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Aging characteristics of bitumen related to the performance of porous asphalt in practice

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Abstract

The performance of two layered porous asphalt (2LPA) surfaces is superior with respect to the reduction of noise produced by road-tyre interaction and the amount of splash and spray during rain, compared to dense surface layers. However, these open surface roads have a drawback with as they have a limited durability. It is assumed that aging of the binder which proceeds faster with these open mixtures has a negative influence on the service life.

However, both the principle driving forces behind aging and the relation between these aging processes and the mechanical properties and, thus, failure are still unclear. Therefore an extensive research program has been set-up to monitor the aging and the performance of 2LPA in practise. One asphalt mixture is applied at four different locations in the Netherlands. Samples are taken at different moments in time and material characteristics related to aging are determined on the binder. The actual performance with respect to ravelling is monitored through visual inspection.

In this paper the trends in material parameters related to aging are presented, showing that the complex modulus changes most significant over time. Visual inspection of the road shows that the service life can vary up to 25% for the same mixture. The section that performed best in practice showed the lowest complex modulus at different loading frequencies. Therefore there seems to be potential to look for a ravelling criterion based on rheological measurements for the expected performance of porous surface layers.

Keywords: Long term aging, Performance in practice, complex modulus, porous asphalt

Introduction

The performance of two layered porous asphalt surfaces is superior with respect to the reduction of the noise produced by road-tyre interaction and the amount of splash and spray during rain, compared to dense surface layers. However these open surface roads have a drawback with respect to durability, namely their relative short service life compared to dense asphalt layers. The governing damage mechanism for two layered porous asphalt is ravelling, the loss of stones from the surface. As aging processes are accelerated by the open structure of these mixes, it is assumed that the failure mode ravelling is related to the fast aging process of open mixtures [1]. Aim of this research is to link ravelling observed in practise to material parameters of the asphalt that is also aged in practise.

The test sections that are studied in this research are part of the ZEBRA test sections. These are sections of two-layered porous asphalt realized by Rijkswaterstaat for research purposes. This research is performed on the top layer of a two-layer porous asphalt (2LPA). 2LPA has a top layer with fine aggregates (4/8 mm) and a bottom layer with coarse aggregates (11/16 mm). One of the unique features of these sections is that the exact same asphalt mixture is placed at four different locations in the Dutch highway network (A15, A28, A30, A59). The sections are placed at different moments in time, the construction dates for the sections can be found in Table 1. The composition of the mixture and construction of the sections was carefully monitored and documented [2]. During service life several performance parameters are monitored, including ravelling.

Table 1: Construction dates of road sections

Construction dates	
A15	22-7-2004
A28	26-8-2002
A30	27-8-2003
A59	26-9-2004

To obtain material for laboratory testing, cores were drilled over a period of four years (2006, 2007, 2008 and 2009). As the sections were constructed from 2002 to 2004, the moment of sampling results in data points showing the performance from 2 to 8 years after construction. At each road location, seven cores were taken from the right wheel track of the right lane and seven cores from the emergency lane. The 2LPA is cut along the interface of the top and the bottom layer, parallel to the pavement surface, in order to separate the layers. In this paper the performance of the bitumen recovered from the top layer is described. Each binder sample is extracted from six cores in order to obtain the average for the section. The binder is extracted using the solvent dichloromethane, followed by vacuum distillation.

On these binders five different types of tests have been performed, in order to establish the aging behaviour in practice. In order to look for trends on chemical aging Infrared Analyses was performed to determine the amount of oxidation and Gel Permeation Chromatography was done to establish changes in the molecule size of the binder. Trends in mechanical behaviour were sought after by determining the complex modulus and the phase angle.

Finally the trends that are found in laboratory on aging are matched tot the data on the amount of ravelling in practice. The aim of this comparison is to relate parameters related to the aging of the binder to ravelling damage that can be observed in practice.

Trends in aging parameters

During the data-analyses of the laboratory measurements, it became clear that the data point just after construction at t=0 is very important when looking for trends. However this insight came after the analyses and therefore this data point is missing for all but one section (A59) [3, 4]. Another detail that was discovered during the data-analyses, was that even though the exact same mixture was requested by Rijkswaterstaat, in some cases laboratory results showed that a different binder was applied. The base bitumen for the A30 and the reference sample is the same, but different from the based bitumen found in the A28, A15 and A59.

Analyses of the laboratory data showed that the determined chemical parameters did not show any statistical significant trend in aging over time. The GPC data did seem to increase over time, however the changes are too small compared to the scatter to distinguish any trends as can be seen in Figure 1. The Infrared tests did not show any trend, this is illustrated in figure 2 by showing the differences in the C=O peak trough time. The only significant difference can be found between fresh bitumen and bitumen that has been on the road for a certain period of time, for the other data points the scatter is larger then the differences sought after.

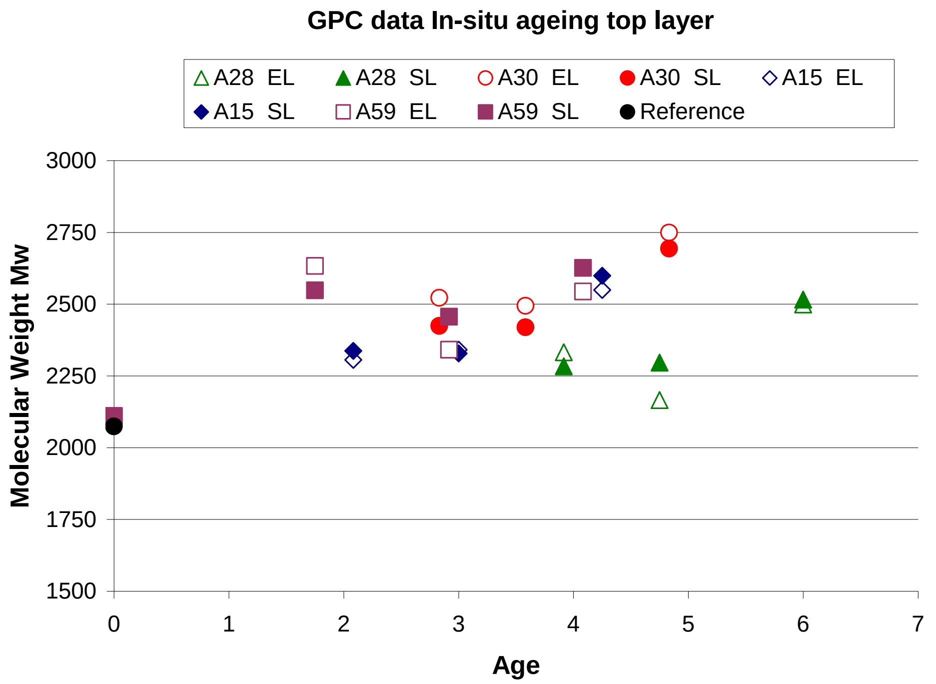

Figure 1: Molecule size (Mw) over time measured with GPC, EL = Emergency Lane, SL = Slow Lane.

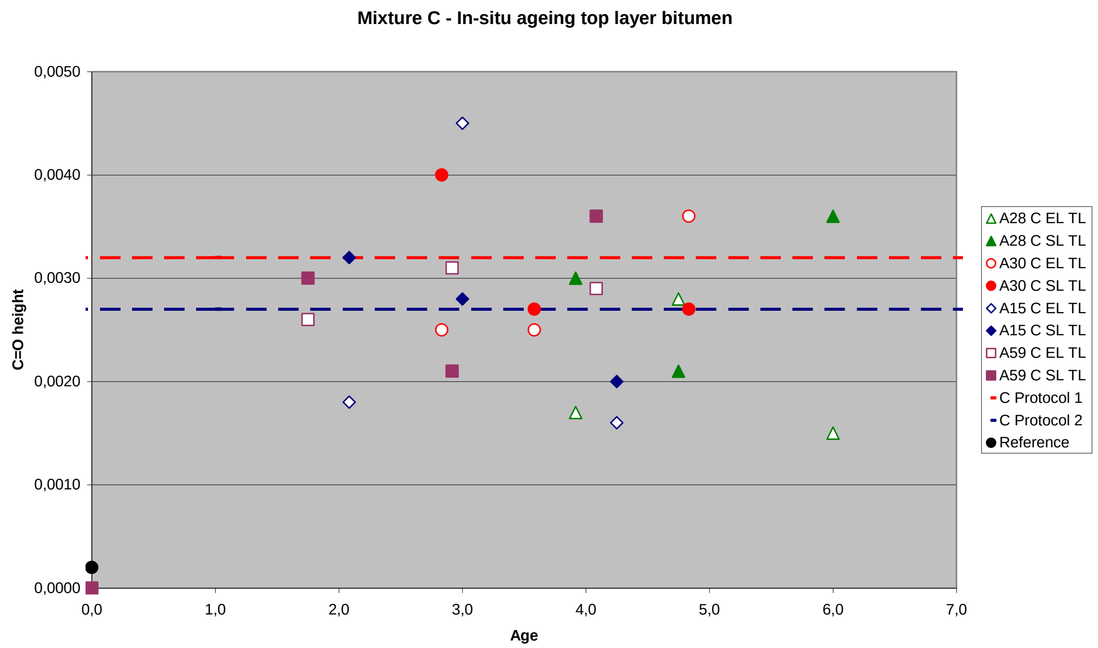

Figure 2: Changes in C=O peaks measured with Infrared

Aging of bitumen is characterized by an increase in stiffness and an increase in viscosity of the binder. To quantify this change in mechanical behaviour, different types of tests can be performed. In this research the complex modulus and the phase angle are determined with a Dynamic Shear Rheometer (DSR).

In a DSR test a sinusoidal loading is applied at a certain frequency and the deformation under this loading is measured. Due to the fact that bitumen is a visco-elastic material there is time delay between the moment of maximum loading and the maximum deformation, this is called a phase angle. Therefore tests result in a complex modulus (G^*) based on the amount of force needed to realize a certain displacement and a phase angle (δ) which shows the difference between the moment of maximum applied stress and the maximum strain. In general for bitumen the complex modulus will increase and the phase angle will decrease due to aging.

The DSR test is performed according to NEN-EN 14770. The bituminous materials were subjected to a sinusoidal loading of constant strain at different loading frequencies (frequency sweep). The frequency sweep test was conducted at eight different temperatures ranging between -10 ºC and 60 ºC. Every test was carried out at frequencies ranging between 0.1 - 400 rad/s. Two parallel plate geometries with a diameter of 8 mm and 25 mm were used. The Time-Temperature Superposition (TTS) principle was used to generate master curves of the complex modulus and phase angle at a reference temperature of 20ºC. To quantify the rate of ageing of the binders, the phase angle values and the complex modulus values were determined at four different frequencies, 0.001, 0.1, 10 and 1000 rad/sec for the different samples.

Figure 3 shows the complex modulus at different moment in time at a loading speed of 1000 rad/s which can be associated with the loading that corresponds to a passing vehicle at 100km/h. The closed symbols represent samples from the right wheel track and the open symbols samples from the emergency lane. The values at t=0 correspond to the virgin binder (reference) and the short term aging (only at A59). The figure shows that the binder becomes increasingly stiffer with time for all locations. The graphs also show that samples from the A28 (triangle) are significantly less stiff compared to the other samples. Some values are marked with a grey circle, this refers to damage that is observed in practice, more details on this will be given in the next paragraph.

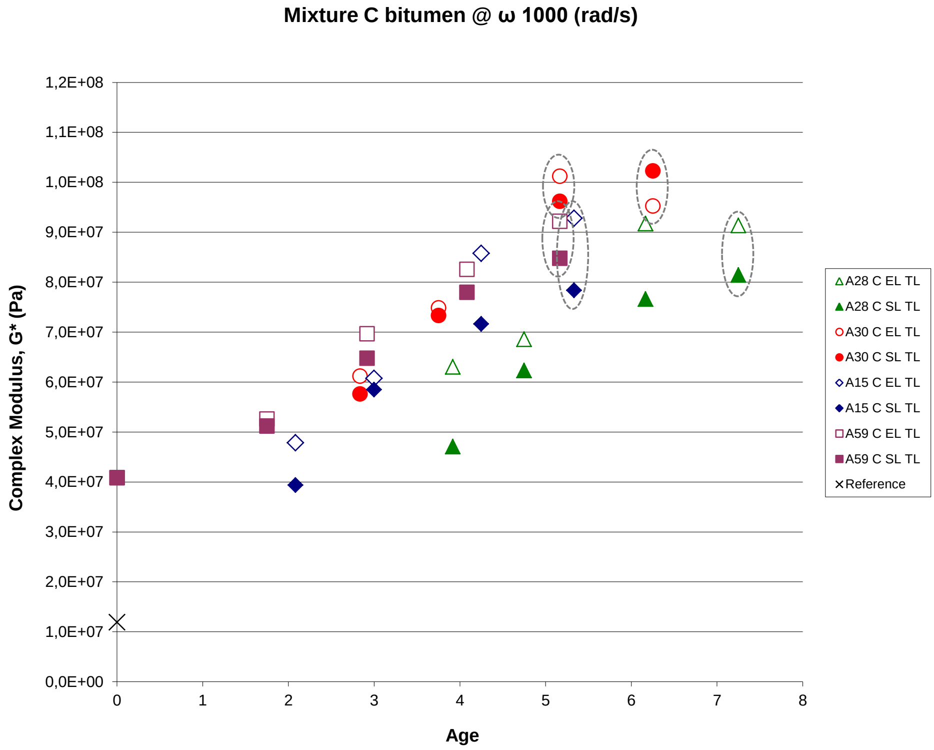

Figure 3: DSR measurements at loading speed corresponding with vehicle passage, values that are circled mark to values that are measured after the damage criterion has been met.

The complex modulus trough time at very low loading frequencies is given in figure 4. This loading rate is associated with daily temperature cycles. At these frequencies it is also visible that the bitumen becomes increasingly stiff with time, although the rate at which the stiffness increases differs quite a lot for each bitumen sample. Again at these low frequencies the A28 is less stiff if compared to the other sections.

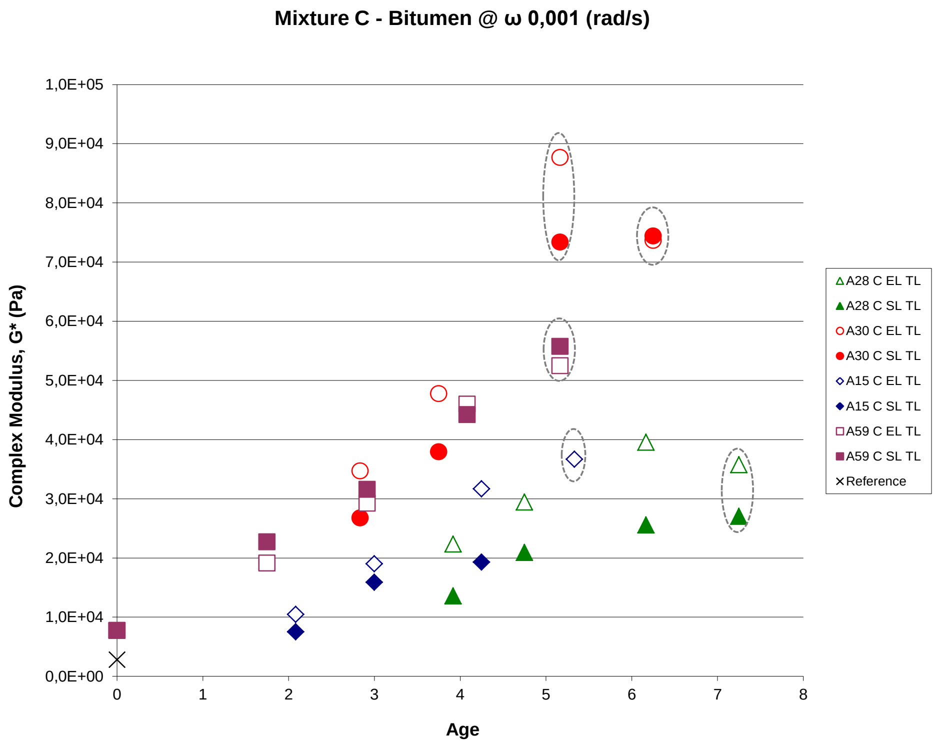

Figure 4: DSR measurements at loading speed corresponding to daily temperature cycles, values that are circled mark to values that are measured after the damage criterion has been met.

From figure 3 and 4 it also becomes clear that the binder obtained from the emergency lane is less stiff compared to the binder from the slow lane. This difference is statistically significant [4], however there is no explanation found so far.

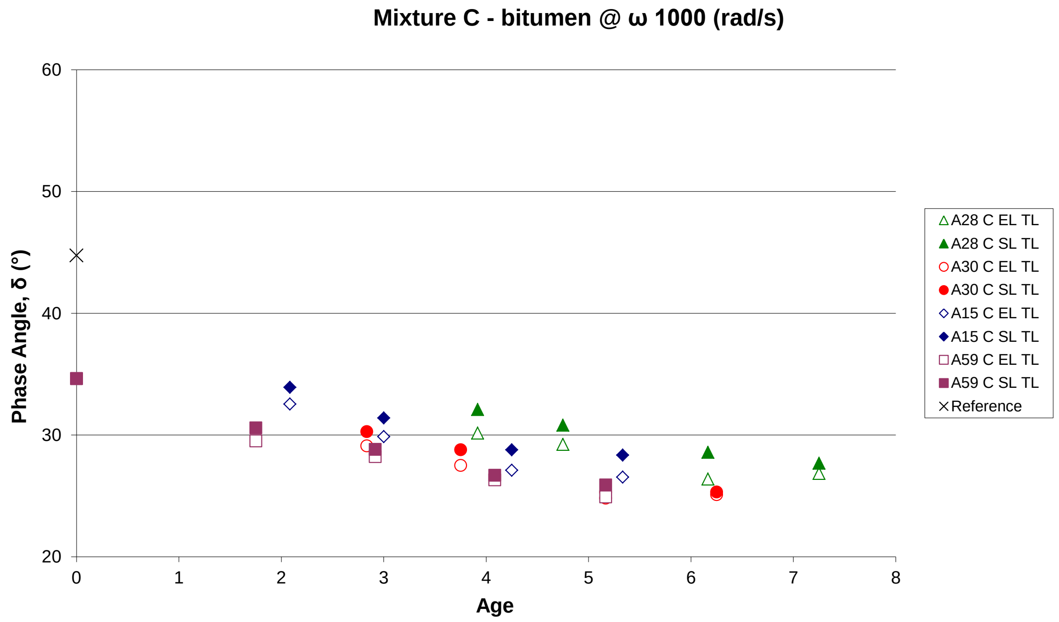

Figure 5: The phase angle of the road sections at loading speed corresponding to with vehicle passage.

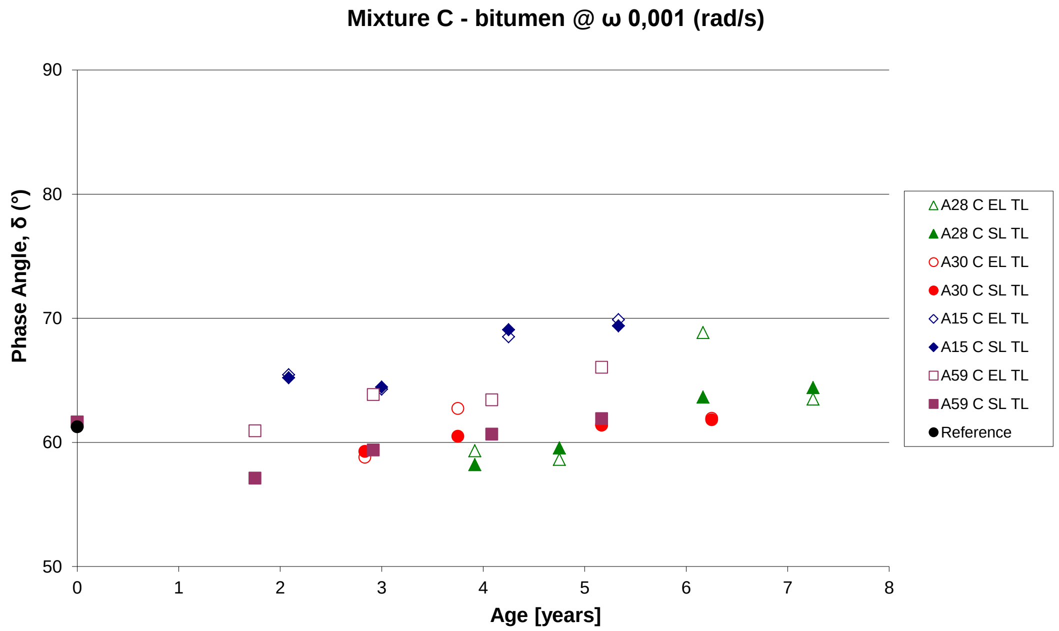

Figure 6: The phase angle of the road sections at loading speed corresponding to daily temperature cycles.

Figure 5 and 6 show the graphs of the phase angle trough time at 0.001 rad/s and 1000 rad/s. At high frequencies of 1000 rad/s it can be seen that the A28 has a slightly larger phase angle. At low frequencies there seem to be no significant trends in the change of the phase angle over time. It is assumed that the slight increase in phase angle over time can be related to the degradation of polymer [3,4].

Summarizing the data it can be seen that the A28 is the least stiff of all bitumen samples at different frequencies. If the phase angle of the material is observed, no significant differences are seen between the road sections at 0.001 rad/s, at high frequencies the A28 has the largest phase angle, the absolute differences in are small however. The A30 displays the largest increase in the complex modulus at higher ages, however the phase angle for the A30 does not show large differences from the other sections. As the differences in the complex modulus seem more significant compared to the phase angle it is decided to focus in the discussion on the correlation between the complex modulus and the damage in practise on the changes in complex modulus. It must be realized that this is a simplification.

Trends in damage observed in practise

The amount of ravelling on a road surface is measured by visual inspection. An inspector drives on the emergency lane and assesses the ravelling damage of the road. Of each section of 100m two damage parameters are noted, the severity of the damage and the extend of the damage (part of the road surface that is affected) by means of classes as described below.

Severity classes of ravelling

Light:	6-10% stone loss in one m^2
Moderate:	10-20% stone loss in one m^2
Severe:	>20% stone loss in one m^2

Extend classes of ravelling

Small:	<15% of 100m of roadsection
Moderate:	15% t/m 20% of 100m of roadsection
Large:	>25% of 100m of roadsection

The visual inspection has been reported over the course of six to eight years, depending on the construction time of each road section, see table 1. Each road section is around 400m long, at one measurement per 100m this results into 4 measurements per road section (in some cases 3 or 5, when the section was a bit shorter or longer). In the analyses the average performance of each section is taken.

In order to show the development of the damage, the extend of ravelling and the severity is combined in one graph and shown over time. On the x-axis the number of days after construction is shown. On the y-axis the affected percentage of the road surface is given (max 100%). The colour is related to the severity of the damage; in light grey the surface subjected to light ravelling is given, medium grey is used for moderate ravelling and black is used for severe ravelling. If the graph is totally white, this means that no ravelling is observed. If the graph is light grey for 30% and moderate grey for 40% this means that 30% of the surface is subjected to light ravelling and 40% is subjected to moderate ravelling, 30% is still intact. The graphs showing the damage for the four sections can be seen in figure 7.

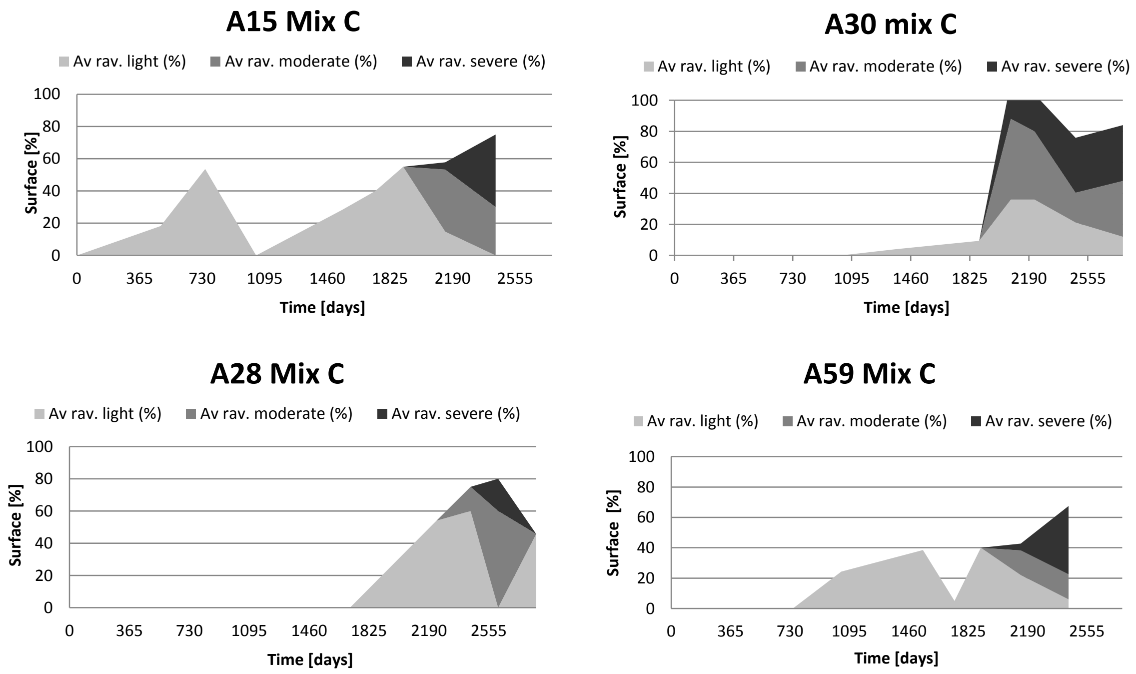

Figure 7: The amount of ravelling for the four different road sections trough time made with the same mixture

Some interesting observations can be done when the graphs in figure 7 are observed. First of all the measurement techniques is not very accurate. For example on the A15 at two years (730 days) there is a substantial amount of ravelling reported, however one year later (1095 days) there is no ravelling reported. It is impossible that both observations are true as no maintenance has been performed between the measurements. A second observation is that even though the mixture and the binder are the same, the performance in practise is different. The mixes on A15 and A59 start to ravel light at younger ages compared to the A28, where light ravelling occurs a bit later. The A30 shows a different trend in failure which might be related to the different binder.

The data as presented in the graphs is complex to use in a comparison with laboratory data, therefore a damage criteria is introduced in order to manipulate the data to obtain a more straightforward set. As the data shows quite some scatter, it is not realistic to define more then one level of damage. The most distinct moment in the data is the initiation of moderate ravelling damage. At this moment the road has not failed yet, but it is a distinct point in the degradation process that can be used for comparison. The result of this data manipulation is given in table 2 by the moment of damage initiation per location. From this table it becomes again clear that the A28 performs better than the other three sections.

Table 2: Defined damage initiation for all road sections and the moment in time that this occurs.

Road	Initiation of moderate damage	Age [days]	Age [years]
A15	7-10-2009	1903	5,2
A28	6-5-2009	2445	6,7
A30	22-10-2008	1883	5,2
A59	7-10-2009	1837	5,0

The inspection data show that the time until the first significant amount of damage occurs on the A28 is 25% longer compared to the other road sections. This is remarkable as bitumen research showed that the binder was the same for the A15, the A28 and the A59 [3]. Data available from the moment of construction on production temperatures and the mixture composition as realized on the road show hardly any difference between the sections [2]. The biggest difference is that A28 shows is a slightly higher bitumen percentage of 5.4 bitumen compared to 5.1 and 5.2 for the other road sections (data is obtained from cores drilled after construction). The A30 has a bitumen percentage of 5.0%.

Relation between laboratory data and performance in practise

The observed smaller complex modulus at the A28 and the better performance in practise implies that there could be a relation between the complex modulus of the extracted binder and the amount of damage on the road. In order to investigate this relation an attempt is made to look for a damage criterion with respect to the complex modulus. For the damage in practise the data points that are described in the previous paragraph are used.

In graph 3 and 4 the data points are circled by a grey dotted line if the damage criterion has been met. First Figure 3, showing values of the complex modulus at high loading frequencies, is studied more carefully to look for a criterion. Based on the grey circles in this graph the following criterion can be formulated: Moderate ravelling damage is initiated when the average value for the complex modulus of the emergency lane and the slow lane exceeds $8.5*10^7$ GPa. However when looking at the data corresponding with low loading speed, as seen in figure 4, no absolute value can be defined. In this graph the grey circles show that damage occurs at all complex modulus values, while at the same values the performance of other sections is still good. From this it becomes clear that the complex modulus at this low loading speeds cannot be used as criterion in itself. The amount of data is limited in this research, therefore the trends found here can not by any means be used to make any general remarks.

A validated damage criterion could help to asses the remaining service life of a road section, which will provide a valuable tool for the planning of maintenance. The life extending potential of maintenance using rejuvenators could be quantified. It could also be used to asses the suitability of different binders for porous road surfaces, based on their behaviour after laboratory aging. Finally it could help to focus the development of new binders that have a higher ravelling resistance due to modified properties.

In the Superpave regulation also described in [5] the following criterion is formulated for fatigue cracking $G^* \cdot \sin\delta < 5000$ kPa. The fact that a criterion for damage was formulated for fatigue cracking indicates that the complex modulus is a good start to find a criterion for ravelling. It also shows that further research into the combination of the complex modulus and the phase angle should be explored. Therefore in future research with respect to ravelling more data will be acquired with respect to these values so that a more broad criterion can be formulated.

It must be noted that in spite of the fact that the complex modulus of the extracted binder (potentially in combination with the phase angle) shows potential as a damage indicator for porous road surfaces in practise, is not likely that this is the only influence factor. The graphs on the complex modulus show that trends differ between the observed behaviour of the A15 and the A59 (figure 3 and 4), while the time until first moderate damage is not very different (table 2). If all the graphs (figure 3 to 7) are viewed it the feeling rises that time in itself also has a very important influence on the service life. This time-related factor could be associated with aging of the binder or the interfaces between the binder and the aggregates, due to temperature, UV-light or moisture. For future research it is recommended to see if data from other research can be related to this this time dependant aging.

Conclusions and Recommendations

In this research the performance of one asphalt mixture applied on four road sections is investigated. In order to look for parameters that influence ravelling on porous road sections, tests are performed on extracted binders to look for aging trends that can be matched with performance in practise. This lead to the following conclusions:

- The chemical tests performed on the extracted binders in this research (GPC and Infrared) did not show any significant trend in long term aging.
- The complex modulus did show a significant trend in behaviour of the extracted bitumen over time, especially at high loading frequencies (1000 rad/s).
- From the comparison of the inspection data it became clear that even though the same mix design was used in different locations the time till damage was 25% longer for one of the four road sections.
- The section that performed best showed the lowest complex modulus values at different loading frequencies.
- The section that performed best showed the highest phase angle at high loading frequencies, but at low loading frequencies no significant difference in performance between the sections was observed.
- Besides the complex modulus the factor time also seems very important with respect to the initiation of damage.

Based on the limited data set presented in this paper there seems to be potential to look for a ravelling criterion based on the complex modulus possibly in combination with the phase angle for the expected performance of porous surface layers with respect to ravelling. However much more data is needed for formulations and validation of such a criterion.

It is recommended that the differences in performance between similar porous asphalt mixtures should be investigated further. Can this difference be explained by the slightly higher bitumen content in the as built situation, or are there other possible explanations?

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