The Effect of Aging on the Rheology and Fatigue Response of Bitumen in Relation to Raveling in Porous Asphalt

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ABSTRACT: Due to ever increasing traffic loading, the need for long lasting pavements is growing. At the same time the demand for quieter roads is also becoming crucial in the Netherlands with its dense population. Porous asphalt (PA) is extensively used as surface layer on motorways in order to reduce traffic induced noise. However, the durability of PA layers is relatively low because of the high voids content in the mix. In this study, the effect of aging on the binder performance was investigated. The rheological investigation revealed that increase in modulus is achieved in the high (low frequency) and intermediate temperatures while no significant change is achieved at low temperatures. The fatigue response of the binder to repeated application of shear loading at intermediate temperatures using the time-sweep test in Dynamic Shear Rheometer (DSR) showed higher rate of damage development in aged binders but the performance was better than the unaged bitumen according to the evaluation made using fatigue resistance parameter Np. Initial test results thus ascertained the need for low temperature binder performance as a most relevant and critical factor for characterizing binder performance in relation to raveling / durability problem in PA.

KEY WORDS: aging, porous asphalt, binder fatigue, raveling

1 INTRODUCTION

PA is used extensively in the motorways in the Netherlands for environmental reasons with the objective to reduce traffic induced noise. The aging of the binder is believed to be a major factor resulting in poor performance or low durability (raveling) of these porous asphalt (PA) pavement layers. The reason is mainly due to high voids content (low density) of PA resulting in high rate of age hardening of the bituminous mortar. Because of the gap gradation of PA the aggregates form a stone matrix structure with point-to-point contact that results in a network of voids in the pavement structure. The aggregates in PA are covered with a relatively thin film thickness of bituminous mortar.

Because of high voids content (approximately 20% and higher), porous surface layers are sensitive to the damaging action of climate and traffic. The lifetime of these surface courses is between 4 and 16 years, depending on traffic intensity and environmental conditions, and the main reason for maintenance is raveling (loss of aggregate from the surface) and, to some extent, surface cracking. Raveling is not only threatening the durability of the surface course (early maintenance is required) but also has a negative effect on the noise reduction capacity of these surface courses. Raveling accounts for 70% of the yearly maintenance costs of PA surface courses [6]. Hence, an extensive research is being carried out to improve the performance of PA pavement layers in the Netherlands in which the raveling problem is also part of the studies.

This paper presents the initial findings of an on-going research study on the effect of binder aging in relation to the problem of durability (raveling) in porous asphalt pavement layers. The study involves accelerating the process of aging of bituminous materials with the objective to understand the influence of the mechanisms of aging on the rheological, mechanical and chemical properties of bitumen. To study the effect of aging, it is intended to study binder aging in the field and accelerated aging under different aging protocols in the laboratory. The research approach is thus categorized into two parts: 1) Aging in the laboratory: both bituminous materials (binder and mastics) and asphalt mixture aging, and 2) Coring samples from the field with different service periods. Interested readers are referred to an internal TU Delft report 7-04-132-2 for the general research plan of the aging project. In this paper only part of the laboratory test results in the first category of aging, i.e. accelerated aging of binders and asphalt mixes, are presented.

The experience in the Netherlands shows that raveling (loss of stones from the pavement surface) is mainly manifested during the winter season. This implies that low temperature performance of the bituminous mortar is a crucial factor with regard to the PA durability. The causes of raveling failure in PA are attributed to cohesive or adhesive failures or combination of the two. Adhesive failure, i.e. strength loss in the binder and aggregate interface, which is caused mainly due to water damage and the chemical interactions between the bitumen and the mineralogical composition of the aggregate, will not be addressed in this paper. The cohesive strength of a PA mixture is the core subject matter in this paper, in which according to Tolman et al [8] depends on factors such as:

- the strength of the binder,
- the mechanical properties of the bituminous mortar, and
- the binder film thickness

The increase in strength of the binder as a result of aging seems to have a positive influence to the mechanical performance of PA. However, age hardening increases the stiffness of the binder or the bituminous mortar and might not necessarily increase the toughness of the material. At low temperatures the hardening of the binder is accompanied by failure at lower strain levels. The relaxation behavior of the material is greatly influenced by aging depending on the bitumen/mortar film thickness. One of the methods to delay age hardening and improve performance at low temperatures is by increasing the binder film thickness without compromising the voids content in the mix and causing drainage of the mortar to occur (binder contents of 4.5% and 5.5% are commonly used in PA). In the intermediate temperatures, the fatigue property of the binder is of importance as the age hardening has an effect on the rate of damage development in the binder. Cyclic traffic loading in the pavement imposes stresses and strains that are relieved by the viscous damping and/or development of damage (micro cracks) in the material. The results of the limited tests performed in this study show that the effect of aging has no negative effect on the fatigue life of the binder at intermediate pavement temperatures[1] according to the fatigue resistance parameter (Np) evaluation. The Np is used as a fatigue resistance parameter denoting the number of load cycles required for transition from crack initiation stage to crack propagation [1, 2]. Thus the low temperature property of the binder, influenced by combination of traffic loading and cyclic environmental impact, is assumed to be critical in determining the performance of PA.

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[1] Weather data in the Netherlands for the last 20 years show that the absolute minimum air temperature goes as low as -19.6°C and the 98th percentile of the distribution is -12.8°C. The highest air temperature during the same period reached 36.2°C according to analysis of weather data from KNMI (Royal Netherlands Metrological Institute).

2 MATERIALS

Materials used in the aging of bitumen and asphalt mixes are presented in Table 1. The selection of the materials was made to correspond to the type of materials commonly used in porous asphalt pavement layers. Accordingly, bitumen pen grade 70/100 was used for short and long-term aging both as a bulk and in asphalt mix aging.

Table 1: Material properties used in the ageing of bulk bitumen and asphalt mix

Type of material	***Grade / Size***	***Density [kg/m^3]***
Bitumen	70/100 pen	1030
Aggregate (Quarry material)	2 mm – 22 mm	2770 (average for all sizes)
Sand (River sand)	0.063 mm – 2 mm	2781
Filler (Wigro 60K)	< 0.063 mm	2620
Hydrated Lime (HL)		2200

NB: The filler proportion used in the mixture consist of 25% HL + 75% Wigro 60K

3 EXPERIMENTAL

3.1 Aging of Bitumen

For short-term aging, RTFOT aging (EN 12607-1) was adopted and long term aging was conducted using the Rotating Cylinder Aging Test (RCAT) in accordance with the recommended procedure [9]. Short term aging simulates the loss of volatiles and oxidation reaction that take place during the production (mixing and transportation) of asphalt mix, laying and compaction stage (i.e. the construction phase). The long-term aging simulates the progressive oxidation during the service period of the pavement. Previous studies indicate that similar effects in the rate of change of the chemical components over the years (i.e. the change in molecular weights and concentrations of oxidation products: ketones and sulfoxides) were obtained as in the field aging of PA by the RCAT aging method [4]. The RCAT is a dynamic aging test and can also be used to combine the short term and long term aging procedures to minimize loss in handling the material during the two phases of aging.

3.2 Aging of PA Samples

Porous asphalt samples were prepared based on Dutch standard specification for ZOAB (Zeer Open Asfalt Beton). Marshal method was used to compact the samples with 50 blows on each side of the tablet. The specimens were of 100 mm diameter size with anticipated thickness of 50 mm. The actual thickness of the samples was measures to be lower than the target thickness (measured thicknesses range between 40 – 43 mm). Besides, it was verified using the CT scan method and conventional procedure of void content determination that the voids of the mixes were uniform throughout the thickness but for almost all the samples it was lower than the anticipated target voids. The expected voids content for Porous asphalt mixture should be in the range 20 – 27%, but test results are based on the actual mean voids content given in table 2. The fact that the voids content are lower than the intended minimum requirement does not change the interpretation of the effect of the different mechanisms of aging on the bitumen property and mixture performance.

The asphalt mixes were aged under two aging protocols: Aging protocol 1) aging under the influence of temperature and Aging protocol 2) aging under the combined effects of temperature and UV light. Table 2 shows the test conditions of the two aging protocols. Prior to binder recovery for subsequent rheological and chemical tests, Indirect Tensile Test (ITT) was performed on the asphalt mixes. The binder recovery was done separately for the upper and lower zones of the asphalt cores to investigate the difference in the aging process in the two zones, which is also believed to reflect the conditions of aging in the field.

Table 2: Test condition for aging protocol 1 (temperature) and 2 (temp. + UV) aging

	Reference samples	Temperature aging (*Aging protocol 1*)	Temperature + UV aging (*Aging protocol 2*)
No. of core samples	8	8	8
Avg. Voids Content [%]	18.2	16.2	17.8
Aging Temperature	Unaged	60^{o}C	60^{o}C
Time of aging	-	1000 Hrs	1000 Hrs
UV exposure	-	-	550 W/m^2

3.3 Rheological and Chemical Tests on Binders

3.3.1 Rheological Tests

After the aging of the bulk bitumen and recovery of the binder from aged asphalt samples, rheological test was conducted on the unaged and aged samples. It is assumed that the binder is subjected to shear stress at the stone-to-stone contact points in PA layer. For this reason the dynamic shear test was performed using the DSR (Dynamic Shear Rheometer) to characterize the effect of aging on the shear modulus of the binder at different loading times (frequencies) and temperatures. The test conditions were performed at temperatures ranging from -10^{o}C to 60^{o}C and frequencies of 0.01 to 400 rad/s. The principle of time-temperature superposition was adopted to generate master curves at a reference temperature of 20^{o}C. Low temperature characterization of the binder samples is currently in progress and not incorporated in this paper.

Moreover, time sweep test was conducted using the DSR equipment to evaluate the fatigue performance of binders. The test was performed at 20^{o}C and 30^{o}C (intermediate temperatures) using 8 mm and 25 mm parallel plate geometry respectively. Each test lasted for 3600 sec to provide enough time for the development of damage in the material (i.e. increase in dissipated energy due to crack propagation or softening of the binder). Stress relaxation test is another type of test performed on long term aged binder (RTFOT+RCAT) to evaluate the material performance to applied constant shear strain. Two strain levels were used, 10% and 25% at 1.0 mm, 1.5 mm, and 2.0 mm binder film thicknesses.

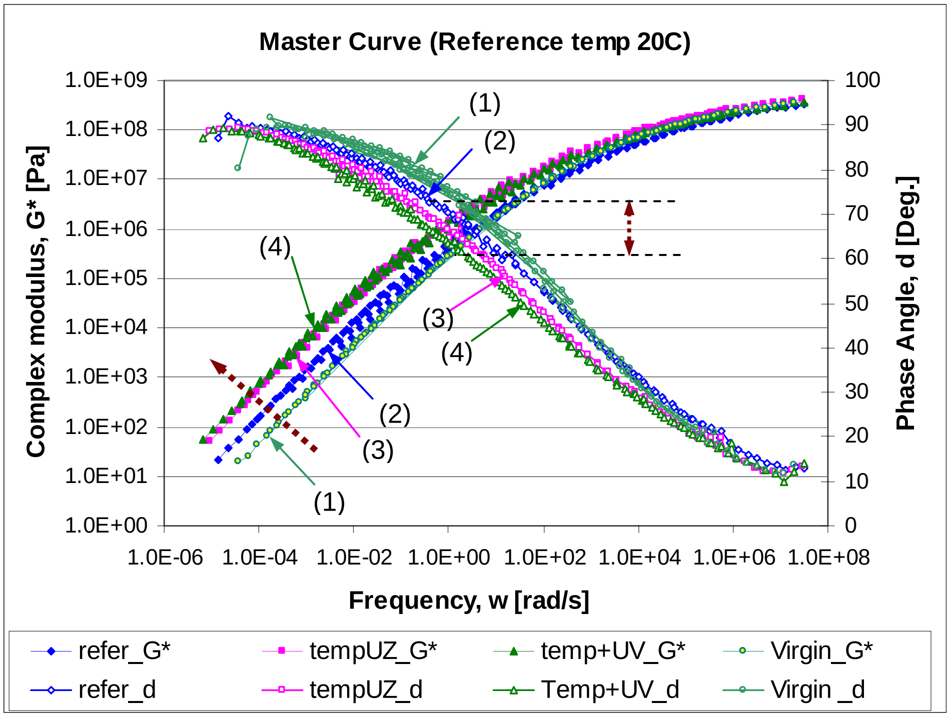
3.3.2 Chemical Tests

All the binder samples, unaged and those aged under different aging procedures were tested for chemical characterization using the Infra Red spectroscopy (IR) technique to understand the effect of different aging mechanisms on the chemical components (oxidation products). The response to infrared rays produces unique absorption peaks corresponding to the chemical composition of the material. The response of binder samples at the finger-print region, i.e. absorption peaks in the range 1800 to 600 cm^{-1} wavelength, provides essential information. Characteristic peaks designating increase in the oxidation products, namely ketones (bond C = O) and sulfoxides (bond S = O) are formed at 1600 cm^{-1} and 1030 cm^{-1} respectively [6]. Test results are shown in Figure 5.

4 TEST RESULTS

4.1 Rheological Tests

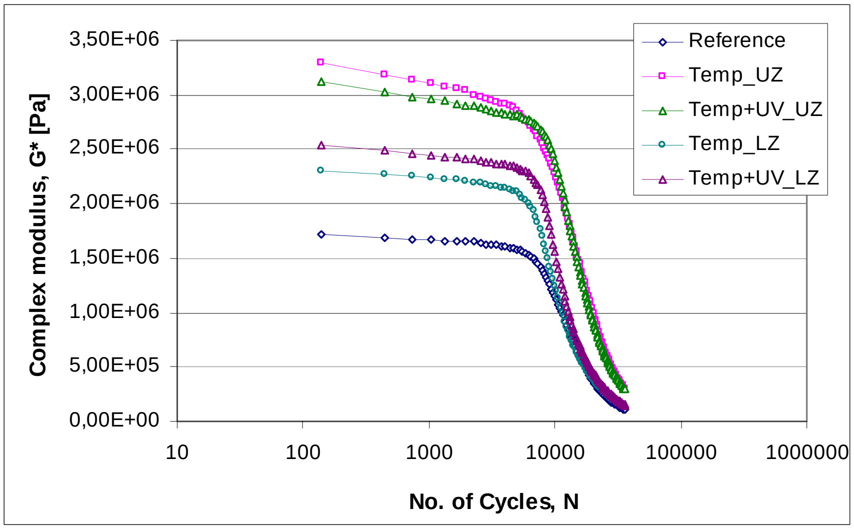
In Figure 1, the result of DSR measurement on the virgin, aged binders (RTFOT and RTFOT+RCAT aging representing short and long term aging respectively) and recovered binders, i.e. from unaged core samples, samples aged under aging protocol 1 (temperature aging), and samples aged under aging protocol 2 (temperature + UV exposure) are shown. The complex modulus and phase angle master curves have been constructed using the time-temperature superposition principle at a reference temperature of 20°C.



Nomenclature:
(1) Virgin_ G* = G* for virgin bitumen
(2) refr_G* = G* for recovered bitumen (Unaged)
(3) tempUZ_G* = G* for recovered bitumen from upper zone of core asphalt sample aged under aging protocol I (temperature aging)
(4) temp+UV_G* = G* for recovered bitumen from upper zone of core asphalt sample aged under aging protocol II (Temperature + UV light exposure)
The same designations apply for the phase angle (_d) master curve

Figure 1: Master curve of virgin and recovered bitumen before and after aging.

Bitumen fatigue test, i.e. strain controlled time sweep test in a DSR, was conducted to evaluate the binder's performance to the resistance of damage development. Time sweep test is a cyclic load application test (either strain or stress controlled tests can be performed) in which the decrease in modulus of the binder is recorded as a function of time or number of cycles of loading. The results of fatigue test for the recovered bitumen conducted at 20°C (average pavement temperature), 10% strain level, and 10 rad/sec frequency are shown in Figure 2. The figure shows the effect of aging on the fatigue behavior of the binder. The results of the effect of strain level and frequency of loading on the fatigue characteristics of aged and unaged binders are not shown.



NB: UZ and LZ are meant to be upper and lower zones in the asphalt samples respectively

Figure 2: Fatigue test on recovered binders at 20°C, ω = 10 rad/sec, and 10% strain level

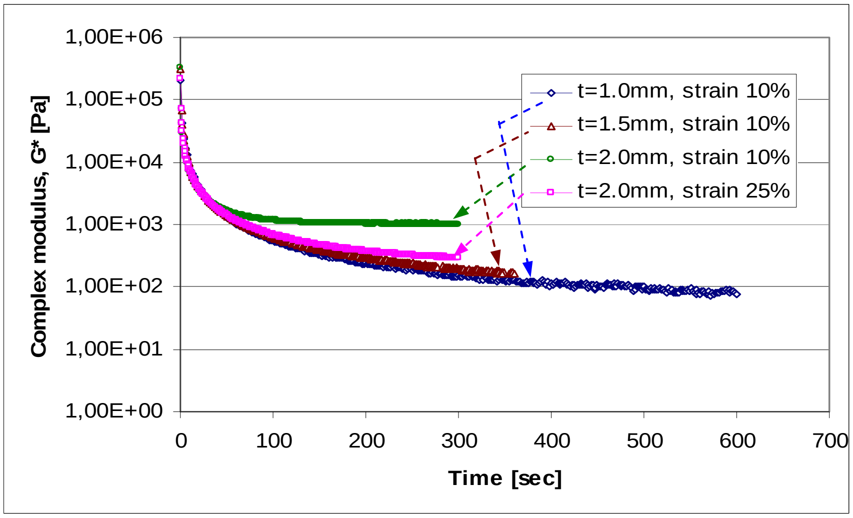


Figure 3: Effect of strain and binder film thickness on the stress relaxation at 20°C

Figure 3 shows the results of relaxation tests conducted on RTFOT+RCAT aged 70/100 bitumen. It is shown that the decrease in binder film thickness not only delays the relaxation time but the material also attains a lower modulus when the stress is totally relieved. Application of higher strain results in a similar effect of reduction in modulus when stress relaxed. In this regard, the relaxation property of the binder (complex modulus as a function of relaxation time) can be seen as an important parameter to relate the effect of binder thickness with PA performance.

Results of mechanical test (Indirect Tensile Test (ITT)) on asphalt mix samples conducted before the recovery of the binder are presented in Table 3. All samples from each aging protocol, i.e. reference (unaged), aged under temperature, and aged under the combined effects of temperature and UV, were tested at 5°C and displacement speed of 50 mm/min. Although the performed ITT test was limited and had large variability, the strength of the samples aged under aging protocol 2 showed intermediate strength between the reference samples and those aged under aging protocol 1.

Table 3: ITT test result for core samples aged under different aging procedures

Aging protocols	No. of Samples	Max. Force Avg. [KPa]	Strength ITS Avg. [MPa]	Stiffness Avg.[KN/mm]	Energy Avg.[KNmm]
Reference	4	12,246	1,811	2,446	30,507
1) Temperature	4	17,017	2,513	3,399	27,596
2) Temperature + UV	4	13,860	2,066	2,767	27,801
Test conditions:	Temperature 5°C, Displacement rate 50 mm/min				

4.2 Chemical Test

Infra Red Spectroscopy (IR) test was conducted to investigate the effect of aging on the chemical components of the binder. The response at wave lengths 1600 cm^{-1} and 1030 cm^{-1} characterize the increase in oxidation products ketones (C = O) and sulfoxides (S = O) respectively. Test results showed that protocol 1 aging of 70/100 pen bitumen increased the sulfoxide concentration while protocol 2 aging increased both sulfoxide and Ketone concentrations. Refer to Figure 5 for the results of IR spectrum in the finger-print region.

5 DISCUSSION

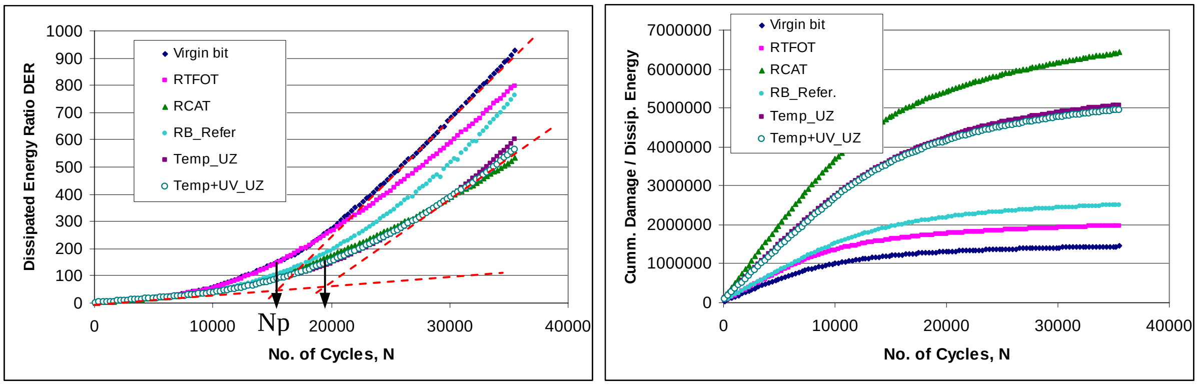
5.1 Interpretation of the Master Curves

The age hardening of the binder results in higher modulus of the binder as anticipated. The effect of the two mixture aging protocols on the complex modulus master curve does not seem to differ much as is shown in Figure 1. The phase angle master curve, however, shows noticeable difference at the intermediate frequency range; the binder recovered from aging protocol 1 exhibits the lowest phase angle. The difference in phase angle decreases and becomes negligible at the higher frequency range (corresponding to low temperatures). On the other hand, the highest difference in modulus due to aging is observed at the lowest frequency region. Increased modulus at high temperature is attributed to an increase in the storage modulus or decrease in the loss modulus component of the binders. Decrease in viscous component of the modulus, however, does not necessarily contribute positively to the strength of the material especially at low temperatures since the strain limit (flexibility) is greatly influenced. The consequences of age hardening thus affect the toughness of the material and increase its susceptibility to cracking.

It is worth noting that different aging mechanisms (protocols 1 and 2) show difference in the effects of binder aging signifying that UV light has an effect on the material rheology, which is also a reflection of changes in the chemical composition. This fact is also revealed in the chemical analysis using Infra Red Spectroscopy (IR) which is discussed in section 4.2.

5.2 Effect of Aging on Fatigue and Relaxation Properties

In binder fatigue test (either stress or strain controlled tests), there are two stages of damage described as stage 1 (crack initiation stage) and stage 2 (crack propagation stage). In stage 1, the energy per cycle of loading is dissipated in viscoelastic damping with negligible damage. The transition phase from stage 1 to 2 is a stage where the crack initiation consumes additional amount of energy beyond the viscoelastic damping. Stage 2 is the critical stage in which noticeable increase in dissipated energy per cycle is observed. This stage is where irrecoverable fatigue damage takes place [1, 2]. According to Bahia et al 2001, the fatigue life to crack propagation (Np) is used as a fatigue resistance indicator parameter to mark the transition from the crack initiation to crack growth. The reason for damage development in the two stages of fatigue could, however, be as a result of crack initiation and propagation or the softening of the material.



(a.) (b.)

Figure 4: Fatigue tests on binders aged under standard procedure and recovered from aged mixes a.) Dissipated energy ratio b.) Cumulative dissipated energy as a function of no. of cyclic loading at 20^{o}C

According to the binder fatigue test results, keeping the frequency and temperature constant and varying the strain level results in a horizontal shift of the fatigue line (data/figure not shown). The shifting of the fatigue line towards the low frequency range at higher strain levels is plausible since early damage development is anticipated in the material. Fatigue test on aged bitumen results in an increase of the slope of the second stage fatigue damage as shown in figure 2. Although stage 1 fatigue of the materials begins at higher modulus for the aged binders, phase 2 seems to follow almost after the same number of loading cycles. In stage 2 fatigue, the loss of energy per cycle of loading is greater for aged bitumen samples as indicated in the cumulative damage development in Figure 4(b.). However, the dissipated energy ratio (DER), as shown in Figure 4(a.), is lower for the aged materials. Accordingly, the fatigue parameter Np (an indicator of the number of cycles for progressive cracking in the material to be initiated) is higher for aged materials than the unaged indicating that the performance of unaged binders is in effect better. It is worth to note, nevertheless, that the difference in Np is not significant. In general, the rate of change of fatigue damage from the first to the second stage is rapid for aged materials followed by greater damage per cycle in stage 2 and this damage development is expected to get more pronounced if fatigue tests are to be performed at lower temperatures.

From Figure 4, it can be deduced that the aging of the binders has no negative effect on the fatigue performance of the binder (i.e. at 20^{o}C) based on fatigue parameter Np. Although the rate of damage development is higher in the aged binders, the fatigue performance indicator Np shows that the aged binders are more resistant to the cyclic loading and thus have relatively longer life (Figure 4). An important assumption with regard to PA is, however, that the higher the rate of damage development in the binder, the higher the acceleration of damage due to coupled additional factors such as water damage or freeze and thaw leading to stripping of the stones. From a practical point of view, a plausible argument on the raveling of PA pavements as a result of aging is because of severe damage imposed on the binder/mortar by low temperature stress coupled with freeze and thaw cycles during the winter season and the action of traffic. Besides, the self healing potential of the bitumen is reduced during this season of low temperatures and as a result of age hardening [1, 3, 7]. As the binder fatigue test results revealed aged binders performed relatively better at intermediate temperatures, hence, the future focus of the research on the effect of aging will give attention to performance of binders at low temperatures (0^{o}C and below). At low temperatures, the effect of age hardening is expected to have much influence on performance of PA since the toughness of the binder governs failure properties of the binder as strain at failure of the bituminous materials is low (characteristic of brittle material) and stress at failure is high.

The role of film thickness can be better understood by the relaxation behavior of the binder to applied stress or strain. The effect of film thickness in PA layers is important since it contributes to improved durability by reducing the rate of aging and increasing cohesive strength. Figure 3 shows the results of relaxation test conducted on 70/100 bitumen aged using RTFOT + RCAT procedure. It shows that the decrease in binder film thickness not only delays the relaxation time but also the material attains lower modulus when the stress is totally relieved. An application of higher strain results in a similar effect as the binder performance with a reduced film thickness resulting in reduced modulus after the relaxation of stress. In this regard, relaxation test (modulus as a function of relaxation time) is considered essential to evaluate binder performance and as performance indicator of PA mixture.

In figure 3, with application of 10% strain the binder with 1.0 mm thickness showed lower modulus after relaxation and took the longest time to relieve stress followed by the 1.5 mm thick bitumen and the 2.0 mm film thick bitumen performed much better. At higher strain level, the relaxation period increases and the final modulus decreases, implying that the decrease in film thickness and higher strain loadings have similar effects on the performance of the bituminous material. It is shown for the 2mm thick binder at 25% and 10% strain levels that at 25% strain the binder has closer performance to the 1.5 mm thick binder at 10% strain. The feasible argument is that the stress developed by higher strains produces higher stress in the material and requires extended time to relax stress. Hence, the relaxation test can be a useful performance indicator tool in relation to film thickness but it is also important to couple it with the fatigue resistance of the binder for a better understanding and judgment of binder performance.

In general, the damage inflicted by traffic on the cohesive strength of porous asphalt pavements is much severe during winter periods. This assertion is believed to be true because of the performance of the binder to repeated loading shows high rate of damage at low temperatures and high strain levels. The effect of increased strain level seems to have a similar effect on the damage characterization of bituminous materials as the development of damage at low temperatures. This implies that roads with high volume of traffic are likely to experience greater durability problem than low volume roads because of the damage developed in the material; for instance, in a multi lane road the heavily loaded lane with relatively low traffic speed is expected to ravel sooner than the fast lane. It is also recognized that the development of damage in the material accelerates failure since it is most probable that other factors such as water damage and frost action induce additional damage. In line with this assertion, aging (increased stiffness / age hardening of the binder) can be considered as having an effect in increasing the rate of damage, decreasing the strain limit and decreasing the healing potential of the bituminous mortar in PA.

The findings of the mechanical test results shown in table 1 seem to be acceptable noting the effect of UV exposure on the rheological and chemical properties of the binder. Thus, the effect of aging mechanism is important in rating the binder as well as PA mix performance.

5.3 Chemical Analysis using IR spectroscopy

The chemical characterization using Infra Red Spectroscopy (IR) reveals that the increase in the peak at 1600 cm^{-1}, characteristic peak for the oxidation product ketone (bond C = O), seem to be affected by the exposure of the bitumen to UV light as shown in Figure 5. The second characteristic peak for the sulfoxide (bond S = O) at 1030 cm^{-1} in the finger print region of the IR spectrum, shows that the aging of the asphalt mix produces a lower peak for aging protocol 2 (combined effect of temperature and UV light aging) compared to aging protocol 1 (aging with temperature alone). Thus, it can be said that the UV influences the oxygen intake of the bitumen during the aging process by sharing the oxygen to produce the two oxidation products, ketones and sulfoxides. The peak for the aged bitumen under temperature aging is higher at the sulfoxide peak since there is no significant increase at 1600 cm^{-1} implying that all the oxygen was used to produce sulfoxide. It is also worth noting that the binders from lower zones of the asphalt mixes have not shown increment in the peak at 1600 cm^{-1}. This can be explained by the fact that the UV effect does not reach the lower zones since both protocols of aging seem to have similar effect on both peaks of oxidation. Some studies claim that the changes in chemical components due to aging in the field are not predicted in the same way as in the laboratory [4, 6]; this could be because of the effect of UV light is not simulated. This result is thus important since changes in the chemistry of the material will likely influence the physical performance of the binder.

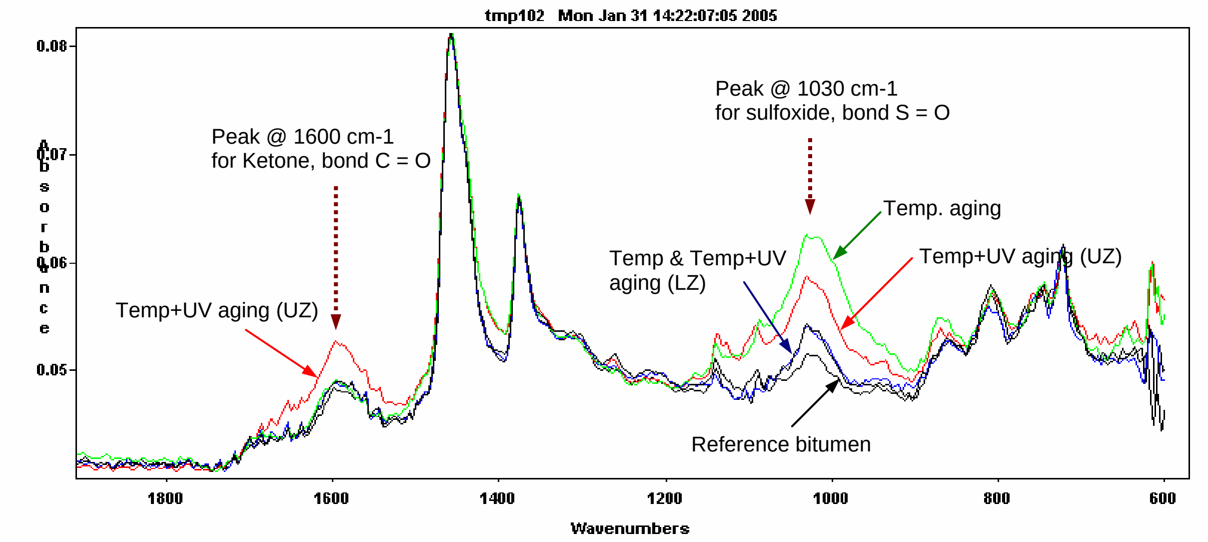


Figure 5: IR test results in the finger print region for reference and aged bitumen recovered from asphalt mixes

CONCLUSIONS

All the conclusions must be related to the voids content of the asphalt samples. Based on the limited tests performed to understand the effect of aging on the binder performance in PA pavement layers, the following conclusions can be drawn.

1. Exposure of bitumen to UV light in the process of aging has an effect on the chemical composition of the material. The physical property of the binder and the asphalt mix is also believed to be influenced by this effect.
2. At intermediate pavement temperature (20^oC), binder age hardening does not seem to have negative effect on the fatigue resistance of the binder, according to the fatigue performance indication parameter Np.
3. The binder film thickness changes the behavior of the binder and thus the performance of PA mixes both in reducing the rate of aging by environmental actions and relaxation of stress imposed by traffic.
4. Low temperature performance of binders is considered to be critical for the effect of aging on the binder performance.
5. Test methods such as ITT can only provide an indication of the effect of aging in relation to raveling in PA. Performance based test methods on mixes are required to link binder rheological and mechanical performance with the resistance to raveling in PA pavement layers.

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