Effects of Traffic and Environmental Loads on Mortar Behavior in PA mixtures: Field and Laboratory Study

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Abstract
Bam Wegen has laid two innovative and one standard porous asphalt (PA) test sections on the A18 motorway near Varsseveld. The performance of these sections is being monitored periodically. One of the technique employed to gain insight on performance is to monitor behavioral changes of the bituminous mortar as a result of traffic and environmental loadings. For each monitoring phase, asphalt cores are being drilled from the test sections and brought into the laboratory. In the laboratory, mortar is extracted from these cores for response investigation using Dynamic Shear Rheometer (DSR) tests. The obtained data is used to compare any differences between the test sections. For each section, data showing the evolution of the response with time is also being gathered. From the data, effects of traffic and environmental loading on the response behavior of the different mortars are obtained. The data also provided insight on the effects of mixing production technology and mixture additives on the mortar response. This paper presents initial findings based on results obtained for the first two inspections that were made to date.

1. Introduction

Since the 1990s the Dutch government policy dictates the use of noise reducing pavement on motorways. That lead to the current state that more than 90% of Dutch motorways have Porous Asphalt (PA) surfacing. While PA's open structure is advantageous for acoustic performance, it has negative consequences in relation to structural durability. As a result the service life of PA is limited, i.e. about 8 years for Twin Layer and 10 to 12 years for single layer PA[1]. Optimizing the structural and acoustic performance of PA layers is therefore of prime importance. The challenge facing road engineers in this regard is double fold: while there is an increasing demand to maximize noise reduction capacity of PA layers (environmental aspect), the PA layers are also desired to have better durability so as to minimize required maintenance intervention and maximize road availability.

BAM Wegen is actively involved in research aimed at developing innovative asphalt mixtures that meets demands both on the durability and environmental aspects. With respect to environment, BAM Wegen aspires not only to reduce acoustic emission of pavements but also to cut CO_2 emissions in asphalt production processes. In relation to new developments in PA applications, BAM Wegen has laid two innovative and one standard PA test sections on the

A18 motorway in the year 2013. The performance of these innovative PA layers has been monitored. The first innovative PA mixture laid on the test section is produced using a Low Energy Asphalt Concrete Technology, in Dutch acronym referred as LEAB. The production temperature for the LEAB mixture is in the range of 90°C to 100°C. Based on successful application of this technology for the production of a hot-mix-equivalent AC mixtures for binder layers as well as for production of PA mixtures laid on regional roads [2], this specific test section aims to provide further proof for the LEAB-PA performance on major motorways.

The second innovative section is a PA mixture consisting of 3.2 mm long acrylic fibers. The fibers, referred from here on as PAN fibers, are obtained from Lambda Furtherance bv. PAN fibers were previously used in a Twin Layer PA on the A15 motorway near Leerdam. The purpose then was to investigate any possible improvements in the initial skid resistance of TLPA layer. Even though there was not any improvements in the skid-resistance, further inspection of the TLPA layer, after 5 and 7 years of service, revealed a distinct performance with respect to raveling. The use of the PAN fibers in this TLPA layer, with pen-grade 70/100 bitumen, seem to enhance the raveling performance. Further follow-up research reveal indications on the positive contribution of the fibers in enhancing the fatigue performance and mastic erosion characteristics of the PA mixture [3-5]. Based on this, BAM Wegen believes application of the fibers in a standard PA mixture can potentially lead to a durable PA mixture. The performance of these two innovative test sections will be compared with the performance of a third test section, which is a standard PA mixture, laid to serve as a reference.

To evaluate the performance of these innovative PA mixture, the test site is periodically being monitored. One of the method used to monitor relative differences is via investigations on the behavior of the bituminous mortar. Since performance of asphalt mixtures is highly dependent on the performance of the mortar [6], monitoring the behavior of the mortar with time is believed to provide valuable insight as to the expected performance of these mixtures. The work presented in this article specifically focuses on the research performed on the mortars taken from these test sections at two distinct time intervals, i.e. immediately after laying and after 6 months of service.

2. Response of Bituminous materials

Bituminous materials in general posses elements of elastic, viscous and viscoelastic response properties. For small loads, the response behavior is dependent on loading time and temperature. For short loading times or lower temperatures, the materials respond nearly elastic. For long loading times and higher temperatures they behave viscous. For intermediate temperatures and loading times they posses both elements of viscous and elastic, visco-elastic, responses [7].

Various tests can be carried out in the laboratory to characterize bituminous materials. Time-domain tests, such as relaxation and creep, are preferred for characterizing materials for long loading times. When the response of the materials for very short loading times is of interest, frequency domain tests are carried out to accurately describe their behavior. The information obtained from frequency domain tests can later be used to indirectly describe the short loading time response behavior of the materials[8].

For the mortars used in this study, frequency domain tests are carried out for temperatures ranging from -10°C to 60°C. At each temperature frequency ranges varying from 0.1Hz to 60 Hz are covered. The data obtained at various temperatures can be brought into a single master curve using time-temperature superposition principle. For this purpose the Williams-Landel-Ferry (WLF) equation, Eq.(1), is used [7].

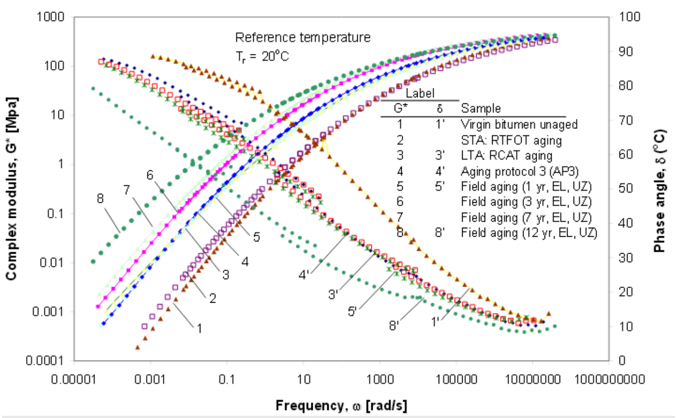
$$\text{Log } a_T = \frac{-C_1(T - T_0)}{C_2 + (T - T_0)} \tag{1}$$

In Eq.(1) C_1 and C_2 are constants, T is the temperature in ^{0}C, T_0 is the reference temperature in ^{0}C and a_T is the shift factor. In constructing the master curve at a selected reference temperature, the shift factor parameters are determined together with master curve model parameters using regression analysis. In this paper the MHS model is used to describe the master curve [9].

$$(G^*(\omega))^{-1} = \left(G_0 + \frac{G_\infty - G_0}{1 + \delta(i\omega\tau)^{-m_1} + (i\omega\tau)^{-m_2}} \right)^{-1} - \frac{i}{\eta_3 \omega} \tag{2}$$

Where G*(ω) denote the shear complex modulus; G_0, G_∞, δ, τ, m_1, m_2 and η_3 are model parameters, and i denotes imaginary number in complex number notation. Even though one can characterize the mortar behavior at a given time, the mortar in a PA mixture undergoes behavioral changes under the influence of traffic and environmental loading. Simulating the field conditions in the laboratory is very complex. This is because the influencing variables for both traffic and environmental loadings in the field are highly random and too complex to quantify. To gain practical insight on the behavioral changes, one approach is to investigate mortar materials taken from existing PA layers. In this regard, samples taken from trafficked areas can provide insight on the combined effect of traffic and environmental loads. Samples taken from un-trafficked area, such as pavement shoulder or locations between wheel paths, can provide insight on the effect of environmental loading such as aging.

Insight on the effects traffic and environmental loads on the mortar behavior is deemed important as it highly determines the overall performance of the PA mixture. Environmental loads cause aging of the bitumen in a PA mix. Bitumen behavior also changes as a result of aging during mixing process, this is commonly known as short term aging. The importance of aging on binder behavior is illustrated in Fig.1 [10]. The literature data given in Fig.1(a) illustrate the effect of aging on the master curve properties of bitumen in PA layers. The labels 5,6,7 and 8 represent master curves for 1,3,7 and 12 years old field-aged PA binders respectively. In Fig. 1(b) illustration is given on the effect of aging during production processes[11]. It can be seen from this figure that the bitumen viscosity is quadrupled as a result of aging during mixing processes.



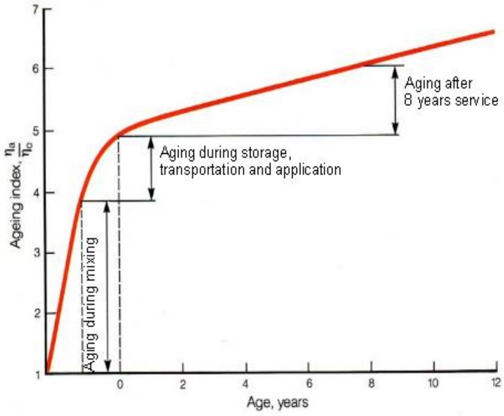


Fig. 1 Effect of field & lab aging on the master curve properties (a)[10], Effect of short and long term aging on bitumen viscosity (b) [11]

3. *Materials and Experiments*

3.1 Materials: Phase-I

The material for the first phase investigation was sampled immediately after laying. Cores having a diameter of 100 mm were drilled from the newly laid PA layer. In addition, loose PA mixture samples were also taken during the laying process. This extra sampling from the loose mixture was made to investigate any possible differences between the materials before and after compaction. Phase-I research will generally provide information on the properties of the fresh mortars used in the PA mixtures.

3.2 Materials: Phase-II

Samples for the second phase investigation was taken after the test sections were open for traffic for a period of 6 months. Similar to Phase-I, cores were taken from site very close to the previous bore locations. The locations for the boreholes were marked in Phase-I. For each bore locations, two cores were made. The first is taken from the right wheel path on the right lane, while the second is taken from the pavement shoulder. The core from the wheel path is meant to provide information on the combined effect of traffic and environmental loading, while the core from the shoulder is meant to exclusively provide information on the effect of environmental loading.

3.3 Experiments

The PA cores were brought into the laboratory. The cores were cleaned to avoid inclusion of dust particles in the mortar. Cleaning was made according to the LOT procedures [10]. This involve warming up the cores to temperatures in the range of 60°C to 70°C, crumbling the cores by hand, and finally wet sieving with a minimum sieve size of 1mm. After cleaning the material is dried at room temperature before mortar extraction can be performed. For extraction, the loose mixture is heated in an oven to a temperature in the range of 160°C to 170°C. From the heated material, the mortar is extracted for making DSR samples. Mortar extraction is performed by stirring and smearing the heated material with a spatula onto a metal pan. The mortar smeared on the bottom of the pan is then collected for DSR testing. For details on extraction method and sample preparation, the reader is referred to available literatures[10] Fig. 2 illustrated the DSR machine with the mortar sample mounted on it.

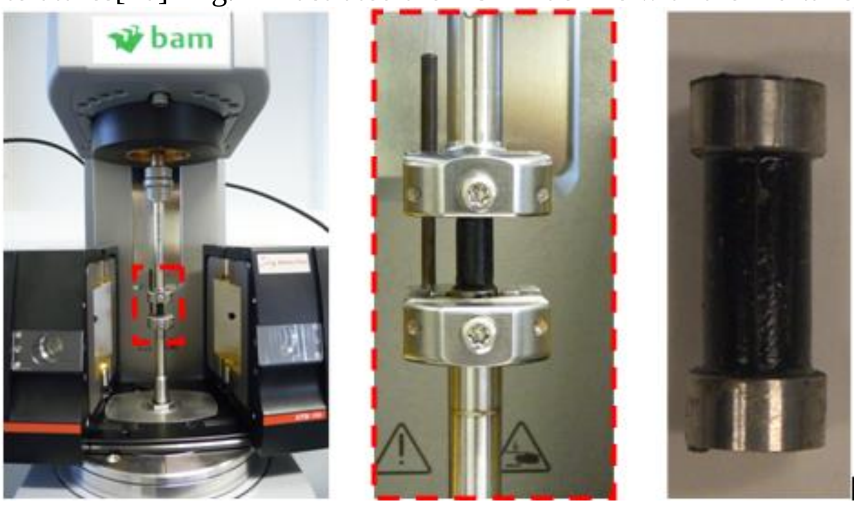


Fig.2 DSR machine(left), detail for mortar test setup(middle), test specimen (right).

For each test section, DSR frequency sweep measurements were carried out on two specimens at various temperatures. The data from the two specimens were then used to compose a master curve for each mortar. The scope of the work presented in this article is summarized in Table.1

Table 1: Plan for Phase I and Phase II monitoring

Tasks	Phase I		Phase II
Field work	Sampling: 100 mm diameter PA cores	Sampling: loose PA mixture	Sampling: 100 mm diameter PA cores (wheel path & shoulder)
Laboratory Work	Mortar extraction		
	DSR test specimen preparation		
	Frequency sweep tests (2 samples)		
Result analysis	Compose master curves & perform analysis		

4. Results and Analysis

4.1 Phase I

The purpose of the measurements carried out in this phase is mainly to obtain the behavior of the fresh mortars. Extra measurements were also performed to compare the behavior of the mortars extracted from loose mix and from the drilled cores. These extra tests were carried out to investigate if there is any changes in the mortar behavior due to unforeseen circumstances during laying and compacting processes. However, measurement results have shown that there exist no difference between mortars extracted from the loose mix and from drilled PA cores. Illustration on the obtained results is given in Fig.3 for the LEAB mix at a reference temperature of -10°C.

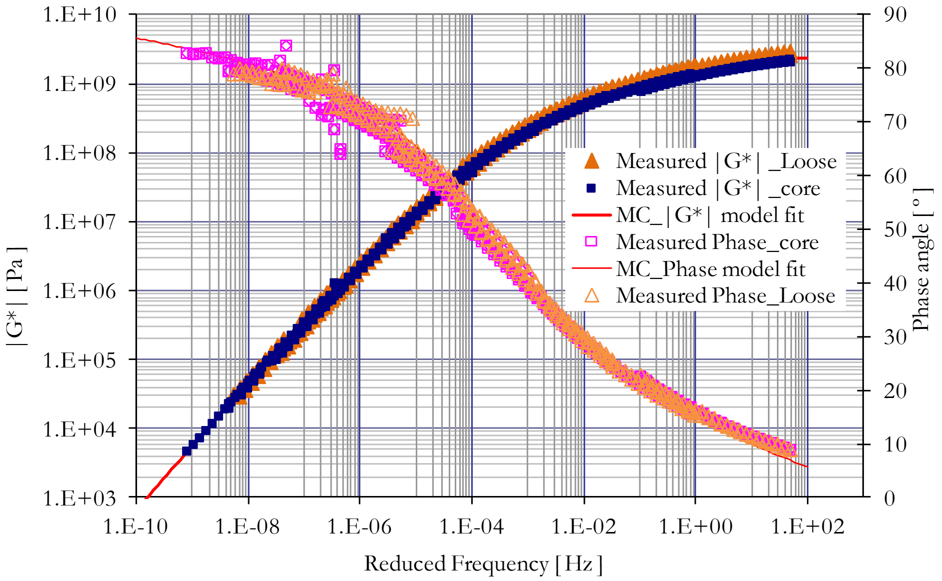


Fig.3 MC comparisons for mortars extracted from loose mix and drilled cores for LEAB

Similarity master curves for Standard and PAN mortars were constructed. For brevity results showing the individual master curves for the various mortars are not presented. However, the master curve comparison between the three mortars at a reference temperature of -10°C is given in Fig.4.

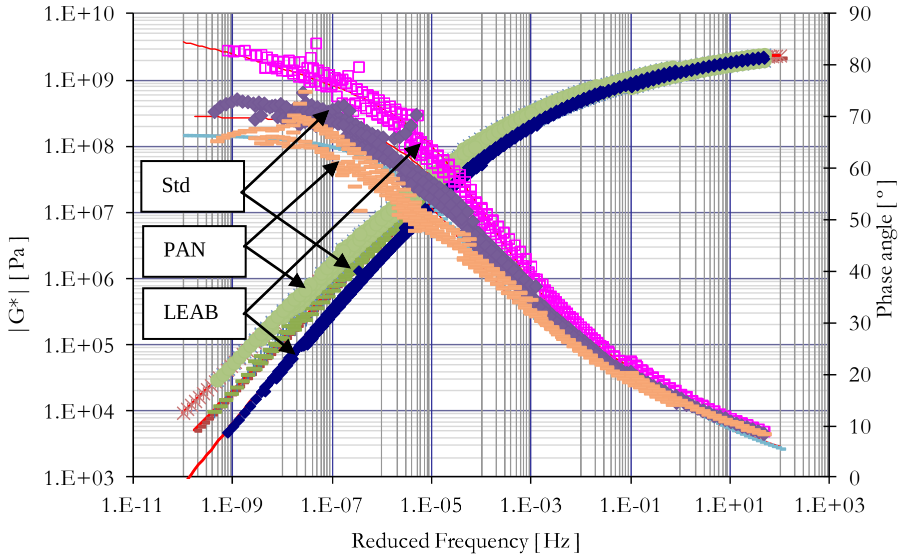


Fig.4 Master curve comparison for standard, LEAB and PAN mortar at Tref= -10°C

For all three mortars, differences at low temperatures (higher frequencies) are nuanced. In the low to intermediate frequency regions the PAN mortar has the highest stiffness. The stiffness for the standard mortar lies in between the PAN and LEAB mortars. The observed difference between the standard and LEAB mortars is intriguing. In the mixture recipe there is no difference between these two mixtures. The basic difference between the standard PA and LEAB PA lies only in the production process. The production temperature for the standard PA is higher (~170°C) than the LEAB-PA, which is in the range of 90°C to 100°C. Due to differences in the production temperatures, differences in aging of the mortars is expected. to some extent. Further investigation, e.g. viscosity measurement on extracted bitumen, is required to determine whether the observed differences in the master curves can fully be attributed to aging or not. It is nonetheless evident that the mortar from the standard mix is in the order of 2 to 4.5 times stiffer than the LEAB mortar for frequencies in the range of 1E-10 Hz to 1E-7 Hz. These frequencies correspond to measurements for temperatures of 50°C and 60°C.

4.2 Results from Phase II

After 6 months of service, PA cores were again drilled from the test sections. The cores were drilled from the wheel path and from the pavement shoulder. Mortar extraction was performed for making DSR samples. Similar to the tests carried out in phase I, frequency sweep measurement on two DSR samples were carried out to obtain one master curve for each mortar. Results were then compared with the fresh mortar behavior from Phase I. Fig 5. Presents the comparison between the fresh and the six month old mortar at a reference temperature of -10°C. Graph legends denoted with "0" refer to the results for the fresh mortars, i.e. mortars taken before the test sections were open to traffic. Legends denoted with "6m" refer results for six month old mortars. Sh and WP notations are used to differentiate between mortars taken from the pavement Shoulder and the Wheel Path.

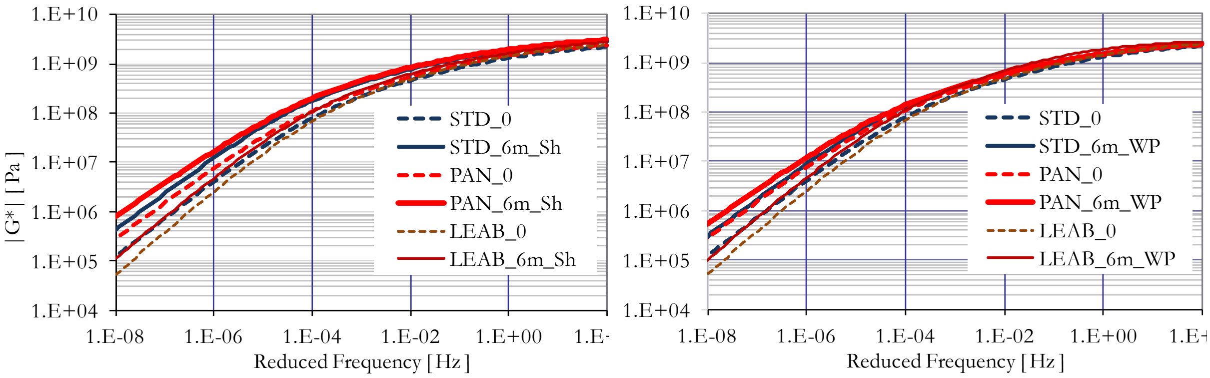


Fig.5. Fresh mortar compared with 6month-old mortar: Mortar taken from shoulder (left), and from the Wheel Path(right).

For all the mortars tested in Phase I and Phase II the master curve and shift factor parameters are summarized in Table 2. For both shoulders and wheel path locations, the mortar behavior after 6 months showed an increase in stiffness especially at low frequency(high temperature) regions. This is an expected trend as significant aging of binders in PA layers start to occur within the first year. Since traffic effects are not present on pavement shoulders, the comparison presented for the mortar from the shoulder material in Fig.5 (left) show exclusively the effect of aging.

Table 2: Master curve and shift factor parameters at Tref=-10°C for all mortars

Mortars	C1	C2	m1	m2	δ	τ	G_∞	G_0	η_3
Std_0	23.42	123.20	0.307	0.779	6.36	42.19	2.73E+09	5.12E-08	3.90E+22
Std_6m_Sh	23.02	116.75	0.280	0.753	6.01	95.76	3.67E+09	5.12E-08	3.88E+22
Std_6m_WP	23.02	116.75	0.281	0.751	6.12	76.62	3.10E+09	5.12E-08	3.88E+22
LEAB_0	20.61	105.51	0.313	0.774	5.60	26.98	2.95E+09	2.64E-08	1.66E+12
LEAB_6m_Sh	22.46	116.57	0.275	0.732	5.26	28.72	3.65E+09	3.18E-08	3.26E+12
LEAB_6m_WP	23.64	129.05	0.348	0.808	5.42	73.10	2.95E+09	3.22E-08	5.62E+12
PAN_0	21.25	106.32	0.299	0.740	6.30	61.03	2.95E+09	1.00E-09	3.83E+22
PAN_6m_Sh	23.58	120.84	0.258	0.682	5.08	64.09	4.01E+09	2.76E-08	6.14E+20
PAN_6m_WP	26.36	141.00	0.286	0.708	6.10	87.18	2.95E+09	2.76E-08	4.10E+20

4.3 Field Aging:

Referring to Fig.5(left), the effect of field aging is evident. Here the effect of traffic loadings are not present. Based on the low frequency region properties, Fig.5 shows that the stiffness of the LEAB mortar has almost doubled in 6 months time. For the PAN mortar, the stiffness increase is about 3 fold. Relatively the largest stiffness increase is observed for the standard mortar at about 3.5 fold.

The effects of aging are evident on master curve data at higher temperatures (also illustrated using literature data in Fig.1). The measurements at low frequency regions in Fig.5 correspond to the high temperature data, 50°C and 60°C. In this frequency region, the property for the 6 month old LEAB-mortar is nearly identical to the fresh mortar of the standard PA. This could be an indication that the production temperature differences between the LEAB and standard PA translates to an equivalent field-aging of 6 months on the master curve properties. Further investigations in the future, such as viscosity measurement ,on extracted binders could provide further proof to validate this equivalency. It is crucial to note that the weather conditions within a given time period can substantially affect the severity of field aging. For example a summer period with more warm days will certainly cause more aging. For the test sections studied in this article, the weather data for the period between the construction to the first Phase inspection is presented in Fig.6. The data is obtained from the Dutch weather website (KNMI). The data is recorded at the weather station in Deelen, which is the closest station to the test sections. The daily temperature, precipitation and humidity levels recorded at this weather station is given in Fig.6.

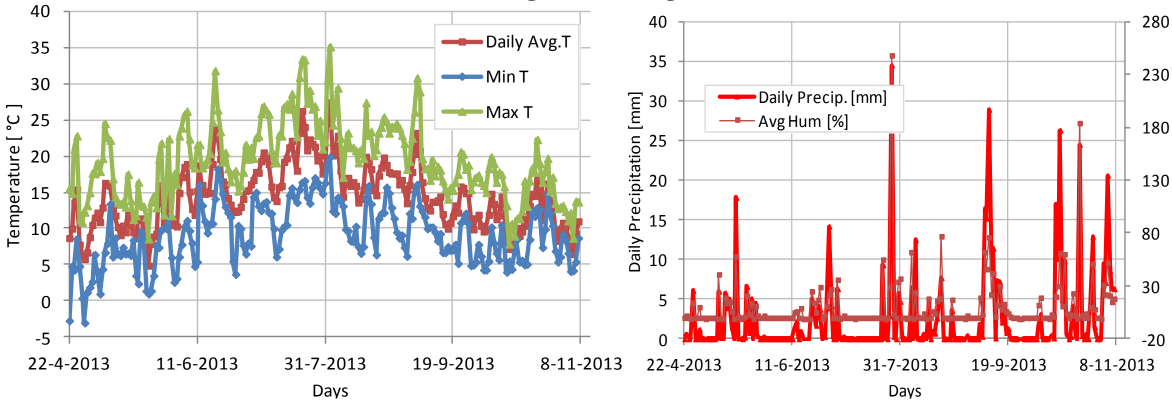


Fig.6 Weather data obtained from KNMI for recording-station located in Deelen

The data in Fig. 6 shows that in comparison to the mean temperature on the construction day, almost all daily mean temperatures within the six months period were warmer days. The data also shows there were some very extreme hot days (above 30°C) which favors accelerated-aging to take place.

4.4 Combined Effects of Traffic and Field Aging:

Direct effects of traffic on the mortar behavior is fatigue. This means in a long term, reduction in stiffness (modulus) is expected as a result of fatigue. Such analysis are valid for fatigue tests in the laboratory. In practice, however, more variables are present while relating effects of traffic with fatigue. One important variable is aging. During the trafficked period, the mortar behavior in a PA mix undergoes changes as a result of aging, which will lead to an increase in stiffness. Fatigue on the other hand causes reduction in stiffness. Due to the presence of combined traffic and environmental effects, it is hardly possible to exclusively obtain the effects of traffic from mortar response measurements alone. However, a general insight can be obtained via comparing mortar results obtained for the shoulder and wheel path locations. Fig.7 presents master curve comparisons for mortars taken from the shoulder and wheel path locations.

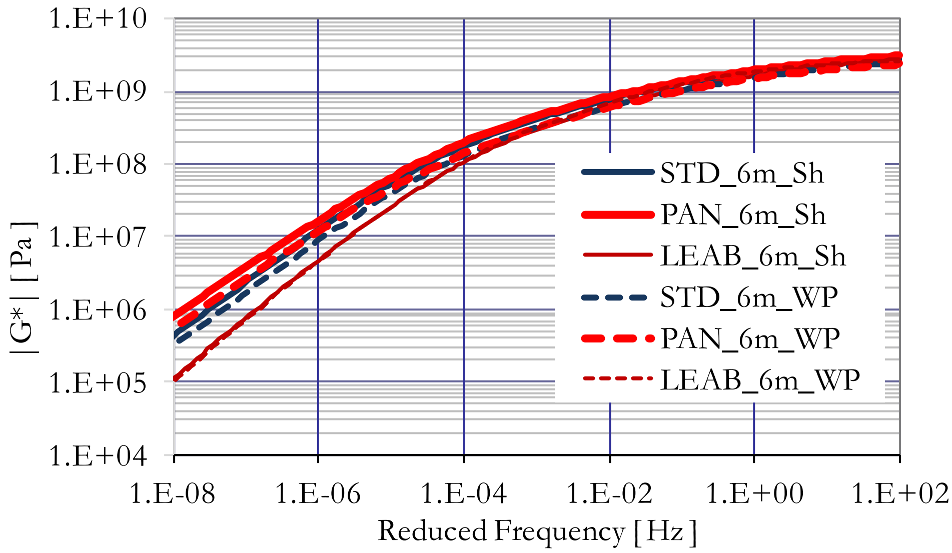


Fig.7 Master curve comparison for mortars taken from pavement shoulder and Wheel path.

The effect of both traffic and aging is present only on the mortars extracted from the wheel path. For the shoulder material, only the effect of aging is present. Referring to Fig.7, the effect of traffic has led to a slight reduction of the modulus at low frequency regions. However, this difference is generally very nuanced in comparison to the differences observed for aging. The differences for the LEAB mortar is even hardly visible. Considering the total traffic volume expected in the life time of PA layers, 6 month service period is relatively very short. The PA layers may have to serve more years for the effects of traffic to be clearly visible.

5. Conclusions and recommendations

Comparative study on the response of bituminous mortars for two innovative PA layers laid on the A18 was presented. The study investigated mortar characteristic for two inspection periods. The first corresponds to the construction moment. The second inspection is made after 6 months of service. Based on the investigations the following conclusions and recommendations are made:

Initial inspection- Phase I:

- The response characteristics of the standard PA mortar, LEAB mortar and PAN mortar were obtained for the newly-laid construction state.
- The PAN mortar is stiffer than the standard and the LEAB mortars. This is due to the presence of PAN fibers.
- The master curves for the LEAB and standard PA mortar are similar for intermediate and high frequency regions. For low frequencies, the LEAB mortar is found to be less stiffer. This is believed to be a result of production temperature differences. The lower production temperature for LEAB may have caused less short term aging.

Second Inspection- Phase II:

- After 6 months of service, mortars extracted from the shoulder of the pavement showed that significant aging already start to take place.
- Based on the low frequency region master curve properties, it is observed that the stiffness of the LEAB mortar has doubled in 6 months time. For the PAN mortar, the stiffness increase is about 3 fold. The largest stiffness increase is observed for the standard mortar at about 3.5 fold. All comparisons are in reference to the respective master curve properties from Phase I.
- The 6-month old mortar for the LEAB mix has similar properties with the fresh mortar for standard mix at very low frequency regions. For LEAB vs. standard mix, this could translate to a difference of 6-month field aging due to differences in production temperatures. Future viscosity measurements on extracted bitumen could provide valuable insight in explaining the observed differences in relation to aging vs. production temperatures for LEAB and standard mixes.
- Based on the first two inspections, the effect of traffic on the master curve properties is nuanced. However, a slight reduction in the complex modulus values at low frequencies is observed.

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