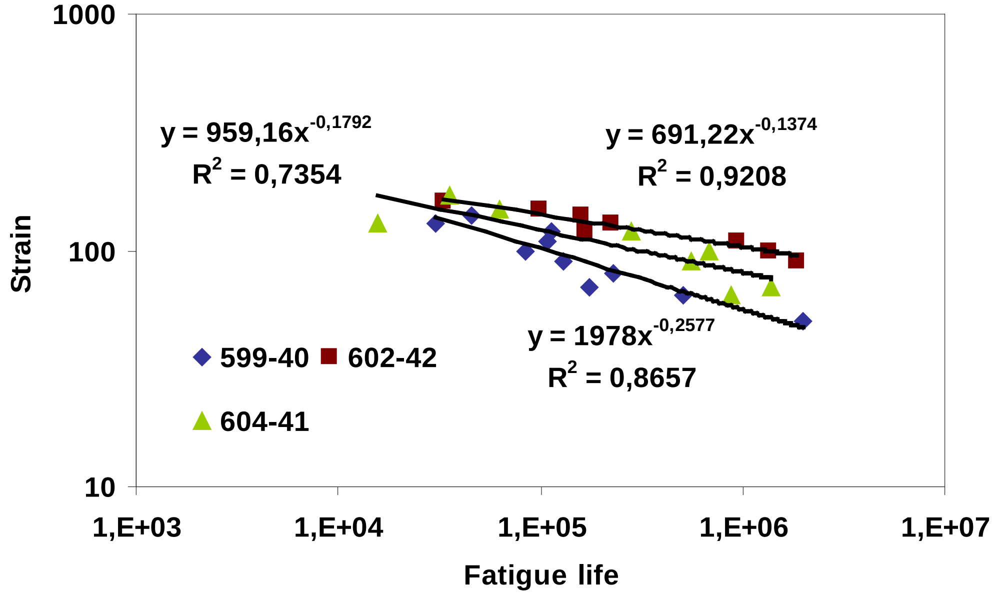



Figure 9. Fatigue test results on the reference mixture (here denoted as 599-40) and two polymer modified mixtures (denoted as 604-41 and 602-42).

## 4. ENDURANCE LIMIT

### 4.1 Calculation of $R_{limit}$

The principle of an endurance limit is used for many years in concrete pavement design. There it is hypothesized that when the ratio of occurring tensile stress over tensile strength is less than 0.5, no fatigue in a concrete pavement does occur. This has lead to research in the USA into the existence of such an endurance limit for asphalt mixtures. In the research reported in this paper such a limit has been established for the three mixtures for which fatigue data and results of monotonic tension tests were available.
First of all it will be described how the endurance limit was determined. Then it is shown how the endurance limit can be estimated for the investigated mixtures from monotonic tension tests and stiffness modulus tests.

In order to determine the endurance limit, the results of the tension tests and the fatigue tests were combined, As a first step the initial stress ratio $R_{initial}$ was introduced, which is defined as the ratio of applied initial stress and tensile strength of the specimen.

$$R_{initial} = \sigma_{initial} / f_t \qquad (1)$$

Where: $\sigma_{initial}$ is the peak value of stress [MPa] at the 50$^{th}$ cycle during the four-point bending fatigue test and $f_t$ is the tensile strength [MPa]. However, the tensile strength is dependent on the loading rate and temperature. From the available data, equation (2) could be developed which gives the tensile strength $f_t$ in relation to loading rate (strain rate) and temperature (T)..

$$f_t = a\left[1 - \frac{1}{1+\left[\dot{\varepsilon}\, e^{(b+\frac{c}{T})}\right]^d}\right] \qquad (2)$$

Where: a, b, c and d are the coefficients. The magnitude of these coefficients is given in table 2.

Table 2. Regression constants of the three asphalt mixtures

| Types of binder | Regression constants | | | | $R^2$ | No. of data points |
|---|---|---|---|---|---|---|
| | a | b | c | d | | |
| 599-40 | 5.05 | -87.02 | 26310 | 1.11 | 0.96 | 10 |
| 602-42 | 5.92 | -64.15 | 19880 | 0.75 | 0.93 | 10 |
| 604-41 | 5.50 | -70.99 | 21770 | 1.56 | 0.97 | 10 |

The tensile strength of the asphalt mixture at the temperature and loading rate that was used during the fatigue tests was calculated in the following way.

In the direct tension test the strain rate is constant. However, during the fatigue test the strain rate is not constant and follows a sine shape. In order to determine the loading rate during the fatigue test, the sine is converted into a triangle signal with the same maximum strain level and duration time, this is shown in figure 10.

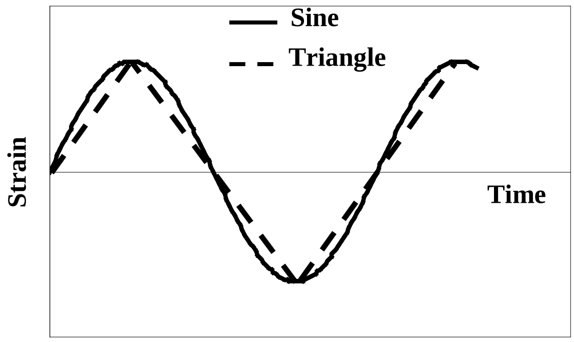



Figure 10. Conversion from a sine signal to a triangle signal

The strain rate of this alternating triangle signal is considered to be an acceptable approximation and can be computed as follows:

$$\dot{\varepsilon} = 4(\varepsilon \cdot f) \tag{3}$$

Where: $\varepsilon$ = strain amplitude [m/m],
$f$ = strain signal frequency, [Hz].

Using this approximation for the strain rate, the tensile strength $f_t$ at 20ºC is computed by using equation (2). Thus the initial stress ratio of applied stress and tensile strength in the fatigue test can be calculated. As a result, each fatigue life corresponds to a specific initial stress ratio, as shown in Figure 11. The relationships between $R_{initial}$ and $N_{f,50}$ of the three asphalt mixture have a similar tendency. In general, $N_{f,50}$ increases when $R_{initial}$ decreases. Taking into account the shape and the trend of the data points, the following regression equation can be used to simulate the *R*-*N* (initial stress ratio versus fatigue life) lines:

$$R_{initial} = R_0 - R_1\left(1 - e^{-aN}\right)^b \tag{4}$$

Where: $a$, $b$, $R_0$ and $R_1$ are regression constants, as shown in table 3.

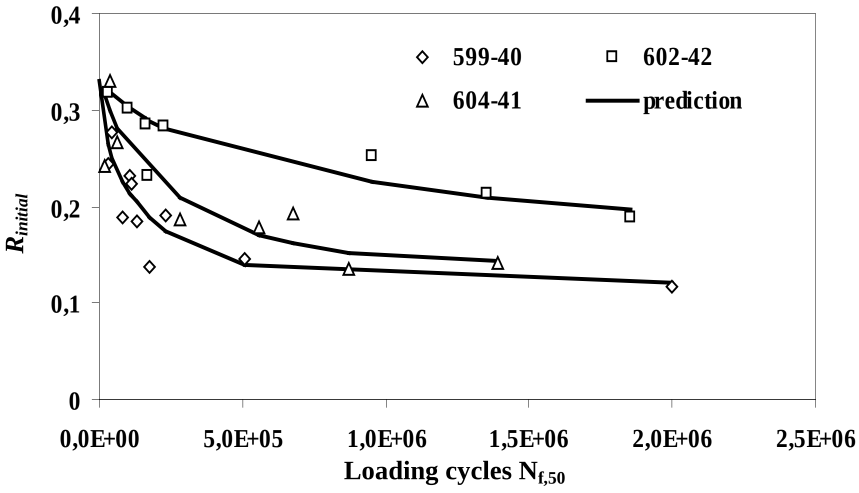



Figure 11. Initial stress ratio versus fatigue life $N_{f,50}$

The correlation coefficients $R^2$ of the equations for these three mixtures are all reasonable. Therefore, it is believed that the equation (4) is capable of providing a fair prediction for the *R*-*N* lines.

Table 3 Regression constants and equations for the three mixtures

| Binder types | Regression constants | | | | Regression equation | $R^2$ |
|---|---|---|---|---|---|---|
| | $R_0$ | $R_1$ | *a* | *b* | | |
| 599-40 | 0.33 | 0.21 | 3.63E-06 | 0.51 | $R_{initial} = 0.33 - 0.21 \cdot \left(1 - e^{-(3.63E-06)N}\right)^{0.51}$ | 0.739 |
| 602-42 | 0.34 | 0.17 | 7.94E-07 | 0.55 | $R_{initial} = 0.34 - 0.17 \cdot \left(1 - e^{-(7.94E-07)N}\right)^{0.55}$ | 0.747 |
| 604-41 | 0.34 | 0.20 | 2.74E-06 | 0.67 | $R_{initial} = 0.34 - 0.20 \cdot \left(1 - e^{-(2.74E-06)N}\right)^{0.67}$ | 0.782 |

Furthermore, it is noteworthy for all three mixtures the initial stress ratio $R_{initial}$ tends to a limit value $R_{limit}$ when the fatigue life becomes infinite. In other words, the specimen will not show any fatigue damage under the loading condition $R_{initial} = R_{limit}$, This ratio is related to the fatigue endurance limit $\varepsilon_{limit}$.

### 4.2 Limit value of initial stress ratio $R_{initial}$

The value of $R_{limit}$ was calculated for the three asphalt mixtures by using equation (4) with the assumption of $N \to \infty$. Table 4 presents the calculation of $R_{limit}$ for the three mixtures. The results are shown in table 4.

Table 4. $R_{limit}$ for the three mixtures

| Types of binder | $R_{\lim it} = R_0 - R_1$ |
|---|---|
| 599-40 | 0,1196 |
| 602-42 | 0,1750 |
| 604-41 | 0,1455 |

According to the definition of $R_{initial}$, the expression of $R_{limit}$ is given by:

$$R_{\lim it} = \frac{\sigma_{\lim it}}{f_{t,\lim it}} = \frac{\varepsilon_{\lim it} \cdot S_{\lim it}}{f_{t,\lim it}} \Rightarrow \varepsilon_{\lim it} = \frac{R_{\lim it} \cdot f_{t,\lim it}}{S_{\lim it}} \tag{5}$$

Where: $\varepsilon_{limit}$ is the fatigue endurance limit [m/m], which is the amplitude of the strain level that can be applied to the material without causing fatigue failure; $S_{limit}$, $\sigma_{limit}$ and $f_{t,limit}$ are the initial stiffness, the initial stress and the tensile strength, all in [MPa], of the specimen under the strain level of $\varepsilon_{limit}$, respectively.
Figure 12 shows that the initial stiffness is not significantly affected by the strain level. The initial stiffness fluctuates around the mean value. Thus the mean value of the initial stiffness $S_{m,initial}$ under the same condition could be considered as a rational approximation of $S_{limit}$.

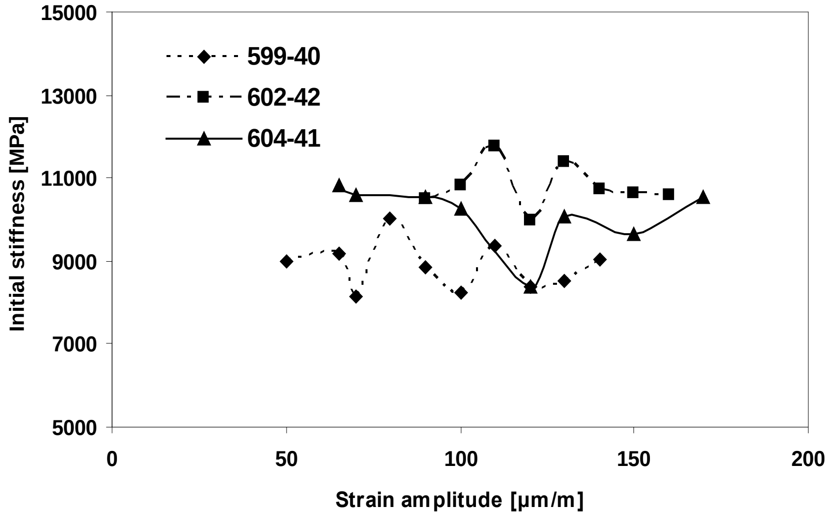



Figure 12 Initial stiffness vs. strain amplitude in the fatigue test.

Based on the calculation of the tensile strength $f_t$ as applicable for the strain rate and temperature as applied in the fatigue test, the following equation can be obtained:

$$f_{t,\lim it} = a\left[1 - \frac{1}{1 + \left[\dot{\varepsilon} e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] = a\left[1 - \frac{1}{1 + \left[4 \cdot f \cdot \varepsilon_{\lim it} \cdot 100 \cdot e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] \tag{6}$$

Where: $a$, $b$, $c$ and $d$ are coefficients; $T$ is the temperature in the test, [K]; $f$ is the strain signal frequency, [Hz].

When equation (6) is substituted into equation (5) and $S_{m,initial}$ is used instead of $S_{limit}$, one obtains:

$$\varepsilon_{limit} = \frac{R_{limit}}{S_{m,initial}} \cdot a \left[ 1 - \frac{1}{1 + \left[ 4 \cdot f \cdot \varepsilon_{limit} \cdot 100 \cdot e^{\left(b + \frac{c}{T}\right)} \right]^d} \right] \tag{7}$$

From the monotonic tests, the coefficients *a*, *b*, *c* and *d* can be obtained for a single mixture. The only remaining problem is to find out if a relationship between $R_{limit}$ and $S_{m,limit}$ can be established.

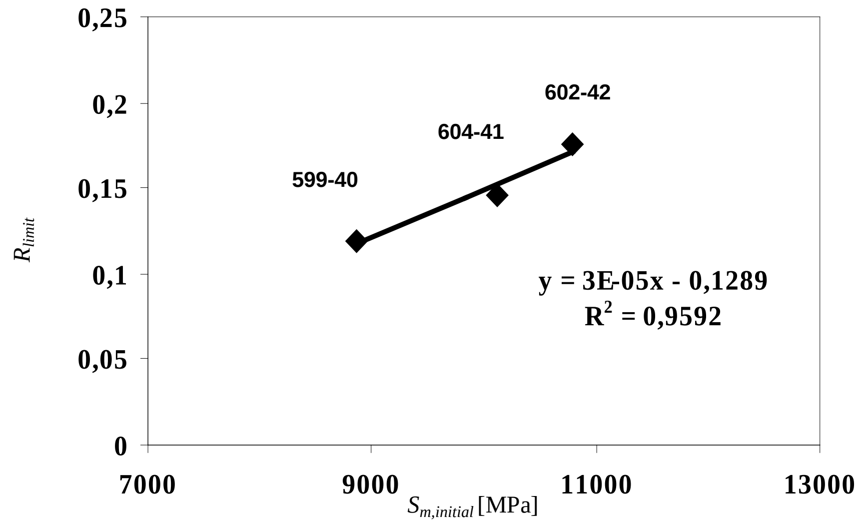



Figure 13. Relationship between $R_{limit}$ and $S_{m,initial}$

Figure 13 shows that the limit value of the initial stress ratio $R_{limit}$ seems to be proportional to the mean value of the initial stiffness. Although three data points are not enough for developing a model, it seems that there is a linear correlation between $R_{limit}$ and $S_{m,limit}$. So the relation between $R_{limit}$ and $S_{m,initial}$ for the asphalt mixtures might possibly be described by:

$$\frac{R_{limit}}{S_{m,initial}} = (2.71 \times 10^{-5}) - \frac{0.1233}{S_{m,initial}} \tag{8}$$

Equation (7) then changes into:

$$\varepsilon_{limit} = \left[ \left(2.71 \times 10^{-5}\right) - \frac{0.1233}{S_{m,initial}} \right] \cdot a \left[ 1 - \frac{1}{1 + \left[ 4 \cdot f \cdot \varepsilon_{limit} \cdot 100 \cdot e^{\left(b + \frac{c}{T}\right)} \right]^d} \right] \tag{9}$$

The question now is what all these equations mean for practice. The answer to this is as follows. When tensile tests are performed at different strain rates and temperature, a generalized equation can be developed which describes this dependency. Equation (2) is an example of such an equation. Furthermore the master curve of the initial mixture stiffness should be determined preferably by means of 4 point beam bending tests. Then $\varepsilon_{limit}$ can be calculated for the frequency and temperature of interest by solving equation (9). For the mixtures under investigation this has resulted in the $\varepsilon_{limit}$ values shown in table 5.

Table 5. The values of $S_{m,initial}$ and $\varepsilon_{limit}$ for the three asphalt mixtures at T = 20 °C and f = 8 Hz

| Types of mixtures | $S_{m,initial}$ (GPa) | $\varepsilon_{limit}$ ($10^{-6}$ m/m) |
|---|---|---|
| 599-40 | 8.9 | 50 |
| 602-42 | 10.8 | 80 |
| 604-41 | 10.1 | 75 |

It is believed that simple protocol has been established for establishing a fatigue endurance limit εlimit, which can be expressed as a function of the temperature, frequency, the mean value of the initial stiffness and the tensile strength. Using monotonic tests, the coefficients a, b, c and d can be calculated. The initial stiffness is measured in a 4 point beam bending test without running the test to failure.
More work however is needed to validate the procedure presented here.

## 5. IMPLICATIONS FOR DESIGN

In order to determine the positive effect of applying one of the polymer modified mixtures, the results shown in table 5 were used as input for a multilayer analysis using BISAR. A three layer was analyzed which was subjected to a 50 kN load which was applied on a circular area with a radius of 0.15 m. The thickness and the stiffness of the asphalt layer were varied while the thickness and stiffness of the unbound base course were kept constant (0.3 m and 300 MPa respectively). Also the subgrade modulus was kept constant in all cases (100 MPa).

Figure 14 shows the relation between the asphalt thickness and the strain at the bottom of that layer for all three asphalt mixtures.

From figure 14 one can derive that the asphalt layer needs to have a thickness of 0.294 m in order to reach a tensile strain value of 50 μm/m in case 599-40 is used. However, the asphalt thickness can be as less as 0.194 m when mixture 602-42 is used because that mixture has an endurance limit of 80 μm/m. When mixture 604-41 is used, which has an endurance limit of 75 μm/m, the asphalt thickness needs to be 0.211 m.
This comparison clearly shows the significant thickness reductions which can be allowed when polymer modifications of the type as investigated in this research are applied.

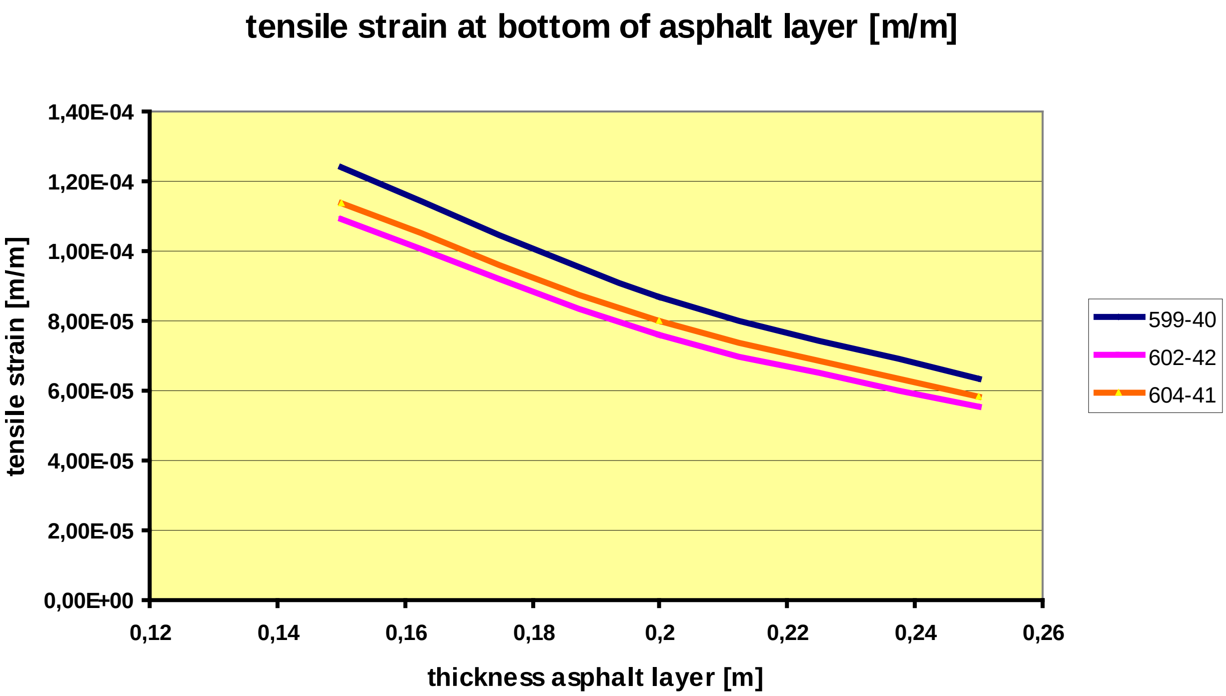



Figure 14. Tensile strain in the asphalt layer vs its thickness

## 6. CONCLUSIONS

The research program as presented here has resulted in the following conclusions.

- Mixtures with excellent mechanistic properties can be produced using specially designed polymers.
- The fatigue behaviour of asphalt mixtures can be described by means of an endurance limit.
- The endurance limit can be estimated using a series of tension tests performed at different strain rates and temperatures and mix stiffness tests.
- Modifying asphalt mixtures with specially designed polymers can result in a significant reduction of the asphalt layer thickness.

## REFERENCES

1. Erkens, S.M.J.G., **Asphalt Concrete Response (ACRe), Determination, Modelling and Prediction,** PhD. Thesis, Delft University of Technology, The Netherlands, 2002.

2. Jacobs, M.M.J., **Crack Growth in Asphaltic Mixes**, PhD thesis, Delft University of Technology, The Netherlands, 1995

3. Medani, T.O., **Design Principles of Surfacings on Orthotropic Steel Bridge Decks**, PhD Thesis, Delft University of Technology, The Netherlands, 2006.4.

4. Ven, M.F.C. van de, Molenaar, S. , **Mechanical testing of polymer modified asphalt mixtures**. Report 7-04-135-2, TU Delft, November 2005.

5. Ven, M.F.C van de, Poot, M.R, Medani, T.O., **Advanced mechanical testing of polymer modified asphalt mixtures**. Report 7-06-135-3, TU Delft, April 2007.

6. Poot, M.R., Ven, M.F.C. van de, **Influence of three polymer modified binder types on the stiffness and the fatigue behaviour of an asphalt mixture**. Report 7-09013504, TU Delft, March 2009.

7. Li, N,. Pronk, A.C. Ven, M.F.F. van de, Molenaar, A.A.A., **Estimation of fatigue endurance limit by using monotonic uniaxial tension test**. Report 7-09-135-5, TU Delft, July 2009.