Influence of UV on Laboratory Ageing of Porous Asphalt Concrete Compared to Field Ageing

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ABSTRACT: In the Netherlands Porous Asphalt Concrete (PAC) is defined as a typical stone skeleton mixture with voids content of at least 20%. Raveling is the major distress, defined as the loss of stones in the top of the PAC layer. In this paper the role of UV radiation in the raveling process is investigated.

Standard laboratory ageing of bitumen was compared with recovered bitumen from PAC mixture ageing under a new developed ageing protocol. Both rheological and chemical analysis techniques were used. The new ageing protocol included temperature, UV light and humidity. In order to have a closer look at the influence of UV radiation, the upper zone (UZ) of the PAC layer was analyzed by recovering bitumen from the upper 20 mm of the layer.

From the FTIR it is clear that UV radiation changes the chemical composition, but it does not really show up in the rheological results. From the rheological tests it can be concluded that the protocol with temperature, UV and relative humidity is the most severe one.

KEY WORDS: PAC, Ageing protocols, UV radiation, FTIR.

1 INTRODUCTION

Porous Asphalt Concrete (PAC) is primarily used on Dutch highways to reduce traffic induced noise. In 2009 almost 90% of the Dutch highways were surfaced with a single layer of PAC. Two layer PAC is also used in cases where higher noise reduction is required. Compared to a reference dense asphalt concrete surface, a noise reduction can be obtained of 4 dB (A) with PAC and 6 dB (A) with two layer PAC (IPG, 2002, Hofman et al. 2005).

Ravelling or loss of aggregates from the pavement surface is a major durability problem of PAC. Aging influences the cohesive characteristics of the bituminous mortar. Because of the high voids content of PAC, the binder is strongly exposed to environmental influences which accelerate aging.

Standard laboratory aging methods like short term aging RTFOT (NEN-EN 12607-1, 2007) and long term aging RCAT (NEN-EN 15323, 2007)) focus primarily on oxidation and results from long term ageing are basically validated for dense mixes only. Long term ageing in a PAC layer is caused by the combined effects of temperature, UV light, and moisture due to the high voids contents. Because stones are disappearing from the surface, it was considered very important to separately investigate the influence of UV radiation and find out if UV radiation could play a role in the laboratory lab ageing procedures.

2 BACKGROUND ON UV RADIATION

Sunlight basically consists of three components: UV (ultra-violet), VIS (visible) and IR (infra-red) light respectively (table 1). The shorter wave lengths have a greater influence on the degradation of a material since higher energies are absorbed by the material that may exceed bond energies.

Table 1: Relative Spectral irradiance (Atlas, 2001).

Range Name	Wavelength range	% of Total
UV	295 – 400 nm	6.8%
VIS	400 – 800 nm	55.4%
IR	800 – 2450 nm	37.8%

Properly filtered Xenon arc lights produce radiation with a spectral power distribution that simulates the average daylight throughout the UV and visible region (Atlas, 2001). Figure 1 shows the spectral energy distribution of sun light and Xenon lights in the UV and VIS region (wavelength 295 – 800 nm). Figure 1 also shows that the Xenochrome 300 reasonably simulates the natural (sunlight) spectrum in the UV region (i.e. 295 – 400 nm).

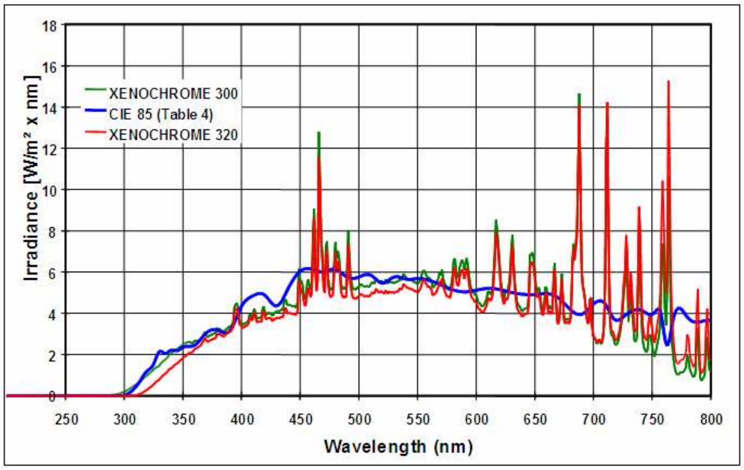


Figure 1: Filter combination for Xenotest instrument (Atlas, 2001).

The local conditions are important to simulate real life weathering. An example is given in Table 2 for the Netherlands (Lochem, inland and Hoek van Holland, at the sea) and for central Europe.

The Xenon light values of table 2 can be used to convert the exposure of a material in field conditions to an accelerated equivalent number of hours in the weatherometer. The theoretical time required to expose a sample material in the weatherometer to an equivalent number of hours in the field can be calculated with Equation 1.

$$t\,(hr) = \frac{Radiant\ Exposure\ H\ (Ws/m^2)}{Irradiance\ E\ (W/m^2)*3600\,(s/hr)} \tag{1}$$

To simulate one year in Central Europe based on 300 – 800 nm exposure in the field with the Xenon light from table 2, it can be calculated from equation 1 that 1035 hours are required. See the calculation below based on equation 1.

$$t\,(hr)=\frac{H\left(Ws/m^2\right)}{E(W/m^2)*3600\,(s/hr)}=\frac{2050*10^6}{550*3600}=1035\,hr \qquad (1\ \mathrm{MJ/m^2} = 10^6\ \mathrm{Ws/m^2})$$

Similarly for irradiance exposed in the UV range (300 – 400 nm) for one year, the equivalent number of hours to simulate field conditions with the Xenon light of table 2 will be:

$$t\,(hr)=\frac{H\left(Ws/m^2\right)}{E(W/m^2)*3600\,(s/hr)}=\frac{215*10^6}{60*3600}=995\,hr$$

Combination of the above calculations means that approximately 1000 hours of UV exposure with the Xenon light of table 2 is needed in a weathering chamber to simulate the effect of 1 year UV radiation. However, because the laboratory aging is conducted at elevated temperatures, the reaction rate is probably also accelerated. Therefore, combination of the effect of high aging temperature with UV exposure with the Xenon light (simulation of sunlight irradiation) will accelerate the overall aging process.

Table 2: Climatological data for Lochem (the Netherlands, NL), Hoek van Holland (NL), and Central Europe (Atlas, 2001) compared to the capacity of the Xenon light of the weatherometer.

Climatological Data	Lochem (NL)	Hoek van Holland (NL)	Central Europe
Latitude	52º30’N	51º57’N	
Longitude	6º30’E	4º10’E	
Elevation above MSL (m)	35	6	35
Average Amb. Temp. (ºC)	9	10	10
Relative Humidity RH Annual mean (%)	83	87	82
Annual mean rainfall (mm)	715	800	800
Annual mean radiant exposure (MJ/m^2)			
Total (295 - 3000 nm)	3700	3800	3550
UV (295 – 385 nm)			215
UV+VIS (295 – 800 nm)			2050
UV at 340 nm			1.90
Xenon light	550 W/m^2 (300 – 800 nm) →(UV + VIS) 60 W/m^2 (300 – 400 nm) →(UV) 0.55 W/m^2 (340 nm) →(UV, one λ)		

3 MATERIALS AND TESTING PROGRAM

The materials used in the preparation of PAC specimens for aging are presented in table 3. The complete composition is given in table 4. Both Marshall specimens and slabs were produced.

The Marshall method was used to compact the asphalt specimens according to the procedure in the Dutch standard specifications (CROW, 2005). The specimens were compacted using 50 blows on each side of the tablet. The diameter of the specimen is 100 mm. The thickness of the samples was between 40 and 43 mm. The average void content was around 17 %. This void content was below the minimum of 20%, but tests were already performed after the lower value was observed. It is assumed in this paper that the difference in voids content has only minor influence, because void content of 17% is also very high.

Table 3: Material properties used in the aging of bulk bitumen and asphalt mix.

Type of material	Grade / Size	Density (kg/m^3)
Bitumen (Kuwait)	70/100 pen	1030
Aggregate (bestone)	2 mm – 16 mm	2770 (average)
Sand (crushed sand)	0.063 mm – 2 mm	2781
Filler (Wigro 60K)	< 0.063 mm	2620

Table 4: Composition of PA mixture based on the Dutch standard (CROW, 2005).

Sieve / Aggregate size (mm)	Density (kg/m^3)	RAW Spec. % retained	% ret. by weight.	Cumm. % ret.	Weight (gm)
C 22.4 – 16.0	2778	0 – 5	1.7	1.7	12.3
C 16.0 – 11.2	2774	15 – 30	21.0	22.7	151.6
C 11.2 – 8.0	2762	50 – 65	33.5	56.2	241.9
C 8.0 – 5.6	2765	70 – 85	21.7	77.9	156.7
C 5.6 – 2.0	2677	85	7.1	85.0	51.3
2.0 – 0.063	2781	95	10.9	95.9	78.7
< 0.063 (Filler: Wigro 60K)	2720	100	4.1	100.0	29.6
					722.0
Bitumen 70/100	1030	4.5% by wt.			34.7
–			Total wt.		756.7

The details of the chosen aging protocols AP1 (temperature), AP2 (temperature +UV) and AP3 (temperature+UV+RH) are given in table 5.

Table 5: Aging protocols used in the weatherometer.

Aging Protocol		Protocol 1 (AP1)	Protocol 2 (AP2)	Protocol 3 (AP3)
		Marshall specimens		Beams from slab
Air temp.	[ºC]	40	40	40
*BST Temp.	[ºC]	60	60	60
UV light (300 - 400 nm)	[W/m^2]	–	60	60
Rain/Water application	[-]	–	–	–
Humidity	[%]	–	–	70
Time	[hr]	1000	1000	1000

**NB: BST = Black Surface Temperature → temperature at the surface of the specimen*

Table 5 shows the test conditions for the aging protocols. The binder recovery was performed separately for the upper and lower zones of the asphalt cores to investigate the difference in the aging process in the two zones, which was also expected to reflect the conditions of aging in the field.

The slabs produced for ageing protocol 3 (AP3) had considerably higher voids content than the Marshall specimens (AP1 and AP2). The voids content of the compacted slabs was around 22 %. The voids content of the Marshall specimens was around 17 %. This difference in voids content should be taken into account when evaluating effects.

The recovered bitumen from aged Marshall specimens and beams from the slab was used for rheological and chemical tests. The rheological tests consisted of DSR measurements to determine master curves for the complex modulus and the phase angle and fatigue tests. The chemical tests consisted of FTIR and GPC tests. For detailed information, see (Hagos, 2008)

4 TEST RESULTS

4.1 DSR test on Binders Recovered from Mixture Aging

The master curves of bitumen recovered after mixture aging under aging protocols 1 (temperature aging), 2 (temperature + UV light aging), and 3 (temperature + UV light + humidity (RH) aging) are shown in figure 2. Standard laboratory aged bitumen after short term (RTFOT) and long term (RCAT) ageing is also included in figure 2. The shifting was performed to a reference temperature (T_r) of 20ºC.

Figure 2 shows that the phase angle of the binders converges both at high and low frequency regions. The partially aged binder (STA: RTFOT) and the recovered bitumen from the compacted mixture (directly after fabrication of the mix) have comparable complex modulus, whereas their phase angles show slight differences. Aging protocol 1 and 2 (AP1 and AP2) seem to give comparable complex modulus values, only at the low frequency region they show some difference. The phase angles are comparable only at higher frequency region. At the lower frequency region, the phase angle of the AP1 binder is also comparable with the STA binder and the binder from the unaged mixture. The binder recovered from the upper zone (UZ) of the mixture aged under protocol 2 (AP2) has a higher complex modulus and lower phase angle compared to the lower zone (LZ). Only aging protocol 3 (AP3) seems to predict similar to the long term aging tests of a binder in the laboratory. The long term aged (LTA) binder and the binder recovered from aging protocol 3 (AP3) show comparable complex moduli and phase angles, with only some difference in the low frequency region. This could be due to the protocol, but also to the higher voids content compared to AP1 and AP2.

In figure 3 typical fatigue results at a shear strain of 10% are reported for bitumen aged under protocols AP1, AP2 and AP3 (Hagos, 2008). Fatigue results of bitumen recovered from field cores (with void content of 20% and more) are also included.

Figure 3 illustrates that the fatigue performance of laboratory aged binders strongly differs from field aged materials. The RCAT (LTA) and recovered AP3 aged binders show similar fatigue performance. The binders recovered from AP1 and AP2 seem to have comparable fatigue behaviour, but have significant lower complex modulus during the fatigue test than the AP3 bitumen. The recovered bitumen from 7 and 12 year old cores from the field show completely different fatigue behaviour compared to bitumen aged under all laboratory aging protocols. The transition from stage 1 to stage 2 fatigue of the field materials is occurring at a lower number of loading cycles while the initial stiffness is much higher.

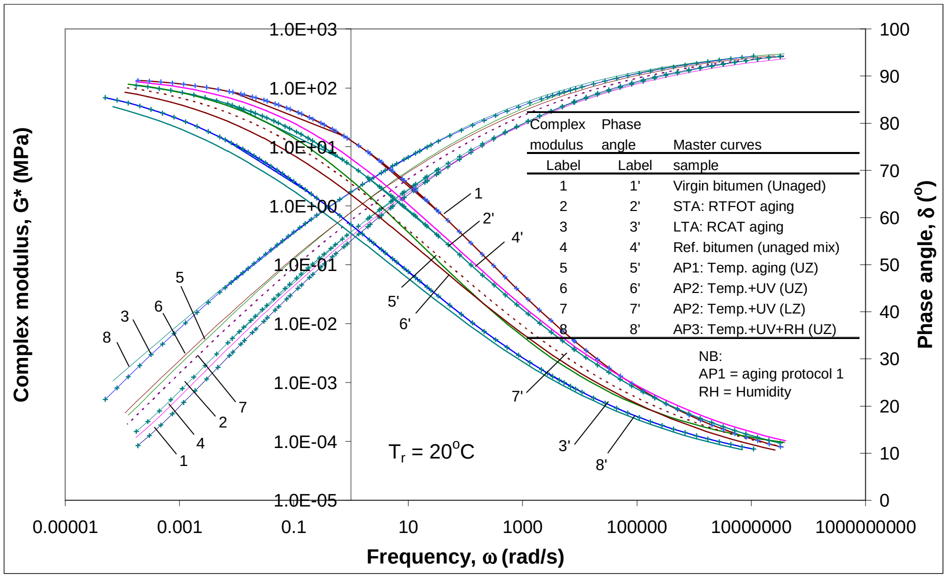


Figure 2: Master curves at 20ºC for complex shear modulus and phase angle of laboratory aged bitumen materials using the conventional bitumen aging methods and new mixture aging protocols.

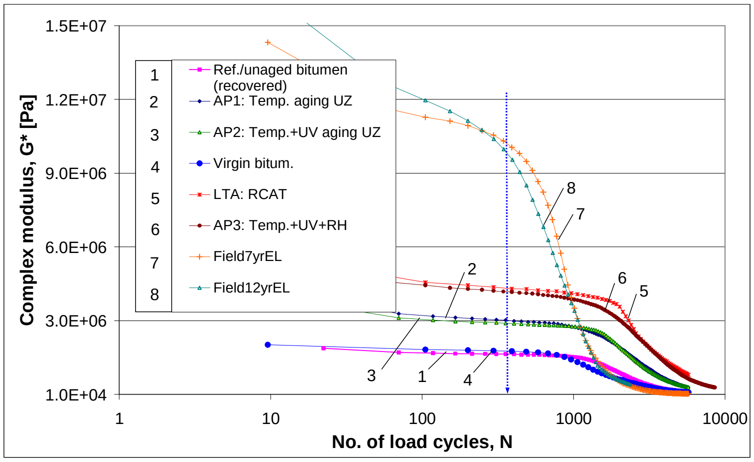


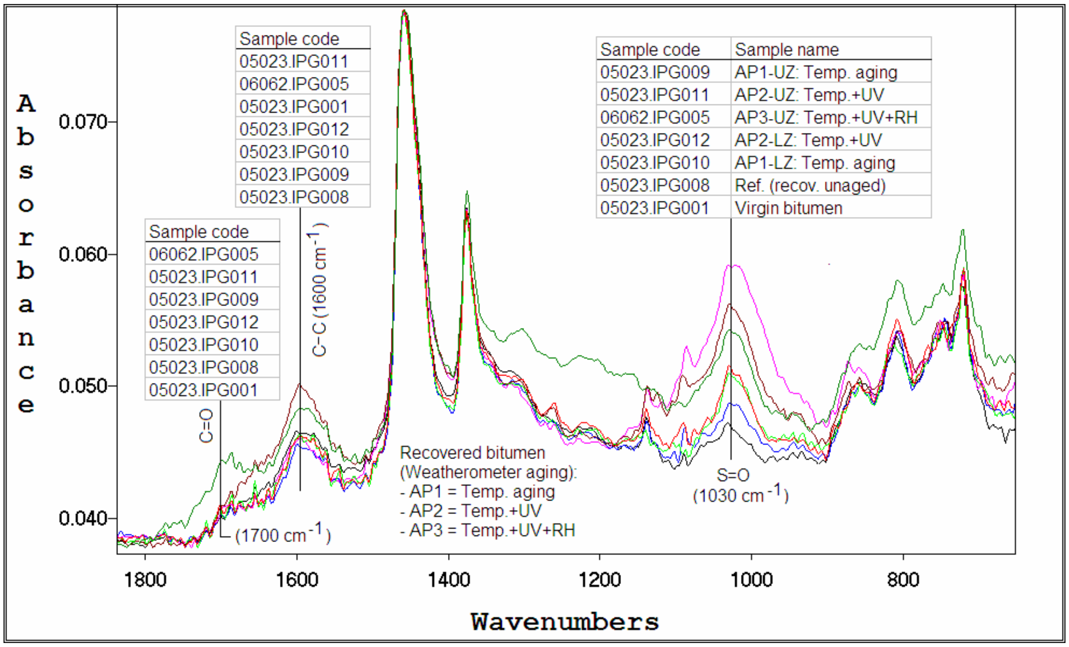
Figure 3: Fatigue test results of binders at 10 rad/s, 10% strain, and 20^{o}C temperature.

For AP1 and AP2 both the complex modulus values and the fatigue results show that UV does not really has impact compared to only temperature ageing. Compared with AP3 the difference seems to be in the relative humidity. However, it is uncertain if the difference in voids content is also playing a role.

4.2 FTIR and GPC on Recovered Bitumen from Mixture Aging

4.2.1 FTIR

FTIR results of bitumen recovered from a PAC mixture aging under aging protocol AP1 (temp. aging), AP2 (temperature + UV aging), and AP3 (temperature + UV + RH) are shown in figure 4. The spectrum includes the upper zone (UZ) and lower zone (LZ) of the specimens aged under AP1 and AP2 protocols and the UZ of the AP3 protocol. According to the IR spectrum results at the finger print region shown in figure 4, the peak heights at the S=O bond are decreasing in the order of AP1, AP2, and AP3 for the UZ samples. The AP3 (UZ) and AP2 (UZ) binders show considerable increment at the C–C peak, whereas only the AP3 seems to result in a significant increment at the C=O peak. In other words, AP3 is contributing to the formation of both sulfoxides and ketones, resulting in the increment of the oxidation peaks at the S=O and C=O. Temperature aging (AP1), however, is resulting predominantly in the formation of sulfoxide characterized with the peak at the S=O bond. The increase in peak height at the two oxidation products (C=O and S=O) seems balanced in the case of aging using the AP3 protocol, while the AP1 protocol predominantly increased the sulfoxide peak.

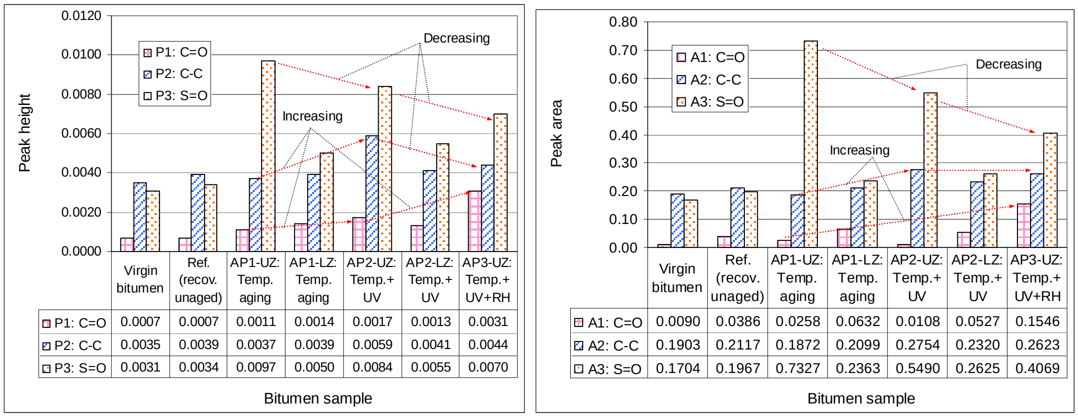


Sample code	Sample name
05023.IPG009	AP1-UZ: Temp. aging
05023.IPG011	AP2-UZ: Temp.+UV
06062.IPG005	AP3-UZ: Temp.+UV+RH
05023.IPG012	AP2-LZ: Temp.+UV
05023.IPG010	AP1-LZ: Temp. aging
05023.IPG008	Ref. (recov. unaged)
05023.IPG001	Virgin bitumen

Figure 4: IR spectrum of recovered bitumen from PA mixture aged under AP1, AP2, and AP3 aging protocols (samples are numbered, and absorbance ranking can be seen vertically).

The AP3 protocol correlates well with the aging process in the field in terms of oxidation peaks of the bitumen at the ketone (carbonyl) and sulfoxide functional groups. In order to correlate the rate of aging of the bitumen with field aging, samples were taken during the progress of AP3 weatherometer aging. Only the aging protocol AP3 shows a general rise in the response/spectrum throughout the frequency range in addition to the development at the specific oxidation related peaks. The peak area and peak height of the functional groups are shown in figure 5.

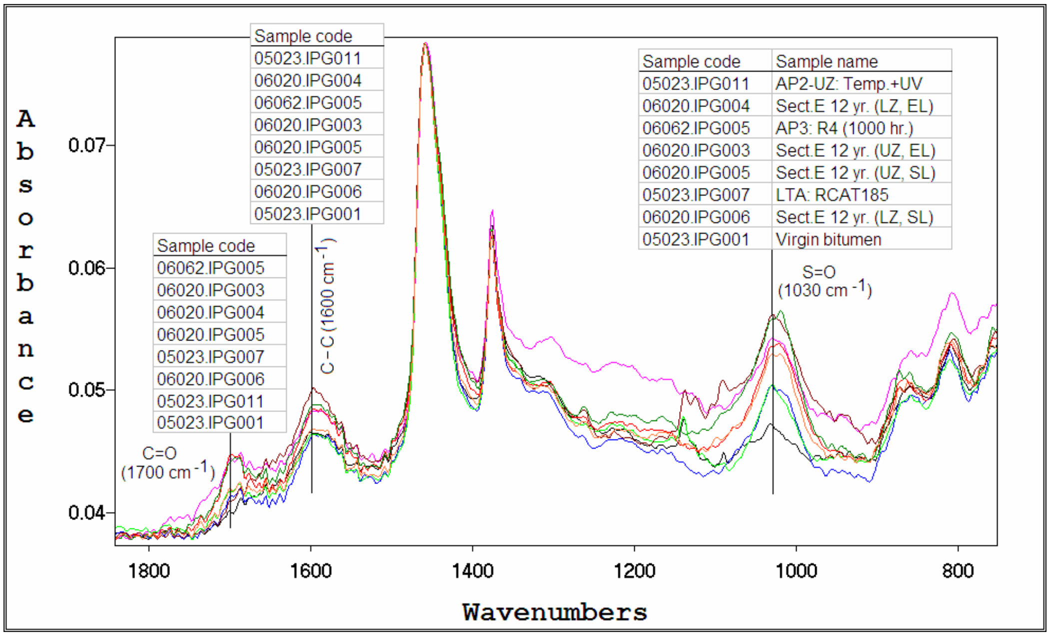
From figure 6 it can be seen that the aging of bitumen in the field seems to be reasonably in compliance with the laboratory aging procedure AP3 with regard to the development of the aging products at the sulfoxide (S=O) and ketone (C=O) peaks. Again AP2 is highest at the sulfoxides peak, but lowest at the ketone peak. The aging method AP3 employed for the aging of mixes in the weatherometer seems good enough to predict field aging conditions both in the emergency and slow lanes of the upper zone UZ. AP3 samples had similar voids content as the field samples.



	Virgin bitumen	Ref. (recov. unaged)	AP1-UZ: Temp. aging	AP1-LZ: Temp. aging	AP2-UZ: Temp.+ UV	AP2-LZ: Temp.+ UV	AP3-UZ: Temp.+ UV+RH
P1: C=O	0.0007	0.0007	0.0011	0.0014	0.0017	0.0013	0.0031
P2: C-C	0.0035	0.0039	0.0037	0.0039	0.0059	0.0041	0.0044
P3: S=O	0.0031	0.0034	0.0097	0.0050	0.0084	0.0055	0.0070

	Virgin bitumen	Ref. (recov. unaged)	AP1-UZ: Temp. aging	AP1-LZ: Temp. aging	AP2-UZ: Temp.+ UV	AP2-LZ: Temp.+ UV	AP3-UZ: Temp.+ UV+RH
A1: C=O	0.0090	0.0386	0.0258	0.0632	0.0108	0.0527	0.1546
A2: C-C	0.1903	0.2117	0.1872	0.2099	0.2754	0.2320	0.2623
A3: S=O	0.1704	0.1967	0.7327	0.2363	0.5490	0.2625	0.4069

Figure 5: Peak heights (left) and peak areas (left) of the oxidation products of bitumen recovered from mixture aging



Sample code
05023.IPG011
06020.IPG004
06062.IPG005
06020.IPG003
06020.IPG005
05023.IPG007
06020.IPG006
05023.IPG001

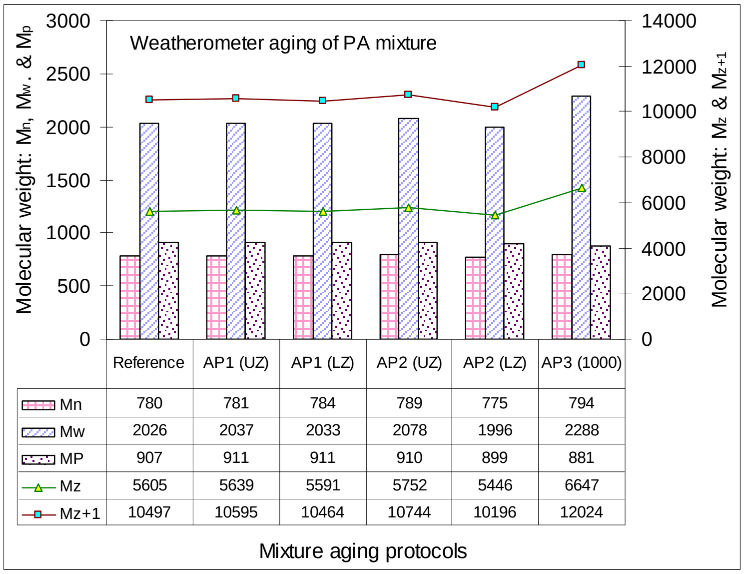
Sample code
06062.IPG005
06020.IPG003
06020.IPG004
06020.IPG005
05023.IPG007
06020.IPG006
05023.IPG011
05023.IPG001

Sample code	Sample name
05023.IPG011	AP2-UZ: Temp.+UV
06020.IPG004	Sect.E 12 yr. (LZ, EL)
06062.IPG005	AP3: R4 (1000 hr.)
06020.IPG003	Sect.E 12 yr. (UZ, EL)
06020.IPG005	Sect.E 12 yr. (UZ, SL)
05023.IPG007	LTA: RCAT185
06020.IPG006	Sect.E 12 yr. (LZ, SL)
05023.IPG001	Virgin bitumen

Figure 6: IR spectrum of binders from laboratory aging and recovered from field specimens (samples are numbered, and absorbance ranking can be seen vertically).

4.2.2. GPC results

The molecular weight of bitumen samples recovered from asphalt mixtures aged under aging protocol 1, 2 and 3 (respectively, AP1, AP2, and AP3) were determined with the GPC test. From the results molecular weight distribution (MWD) indicators were determined as reported in figure 7 (Hagos, 2008).

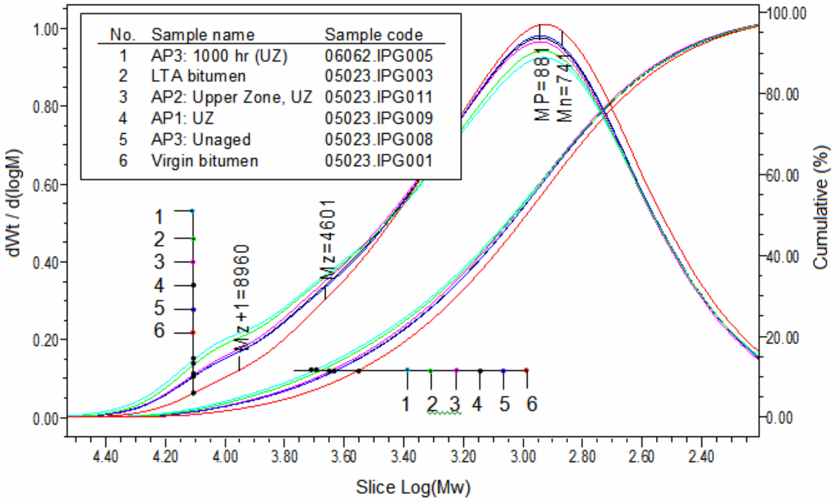


	Reference	AP1 (UZ)	AP1 (LZ)	AP2 (UZ)	AP2 (LZ)	AP3 (1000)
Mn	780	781	784	789	775	794
Mw	2026	2037	2033	2078	1996	2288
MP	907	911	911	910	899	881
Mz	5605	5639	5591	5752	5446	6647
Mz+1	10497	10595	10464	10744	10196	12024

Figure 7: MWD indicators for bitumen samples recovered from weatherometer aging (AP1, P2, and AP3) of the PAC mixture.

If the results from the upper zone (UZ) are compared from figure 7, hardly any difference can be seen for AP1 and AP2, again indicating that UV radiation is not make large impact. Only for AP3 some significant differences can be observed from the MWD indicators, again confirming the addition of relative humidity is making impact. This is only valid if the difference in voids content can be neglected.

Figure 8 shows that the samples recovered from the upper zones of AP1 (temperature aging) and AP2 (Temperature + UV aging) have similar molecular weight distributions. The AP3 aging, which is the aging protocol that combines the effects of temperature, UV light, and humidity (RH), again shows significant differences compared to the AP1 and AP2 aging as shown by the increment of the LMS of the distribution. The AP3 protocol seems to result in comparable large molecular size (LMS) fractions as the LTA protocol.



No.	Sample name	Sample code
1	AP3: 1000 hr (UZ)	06062.IPG005
2	LTA bitumen	05023.IPG003
3	AP2: Upper Zone, UZ	05023.IPG011
4	AP1: UZ	05023.IPG009
5	AP3: Unaged	05023.IPG008
6	Virgin bitumen	05023.IPG001

Figure 8: MWD of bitumen samples aged under standard protocol and recovered from mixture aging in the weatherometer.

5. CONCLUSIONS

From the results of recovered bitumen from the top 20 mm of the PAC layer the following conclusions can be drawn (assumed that the difference in voids content between AP1, AP2 samples at one side and AP3 samples at the other side can be neglected, while AP3 samples have void content similar to field cores):

UV radiation in itself is not a deciding factor in the ageing of bitumen in PAC

AP1 (Temperature) and AP2 (temperature + UV) show quite similar rheological behaviour. Adding humidity (AP3) has a huge impact on the rheological properties, comparable to long term ageing.

AP1 (temperature) and AP2 (temperature + UV) show difference in chemical composition as can be seen from the FTIR results. However, the GPC does not show different molecular distributions.

Based on FTIR and GPC the combination of temperature, UV radiation and relative humidity comes closest to the long term field ageing with regards chemical ageing. In terms of chemical changes, the weatherometer aging procedure AP3 (temperature + UV light + humidity) simulates field aging very well.

Standard Long Term Aging tests (like RCAT) working at very high temperatures give very different chemical reaction products compared to AP3 and field ageing.

Based on the rheological properties all laboratory aging methods do not simulate field aging of PA. Only AP3 can simulate chemical results more or less related to 3 years of field aging.

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