Asphalt mixture performance and testing

Relaxation property as a key factor for predicting the lifetime of porous asphalt mixtures

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Abstract

Porous asphalt (PA) mixtures are very sensitive to ravelling, as a result the lifetime of PA is limited. The use of better quality materials were implemented in an effort to improve the lifetime of porous asphalt mixtures. But these were quantified empirically based on the performance of the binder/mortar as well as resistance to ravelling of the mixture. In this study, effort is made to use the relaxation property as a key factor in relation to the durability of the mixture to predict the life-time of PA mixtures. Ravelling occurs when the relaxation property of the binder, indirectly that of the mortar and/or the mixture, becomes very limited. In other words, it becomes very sensitive to damage as a result of applied strain/stress. A new semi-empirical model, named APAS model, is developed to calculate incremental damage development in PA mixtures as a result of repeated thermal-loading (day/night and winter/summer periods). A study to pavement failures with PA surfacing is the underlaying perdition model for the evaluation of the mixture performances. In this study were in total 8 mixtures investigated, in which the effect of binder type, aggregate type and aggregate size are taken into account. The rheological properties of the extracted binders from fresh (virgin) and aged mixtures were studies together with the relaxation properties of the mixtures. These were used as an input in the APAS model. It is noted that damage development in the winter periods is the main cause for the deterioration or ravelling of the PA pavements. The result of the modelling show that the type of binder plays a significant role in the development of damage, which predominantly determines the life-time of the PA mixtures. The lifetime of the studied asphalt mixtures ranges between 9 to 16 years and one binder exceptionally out performs the others with a predicted lifetime of > 18 years.

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1. INTRODUCTION

Porous Asphalt (PA) is a type of asphalt that is widely used as a surfacing layer on highways in the Netherlands. Because of the high voids content of the asphalt mixture, the lifetime of standard PA is limited to approximately 11 years and 8-10 years in case of double layered asphalt due to its sensitivity to ravelling. There are claims that PA can have longer lifetime as a result of smart selection of materials and optimization of the mortar that bridges or holds together the stone skeleton/structure of the PA mixture. In addition, it is claimed that by addressing the factors that influence the quality of the PA mixture during the production, transportation and laying of the material, the rather significant variability in the lifetime of the PA mixtures could be minimized. However, there are no tools or methods to quantify the impact on the lifetime of the PA mixture in terms of extension in years. So far, performance indicators such as the resistance to ravelling and fatigue properties of the mortar have been used to provide relative comparisons in performance.

In this study, efforts are made to predict the lifetime of Porous Asphalt (PA) based on its relaxation properties in relation to temperature changes. As most studies and/or practical observations indicate, ravelling (loss of stones from the asphalt surface) primarily occurs during the winter season or immediately after the winter season [1, 2]. Research conducted at the Netherlands organisation for applied scientific research (TNO) indicates that, in the long term, the impact of the temperature changes is much more significant for damage development compared to for example the impact of traffic loading [3]. This as is because of the large strain levels caused by temperature differences (day/night and/or summer/winter). This phenomenon shades more focus on the low temperature performance of the asphalt as a determinant factor. Ravelling occurs when the relaxation properties of the binder, indirectly that of the mortar and/or the mixture, degrade. In other words, it becomes very sensitive to damage as a result of applied strain. The effect of aging is one of the factors that influence this degradation, which is taken into account in this study to address the long term durability of the mixture.

The prediction model used in this study, known as the APAS temperature model (APAS = Accelerated Pavement ASsessment), is developed by TNO based on the performance of PA in different locations of the road network. The model was constructed with a validation of laboratory test results with regard to resistance to ravelling with the evaluation of PA performance on different roads with relative differences in traffic loading and weather conditions. The principle of the model is explained in the following sub-section.

In total 8 mixtures were investigated, in which the effect of binder type, aggregate type and aggregate size are the variable factors. The rheological properties of both the extracted binders from fresh and aged mixtures as well as the relaxation properties of the total mix were established. The APAS model is the underlaying prediction model for the evaluation of the mixture performances. The research shows clear, quantifiable, differences in performance that are in line with previous studies on mortar fatigue [4] and observations in practice.

1.1. Background - APAS temperature model

Asphalt mixtures are viscoelastic materials, subject to cyclic loading by traffic and temperature changes. Research have been conducted by TNO to establish fatigue properties of asphalt mixtures (based on 4-point-bending test) under simulated traffic and temperature loadings [5]. The repeated loading or “fatigue tests” were conducted at low temperature where the relaxation properties of the asphalt are limited. The results show that the performance of, especially aged, asphalt is much more influenced by the temperature loading rather than by the impact of traffic loading. The damage development as a result of temperature loading determines the “fatigue life” or number of cycles to failure. Provided that much of the aging of PA mixtures occurs in the first 3 to 4 years, the focus should lay on temperature loading. In other words, aging and temperature loading (low temperature performance) are the determinant factors with regard to the prediction of the lifetime of porous asphalt mixtures.

For this reason and for simplicity of the model only the temperature loading is taken into account in this study. In reality, however, the combined effect of the two factors (traffic and temperature loading) takes place. It should be noted that some damage caused as a result of traffic loading, shear loading in curves for example, can lead to early ravelling occurrence which limits the lifetime.

1.2. Principle of the APAS temperature model

The APAS temperature model is based on the fatigue performance of the asphalt layer, more specifically that of the PA surfacing layer as a result of cyclical temperature changes which is also referred as thermal shrinkage. Temperature variations (thermal shrinkage and expansion) are caused because of changes in day/night and summer/winter periods. This causes stress to develop in the asphalt mixture, which depending on the relaxation behaviour of the mixture, varies from mixture to mixture. The binder/mortar plays an important role in this regard as the relaxation properties will be influenced by the visco-elastic behaviour of the binder/mortar and its sensitivity to aging.

In the APAS temperature model fatigue lines are determined by means of four point bending testing. As default the fatigue property of an asphalt mixture is given in eqn1. From research conducted by Li in 2013 [6] the value of the fatigue parameters k and b are determined as k = 1.6 x 10^{17} and b = -6.03. The fatigue formula with these values is given in eq.2.

$$\boldsymbol{N_f = k \cdot \varepsilon^b = k \cdot [|E| \cdot \sigma]^b} \qquad \textbf{Equation 1}$$

$$\boldsymbol{N_f = 1.6 \times 10^{17} \cdot [|E| \cdot \sigma]^{-6.03}} \qquad \textbf{Equation 2}$$

N_f = Number of load cycles to failure (-)
ε = Strain (-)
σ = Stress (MPa)
E = Stiffness modulus (MPa)
k and b = Model constants (equation 1)

Two inputs are required in the fatigue formula given in eq.2. The first one is the stiffness modulus E of the asphalt mixture and the second one is the stress developed as a result of the thermal shrinkage/expansion. The stiffness modulus can be calculated using the principle of Shell BANDS software [7] (empirical approach to estimate the stiffness of the asphalt mixture based on the bitumen stiffness and the volumetric composition of the mixture. Temperature and loading time are also additional inputs.). The second parameter, stress developed during temperature change, can be simulated with the Thermal Stress Restrained Specimen Test (TSRST). A schematic description of the test method is shown in Figure 1.

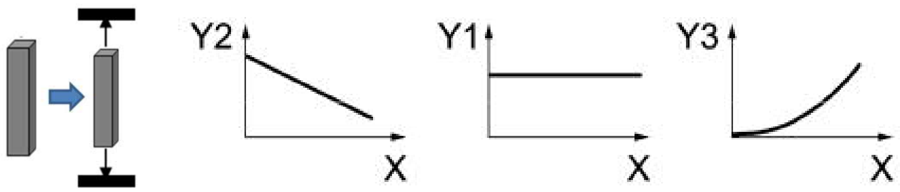


Figure 1: Relaxation test TSRST method (X = time, Y1 = strain, Y2 = temperature and Y3 = stress)

The APAS temperature model uses the stress developed as a result of temperature changes (thermal shrinkage) as an input in the fatigue equation. The formula is given in eq.3.

$$\boldsymbol{\sigma_x = -E\frac{\Delta l}{l} = -E \cdot \alpha \cdot \Delta T} \qquad \textbf{Equation 3}$$

σ_x = Stress (MPa)
E = Stiffness modulus (MPa)
Δl = Change in length (mm)
l = Length (mm)
α = Linear coefficient of thermal expansion (°C^{-1})
ΔT = Change in temperature(°C)

The stiffness of the PA mixture will decrease over time as damage develops in the mixture as a result of fatigue due to thermal changes. With temperature changes during day and night as well as summer and winter periods, the damage caused on the road will vary according to the season but will add up till complete failure is reached. The daily development of damage as a form of fatigue can be calculated based on the stress developed on the asphalt layer. This phenomenon can be expressed with the Miner's rule given in eq.4.

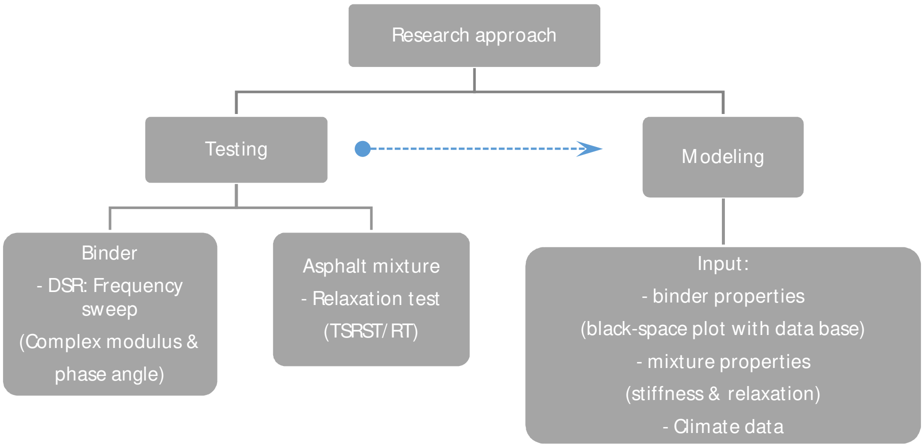
$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

Equation 4

From the above approach, it can be understood that the damage development will be significant during winter periods compared to summer and as a result of binder aging. This implies that limited relaxation properties will be critical in terms of damage development and the performance of PA.

2. RESEARCH METHODS

The research approach is based on testing and modelling. The details of the testing and modelling aspects are given in a flow-chart below. Tests were performed both on the virgin and aged specimens.



With regards to the testing programme the following were conducted:
Recovered binders:
Frequency-sweep tests were performed on a wide range of temperatures (-10°C to 60°C) using the DSR (Dynamic Shear Rheometer). Using the principle of Time-Temperature Superposition, master curves were constructed. Test results at 20°C and frequency of 10 rad/s were used in a black-diagram plot together with the data-bank (samples acquired from different road locations with different service periods).

Test conditions, DSR:

• Temperature	-10 to 60°C
• Frequency	0.1 to 400 rad/s
• Strain	LVE / Linair visco-elastic range
• Specimen thickness	1 mm (ϕ 25 mm spindle) and 2 mm (ϕ 8 mm spindle)

Asphalt mixtures:
To simulate the effect of temperature change on the building of stress and relaxation properties of the PA mixtures, a laboratory test was conducted based on the TSRST and Relaxation Test (RT) methods [8].

Test conditions of the TSRST / RT test:

• Specimen dimensions	40 x 40 x 160 mm beams
• Tests per mixture	3 (before and after aging)
• Aging protocol, mixture	85°C, 3 weeks in oven
• Temperature progression	+20°C to -15°C within 12 hours (approx. 2.92 °C/h)

Note:
- Testing was conducted on both unaged and aged specimens.
- The specimens are conditioned before testing is resumed. A control specimen is used to make sure that the temperature inside the asphalt mixture is the same as the start temperature of 20°C.
- At the end of the temperature decrease, i.e. when -15°C is reached, the test is kept on hold for about 7 hours to simulate the relaxation behaviour of the asphalt mixture.

Considering the principle explained in section 1.2, the development of damage in PA mixtures depends on the temperature loading and the material properties (i.e. the binder/mortar and mixture). These two relevant factors and the associated input parameters for the model are given in Table 1.

Table 1: Input parameters in the APAS temperature model

Climate data	• Temperature
	• Loading time
Material properties	• Mixture composition
	• Stiffness
	• Linear coefficient of thermal expansion, relaxation

2.1. Climate data

Climatic data is necessary to simulate the effect of temperature changes during the day as well as throughout the year. A database of actual climate information over the years was obtained from the Metrological Institute of the Netherlands (KNMI). There are differences between regions in the Netherlands and for the purpose of this study the region of Twente was selected as this region has higher temperature changes compared to the others. This is believed to result in a better chance to reflect on differences in performance of the investigated PA mixtures. The difference between the daily minimum and daily maximum temperature is taken as an input for the variable ΔT in eq.3. A loading frequency for the day/night changes will be 1/24 hr = 1.157 E-05 Hz.

2.2. Material properties

Mixture composition

The composition of the PA mixture is used to calculate the mixture stiffness. The percentages of the aggregate fraction (size > 2 mm), the sand (size between 2 mm and 0.063 μm), the filler (size < 0.063 μm) and the binder content of the mixture are required to calculate the mixture stiffness which is used as an input in the APAS model.

In total, 8 mixtures were incorporated in the study. These include primarily a PA 8 asphalt mixtures with different types of binder. Mixture A has a different type of aggregate than the others. The aim being to address the effect of bitumen-aggregate interaction (adhesion) and/or aggregate form on the mixture properties. Furthermore, a PA 5 mixture (Mixture B) was included to investigate the effect of nominal aggregate size on the performance of the mixture. An overview of the PA mixtures is shown in Table 2. Figure 2 shows the gradation of the different mixtures.

Table 2: PA mixtures considered in the study

Mixture name	Mixture type	Aggregate Size (nominal)	Aggregate type	Type of binder	Binder content
Mix A	PA 8	4/8	1	PMB 1	6.0
Mix B	PA 5	2/5	2	PMB 1	6.1
Mix C	PA 8	4/8	2	PMB 1	6.0
Mix D	PA 8	4/8	2	PMB 2	6.0
Mix E	PA 8	4/8	2	PMB 3	6.0
Mix F	PA 8	4/8	2	PMB 4	6.0
Mix G	PA 8	4/8	2	PMB 5	6.0
Mix H	PA 8	4/8	2	Pen bit.	6.0

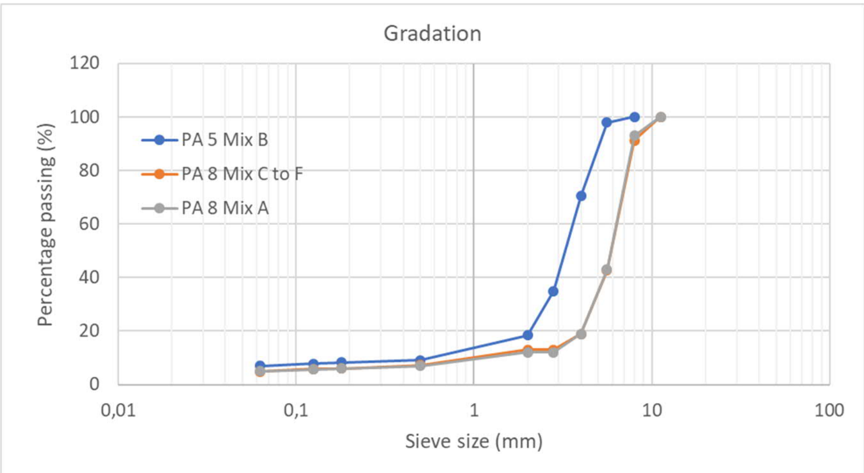


Figure 2: Gradation of the PA mixtures

Stiffness modulus (Smix)
The stiffness of the PA mixtures was calculated with a method similar to the Shell BANDS software using the mixture composition (volumetric properties) and the binder stiffness at 20°C and 10 rad/s determined with the use of the Dynamic Shear Rheometer (DSR). Using the daily average temperatures obtained from KNMI climatic data, the average stiffness of the mixture per day was calculated. The effect of aging in the course of time is taken into account based on a study conducted by TNO [5]. The study established a relationship for the stiffness of the binder through its service period based on an extensive database collected from different road sections in the country.

The effect of aging was also simulated in the laboratory using a TNO protocol for PA asphalt mixture (Oven aging: temperature 85°C, 3 weeks) [9, 10]. This protocol has been shown to simulate on average 3 to 4 years of aging on the road. The need for simulating field aging is necessary because the standard aging methods, such as Rotating Thin Film Oven Test (RTFOT) followed by Pressure Aging Vessel (PAV), do not represent field aging in terms of rheology and chemical properties. Currently, a research project is in progress to simulate long-term aging of the binder according to the aging characteristics of the binder on the road.

Coefficient of thermal expansion and relaxation
Temperature changes result in the built-up of stress conditions in the PA asphalt mixture. The factors that play a role in this regard are the temperature itself, the time duration of the temperature loading and the linear coefficient of thermal expansion of the mixture. The linear coefficient of thermal expansion (α) of a PA mixture is assumed to be $3.0x10^{-5}$ /°C.

The stress build-up as a result of temperature changes and the relaxation properties of the mixture play an important role in the development of damage that ultimately lead to ravelling to take place. A mixture that can quickly relax stresses will have a lower chance of developing damage, which is seen as a positive attribute.

3. TEST RESULTS AND ANALYSIS

3.1. Bitumen rheology
Figure 3 shows the rheology of the recovered binders in a black-diagram. Only the complex modulus G* and phase angle δ at 20°C and 10 rad/s are used in the black-space diagram in Figure 4 and in the calculation of the stiffness of the asphalt mixtures.

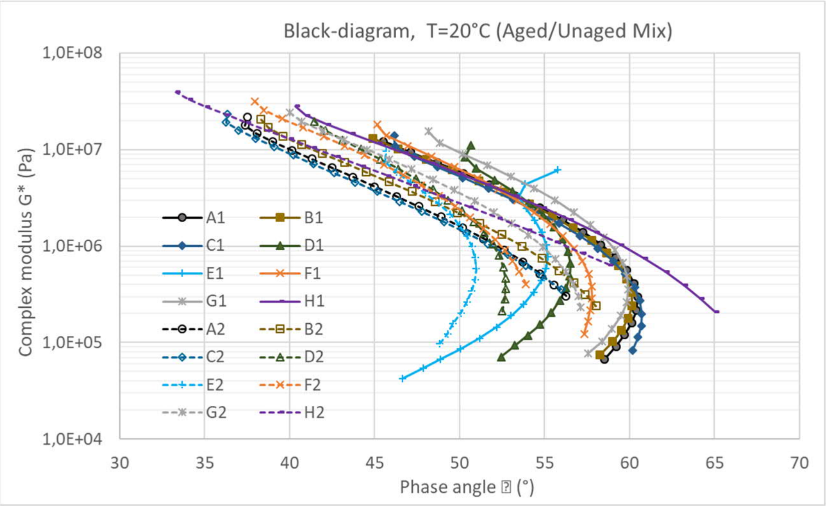


Figure 3: Black-diagram – recovered binders T = 20°C

Figure 4 shows the complex modulus and the phase angle of the recovered binders from the PA mixtures together with the database-data of recovered binders from different mixtures on the road. The complex modulus (G*) and phase angle (δ) data in the black-diagram plot are obtained from a DSR test data at 20°C and 10 rad/s. A1 to H1 concern unaged mixes, while A2 to H2 concern the corresponding aged mixes. It is noteworthy that unaged mixtures have undergone some short-term aging due to the mixing and compacting of the mixture.

In Figure 4, the data-base or data-bank have a filled rectangular shape (grey) while the test data from this study have shapes other that rectangular. Based on the comparison with the data-base in Figure 4, the laboratory aging protocol simulates 2-3 years of mixture aging on the road. For this reason, it is deemed necessary to use the relationship established by TNO to predict long-term aging of the binder based on field data. It can be noted that some binders are more sensitive to aging than others. For example, the H1 unaged binder is more or less comparable with the aged binders G2 and B2 or even more aged that the E2 and D2 binders. H1 has the highest |G*| and lowest δ among the binders recovered from unaged mixture. Binders C2 and F2 also seem to be sensitive to aging next to the H2 binder. It is evident from the graph that the E binder showed deviation from the others. A special attribute of this binder is that it has a lower |G*| value while the phase angle is similar to the other binders. The D binder is the least aged next to the E binder.

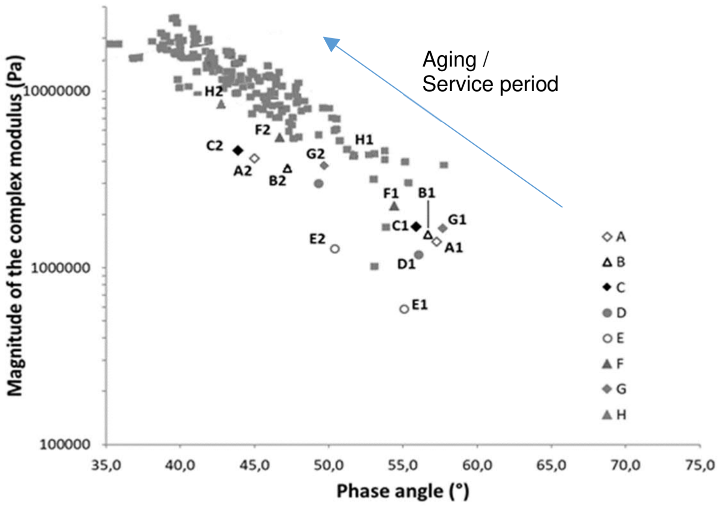
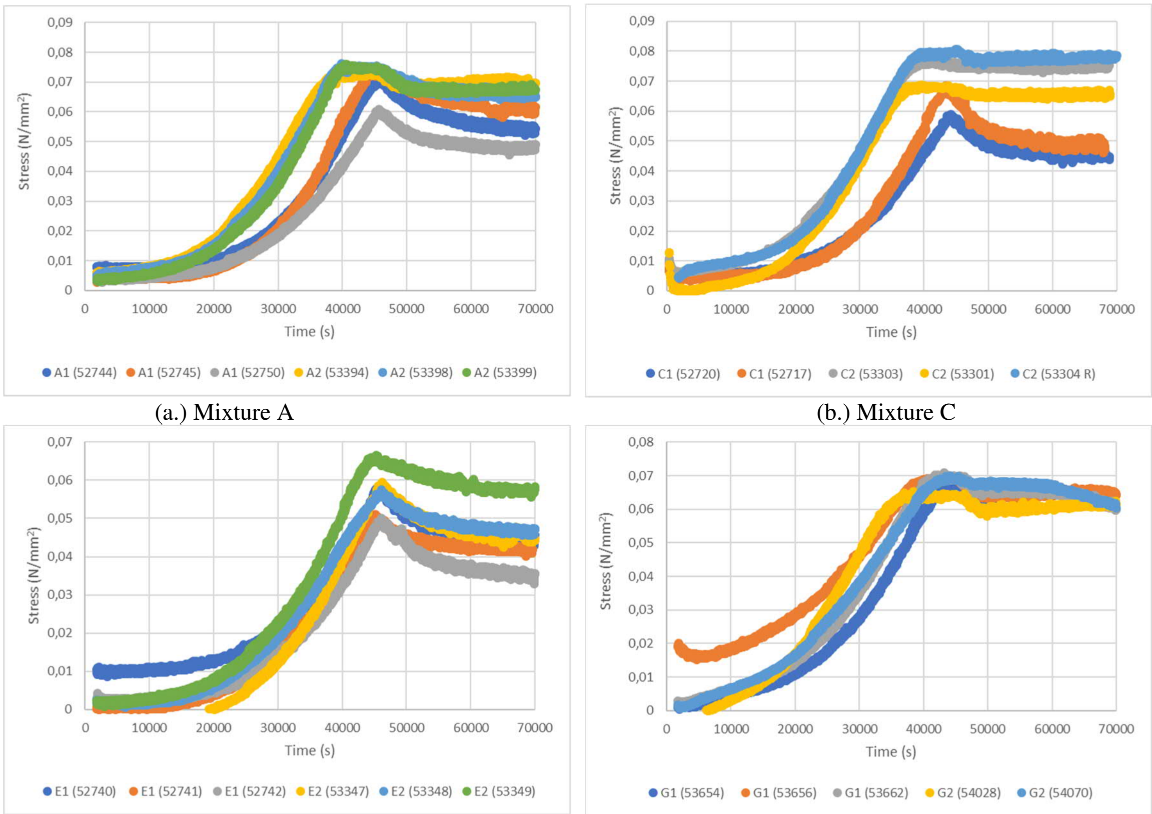


Figure 4: Black-diagram | G* | and δ by 20°C and 10 rad/s

3.2. Mixture properties

Some examples of the TSRST/RT test are shown in Figure 5. It is to be noted that the stress built-up of the aged mixtures begins earlier than the unaged mixtures. But with some mixtures, for example mixture E and G, the difference in built-up of stress is minimal. After the end-temperature of -15°C is reached, the mixtures exhibit relaxation of the built-up stress. However, mixtures such as C and G do not seem to show relaxation after aging.



(a.) Mixture A (b.) Mixture C

(c.) Mixture E (d.) Mixture G

Figure 5: TSRST stress built-up in asphalt mixture A

3.3. APAS temperature model

The analysis of damage development as a result of temperature loading or thermal shrinkage/expansion is carried out using the APAS model. The APAS temperature model basically assumes “fatigue”, incremental damage as a result of repeated loading, as a benchmark for the development of damage in the PA mixture. The incremental damage based on Miner’s law provides the prediction of the expected lifetime of the mixtures in real situation.

The results of the APAS temperature model analysis are given in Figure 6. Basically, Figure 6 shows the results of the APAS model (principle explained in section 1.2) based on all the input data (climate data, mixture stiffness, stress built-up and relaxation characteristics of the mixture). The step increment of damage in Figure 6 is explained by the impact of winter periods (low temperature). PA Mixture H, based on straight run bitumen shows rapid damage increase. The “lifespan” of approximately 10 years coincides with the performance that can be expected in practice. He other mixtures contain a (polymer) modified binder, resulting in a much longer expected life span. However, there is also a huge difference in the performance of the mixtures with these modified binders. Mixture F, for example, has performed the least next to Mix H. Mixture A and C are two mixtures with the same binder type, these mixes seem to perform relatively similar to a standard PA mixture based on collected field data. The difference in aggregate type seem to have not significant impact on the performance. In comparison with mixtures A and C, the performance of mixture B is better contrary to the experience and thought that ravelling occurs earlier in mixtures with finer aggregate nominal size. Mixtures G and D performed relatively better than the benchmark performance for a standard PA mixture. The performance of mixture E is extraordinary which seem to overcome the development of damage due to its resistance to aging and relaxation potential of stresses at low temperatures. This characteristics are a reflection of the material properties which has manifested itself in the binder rheology as well as relaxation of the PA mixture.

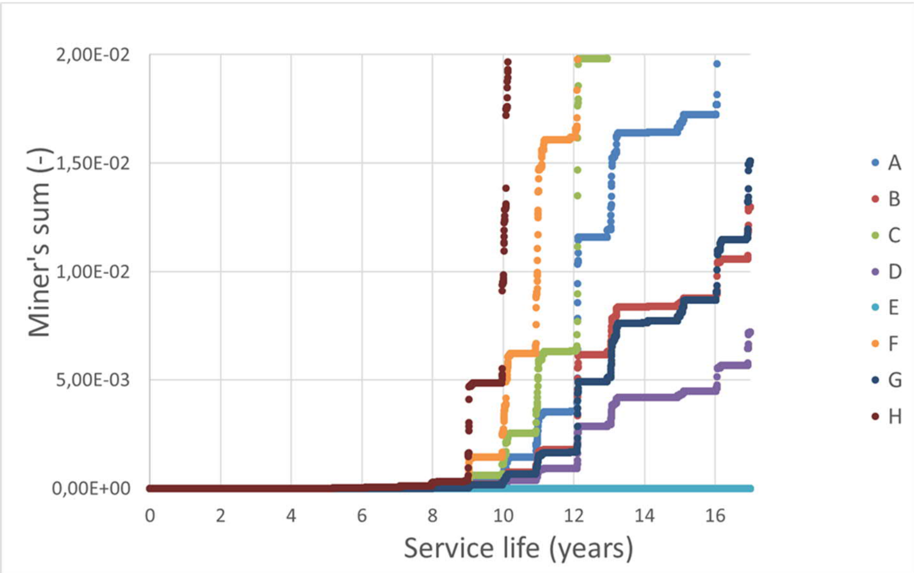


Figure 6: Miner’s numbers based on the APAS temperature model

The results of this study (which are discussed above) are in agreement with a previous, more qualitative fatigue study conducted on the mortar of the PA mixtures [4]. In the study, the mortar fatigue properties of the mixtures C, F and G with, respectively, binder types 1, 4 and 5 were studied. The results of the mortar fatigue test at 20°C are shown in Figure 7. The mortar in mixture F showed poor fatigue properties compared to the mortar from mixture C and F with comparative relative performance.

The observed behaviour and the derived quantitative life time expectations are in line with what can be anticipated considering the grades of the binders investigated. There is for example a clear relationship with an increasing Pen range and increase in expected life time and fatigue resistance. But also the anti-ageing properties show a clear benefit. Obviously, a slow ageing behaviour results in good fatigue properties over time. One should not forget that Porous Asphalt, if laid correctly, rarely fails within the first 5 years.

Although the results of the mortar fatigue are conducted at intermediate temperature while the results of the APAS model are based on low temperature performance of the mixture, the two studies are in agreement. Nevertheless, the APAS model has an advantage because it predicts the life-time of the mixture in service.

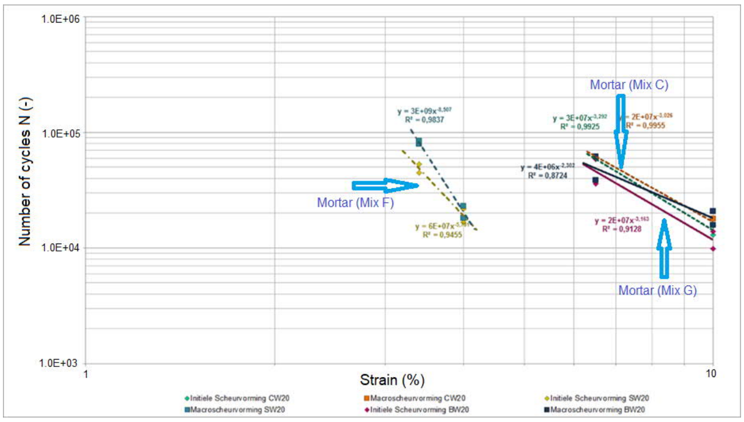


Figure 7: Fatigue lines of mortar (T = 20°C)

CONCLUSIONS

The following conclusions are drawn from the analysis on the performance of PA mixtures.

- The binder type has more dominant effect on the performance of PA mixtures that aggregate type and/or size. The rheology of the binder and its resistance to aging has a significant impact on the performance of PA mixtures.
- Significant damage occurs in the winter periods (low service temperature) compared to summer periods (high service temperature).
- The potential to relax stress of the PA mixture at low temperatures, most importantly after undergone ageing, is a crucial quality aspect. In other words, relaxation potential is closely related with durability or resistance to ravelling. Mixtures D and H seem to have this quality.
- The APAS temperature model is a reliable tool that has the potential to give a quantitative basis for decisions regarding both mix design as well as maintenance strategies during the tender phase of a project. It is certainly a good addition, if not replacement, for conventional methods such as resistance to ravelling based on a Rotating Surface Abrasion Test (RSAT) in predicting the performance of PA mixtures.

ACKNOWLEDGEMENTS

KWS would like to acknowledge the contribution of TNO to a successful completion of this project. In particular, we extend special recognition for the efforts in the development of the APAS model. It is considered that this research project brings the modelling and the prediction of the lifetime of PA mixtures a step forward.

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