Shear Box Tester for Characterization of Polymer Modified Bituminous Mixtures

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ABSTRACT

Dynamic shear modulus is one of the primary viscoelastic parameters used as an indicator of the resistance to permanent deformation of asphalt mixtures. The present paper describes a recently developed shear box testing device for determining the dynamic shear modulus and phase angle of asphalt concrete mixtures. The shear box tester was used to obtain the dynamic shear modulus of several types of conventional and polymer modified (using Styrene-Butadiene-Styrene (SBS) and Ethyl Vinyl Acetate (EVA)) asphalt concrete specimens drilled from a test pavement structure soon after opening the road and 6 years later. The results from the shear box tester were evaluated based on the performance ranking of the mixtures from other standard mixture performance testing procedures: the indirect tensile (IDT) stiffness and repeated load creep tests and field rut depth measurements. It was observed that both the IDT stiffness tests and the repeated creep tests produced a ranking of the mixes similar to that obtained from dynamic shear modulus tests at low to intermediate temperatures and high temperatures, respectively. It was concluded that the shear box testing device is a reliable means of measuring the shear modulus and phase angle of asphalt concrete mixtures for over a broader range of temperatures and loading frequencies. Moreover, the mechanical tests indicated that the unmodified mixes exhibited considerable ageing and it was demonstrated that the SBS modified surface and binder mixes were the least affected by ageing.

Keywords: Ageing, Modified Binders, Performance testing, Permanent Deformation, Viscosity

1. INTRODUCTION

Asphalt concrete mixtures deform or flow under the action of heavy traffic with respect to climatic factors. The permanent deformation behaviour is characterized by two phases: the primary phase and the secondary phase. The primary phase is the volume change due to the effect of compaction that occurs during the first few years after construction. The secondary phase is characterized by shear deformation or flow rutting which is mainly due to mix displacement without volume change. It is therefore necessary to evaluate the shear properties of asphalt mixtures in order to predict the rutting performance of asphalt concrete mixtures.

Asphalt mixtures also exhibit unique characteristics of both viscous and elastic properties, and hence are categorized as viscoelastic materials. Viscoelastic materials possess time-dependent or loading rate sensitive stress-strain relations. In other words, the stress-strain relationship changes as the loading speed (or strain rate) changes. Understanding the viscoelastic properties of asphalt mixtures is therefore important to achieve performance-based structural designs of asphalt concrete layers [1], which often includes performance prediction, effect of ageing, and distress evaluation.

Cyclic or dynamic tests, such as dynamic complex modulus or dynamic shear modulus tests, are used to obtain viscoelastic properties of asphalt mixtures such as complex shear modulus ($G*$) and phase angle, which provide an understanding of the mixes' viscoelastic properties. The viscoelastic responses of bituminous mixtures are determined by means of various mechanical tests [2-7]. These tests are usually performed at several different frequencies (frequency sweep tests) and temperatures to capture the influence of loading rates and time-dependent properties.

Several types of shear testing devices and procedures have been employed to determine shear properties of asphalt concrete mixtures. The most common approach to subject an asphalt specimen to shear forces is to glue a cylindrical specimen to steel loading plates [2]. Attempts have also been made to induce shear stresses using a rod glued to a hole in a cylindrical asphalt concrete specimen [3]. As part of the Strategic Highway Research Program (SHRP) [4], the Superpave Shear Tester (SST) was developed. The SST is used to subject the specimen to a variable confining pressure so as to keep the specimen at constant height. Hugo and Lorio [5] modified a soil shear box to test cylindrical asphalt specimens and the ratio of the highest imposed shear stress from a vehicle load to the shear strength of asphalt concrete was recommended as an indicator of flow rutting behaviour. Said et al. [6] demonstrated the constant normal force shear test box while Adam et al. [7] recently presented a constant normal stiffness shear testing device.

The main objective of this paper is to evaluate the performance of polymer modified asphalt concrete mixtures from an in-service test pavement structure using the constant normal force shear box tester. The ranking of the asphalt concrete mixtures based on the shear box tester was verified using other standard test procedures, i.e. the indirect tensile stiffness modulus test and the repeated creep test. The tests were conducted on asphalt concrete samples drilled from various sections of the test pavement.

2. BACKGROUND AND SCOPE OF THE STUDY

This paper evaluates the performance of the asphalt concrete surface, binder and base course mixes of a test pavement structure using a shear test device to determine the shear modulus and phase angle of asphalt concrete mixes [6]. The shear box used in the present study, shown in Figure 1, consists of two guide plates. A cylindrical asphalt specimen with a diameter of 150 mm and a thickness of less than ¼ of the diameter is glued to two loading steel disks using epoxy. An adhesion rig, shown in Figure 1a, is used to centre the specimen and ensure that the loading disks are parallel. The glued specimen is then mounted on the shear box tester and one of the guide plates is rigidly fixed while the other moves freely in the shearing direction and is connected to the hydraulic actuator. The specimen is then exposed to a repeated or sinusoidal cyclic loading over a range of frequencies.

The movement of the disks relative to each other (the shear deformation) is measured using two strain gauges. The condition that the specimen's thickness should be less than ¼ of its diameter is necessary to ensure that the specimen is under the state of pure shear. It is thus possible to test even thin drilled specimens from asphalt concrete pavement layers for forensic analysis.

A constant normal compressive stress is applied to the specimen to ensure that no excessive dilation of the specimen occurs during testing [6].

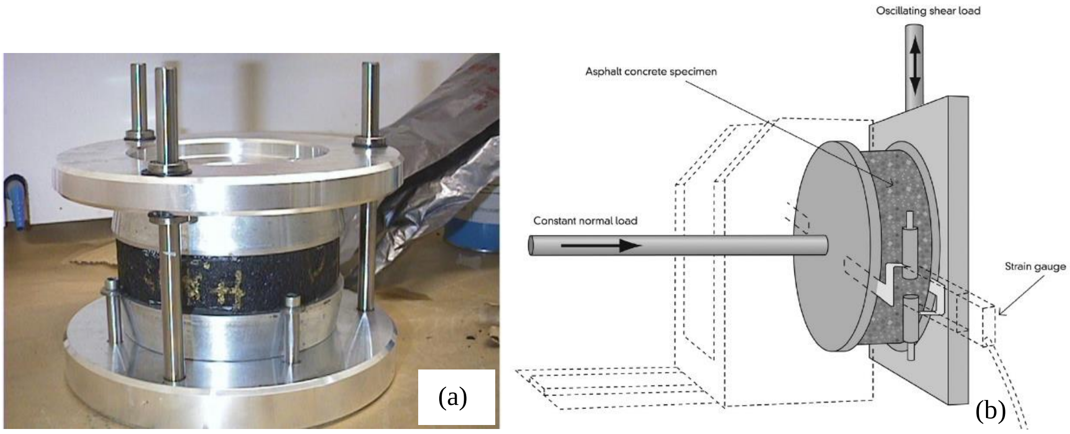

Figure 1: Adhesion ring (a) and schematic diagram of the shear box setup (b)

The shear box was used to evaluate the performance of asphalt concrete mixes (surface, binder and base) in the test pavement structure. A brief description of the test pavement structure is presented in the next section.

3. TEST PAVEMENT STRUCTURE AND MATERIALS

The test section considered in this paper was built between 2003 and 2006 to study the performance of different types of polymer modifier [8, 9]. The structure was divided into ten sections, each characterized by a combination of polymer modifiers applied to different layers. Figure 2 shows a cross-section of the test structure. A plate loading test was conducted to ensure that the test sections were built on a fairly similar subgrade condition. Figure 3 shows the plate loading test results for the subgrade in the test sections.

Prior to construction of the test structure, a comprehensive laboratory study was conducted to select the appropriate binder and polymer types. A detailed description of the selection of the binders and polymers can be found in [12]. It was concluded from this study that three variants of the polymer modified binders (PMBs) be used for the test structure. Two of the selected PMBs were variants of Styrene-Butadiene-Styrene (SBS) (linear SBS and radial SBS) and the third PMB was Ethyl Vinyl Acetate (EVA) copolymer. Research has shown that SBS modified binders have good elastic properties, thus resulting in small residual deformation after unloading. On the other hand, EVA polymer modified binders have a relatively high modulus. The SBS polymer modified bitumen can therefore be suitable for thin structures with relatively large deformations. The EVA polymer bitumen can be used to raise the bearing capacity of the structure in addition to resistance to permanent deformation in the binder layer. Table 1 shows the material descriptions of each test sections and Table 2 the binder properties of the surface, binder and base course mixes. Note that PMB 50/70-53, 50/100-75 and 100/150-75 are currently 45/80-55, 40/100-75 and 90/150-75, respectively. A maximum aggregate size of 16 mm was used for the stone mastic asphalt surface course (SMA 16) and a maximum aggregate size of 22 mm was chosen for both the binder course (ABb 22) and the base course (AG 22).

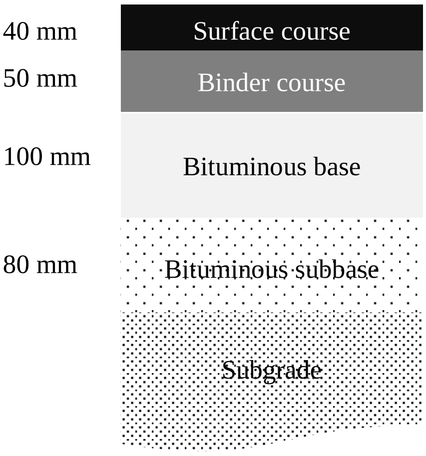

Figure 2: Test structure

Table 1: Description of test structure

Test Section / Layer	Ref 1	1a	1b	2a	2b	3a	3b	4a	4b	Ref 2
Length (m)	400	275	275	124	226	128	292	398	102	260
Surface Course (SMA 16)	70/100	70/100	50/100 -75 4% SBS-Radial			70/100	70/100	70/100	70/100	70/100
Binder Course (ABb 22)	50/70	50/70	50/70-53 6% EVA					50/70-53 3% SBS-linear		50/70
Upper Base Course (AG 22)	100/150	100/150-75 6% SBS-linear		100/150						
Lower Base Course (AG 22)	100/150	100/150-75 6% SBS-linear		100/150	160/220	160/220	100/150	160/220	100/150	100/150

Table 2: Properties of the binder

Layer	Binder Types	Binder Content %wt	Air Void Content %	Polymer % wt	Penetration @ 25°C, 1/mm	Softening Point, °C
Surface	70/100	6.9	1.3	0	77	46
	50/100-75 SBS	6.9	1.3	4	58	98
Binder Course	50/70	5	1.4	0	55	50
	50/70-53 EVA	5	1.4	6	52	66
	50/70-53 SBS	5	1.4	3	58	58
Base Course	100/150	5	5	0	127	43
	100/150-75 SBS	5	5	6	123	90
	160/220	5	5	0	190	38

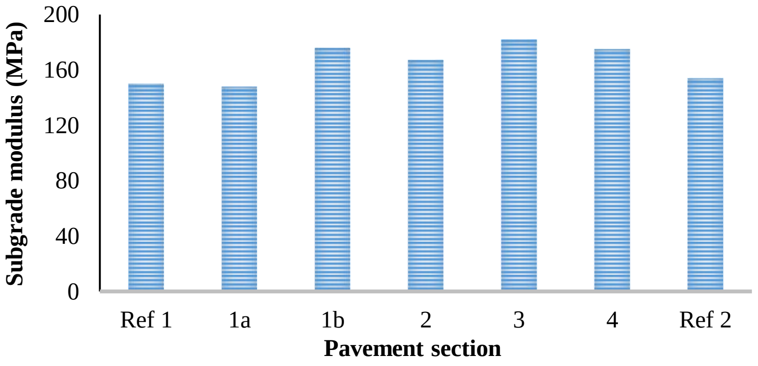

Figure 3: Static plate loading test results for the subgrade

4. LABORATORY TESTS

Asphalt concrete specimens were drilled from the different test sections to conduct mechanical tests. The tests conducted were the dynamic shear modulus test, the indirect tensile (IDT) stiffness test and the repeated load creep test. The dynamic shear modulus test was performed to evaluate the performance of the mixes over a wider range of loading frequencies and temperatures. The IDT stiffness test was chosen to evaluate the performance of the mixes at low to intermediate temperatures. On the other hand, the repeated load creep test was carried out to assess the mixes' performance at higher temperatures. The following sections present brief descriptions of the tests. Furthermore, brief discussions of dynamic shear rheometer (DSR) and multiple stress creep and recovery (MSCR) test results of the bitumen's are presented in section 5.

4.1. Dynamic shear modulus test

The shear resistance of the asphalt concrete mixes were evaluated based on the dynamic shear modulus test. The dynamic shear modulus test (G^*) was conducted using the shear box. The test was carried out at five different temperatures (-5, 5, 20, 35 and 50 °C) and 8 loading frequencies (16, 8, 4, 2, 1, 0.5, 0.1 and 0.05 Hz). Figure 4a shows the shear box apparatus. The outputs of the G^* test are shear modulus G^* and phase angle.

4.2. Indirect tensile (IDT) stiffness modulus test

The stiffness modulus test, or cyclic indirect tensile test, is considered to be a simple and cost-effective non-destructive laboratory test method for measuring the stiffness modulus of bituminous mixtures [13]. The test is conducted by applying a certain number of repeated loading cycles, consisting of 0.1 sec loading and a 2.9 sec rest period, along the vertical plane of a specimen to achieve peak horizontal strain. The procedure is repeated by rotating the specimen through 90° and applying a second set of loading cycles. The IDT stiffness test was carried out at three temperatures (5, 10 and 20 °C) in accordance with European Standard EN 12697-25 Annex C. The actual test setup is shown in Figure 4b.

4.3. Repeated load creep test

Repeated load creep test was recommended as a simple performance test to complement the mixture design process. This test was conducted to evaluate the permanent deformation characteristics of the asphalt concrete mixes. In the repeated load creep test, a cylindrical asphalt specimen with a diameter of 150 mm and a thickness of 60 mm is subjected to a repeated loading cycle consisting of 1 sec loading followed by a 1 sec rest period. Figure 4c shows an actual test setup for the repeated load creep test. The repeated load creep test was conducted at a temperature of 40 °C according to European Standard EN 12697-25, Method A.

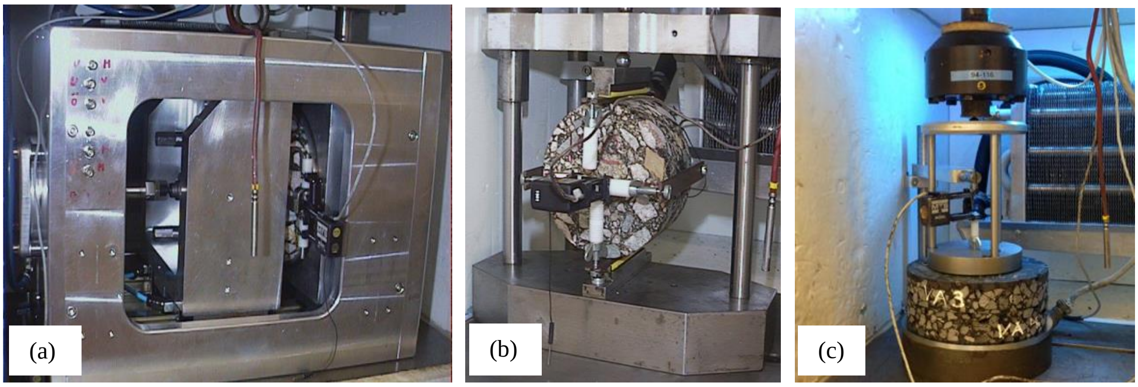

Figure 4: (a) Dynamic Shear Test; (b) Indirect Tensile Stiffness Modulus Test; (c) Repeated Load Creep Test

5. RESUTLS AND DISCUSSION

5.1. Dynamic shear modulus tests

The master curves conducted in 2011 for the dynamic shear modulus and the phase angle for the surface, binder and base course mixes of the test structure are shown in Figures 5 to 7. A sigmoidal fitting function, shown in Equation (1), was used to fit the dynamic shear modulus and a fitting function in Equation (2) was used to fit the master curve for phase angle [6]. Arrhenius equation, Equation (3), was used as a shifting function.

$$log(G) = \delta + \frac{\alpha}{1 + \exp(\beta - \gamma log(f_r))} \tag{1}$$

$$\phi = d\left(1 - \frac{e^{\frac{f_r - a}{e}}}{1 + e^{\frac{f_r - a}{e}}}\right) + \frac{c}{1 + (\frac{f_r - a}{b})^2} \tag{2}$$

$$log(a_T) = R\left(\frac{1}{T + 273} - \frac{1}{T_{ref} + 273}\right) \tag{3a}$$

$$a_T = \frac{f_r}{f_T} \tag{3b}$$

where ϕ is phase angle; *a*, *b*, *c*, *d* and *e* are phase angle master curve fitting parameters; *G* is the dynamic shear modulus, f_r is the reduced frequency, f_T is the frequency at temperature *T*; α, β, γ and δ are sigmoidal fitting function parameters for the dynamic modulus master curve; a_T is the shift factor, *T* is the temperature in °C, T_{ref} = 10 °C is the reference temperature and the Arrhenius constant *R* = 10920.

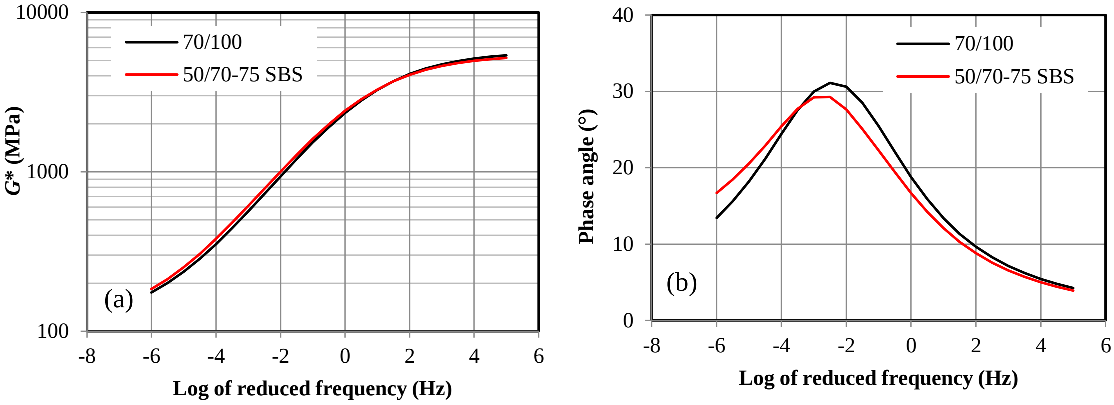

Figure 5: Master curves of (a) Dynamic shear modulus, (b) Phase angle of the surface course mixes SMA 16 with different binders conducted in 2011 at a reference temperature of 10 °C

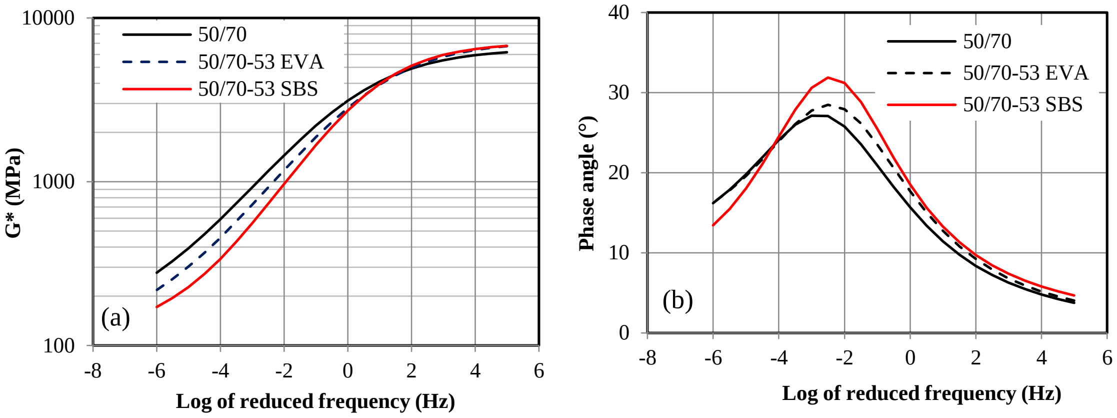

Figure 6: Master curves of (a) Dynamic shear modulus, (b) Phase angle of the binder course mixes ABb 22 with different binders conducted in 2011 at a reference temperature of 10 °C

The shear modulus master curves in Figure 5 indicated that both the modified and unmodified surface mixes demonstrated a similar performance over a broader frequency and/or temperature range. Furthermore, it is known that asphalt concrete mixtures exhibit both viscous and elastic properties. These properties are measured using the phase angle parameter; for a purely elastic material the phase angle is thus 0° and for a purely viscous material 90°. From Figure 5b, the phase angle of the SBS modified surface mix was therefore less than the unmodified mix, indicating a better elastic property. The unmodified binder mixes in the binder course mixes produced a higher shear modulus and lower phase angle than both the EVA and SBS modified mixes in Figure 6, indicating that an unmodified binder mix demonstrates better rutting resistance than modified binder mixes based on shear modulus and phase angles. This might be attributable to the effect of ageing of the unmodified binder mixes after six years in situ, indicating that the polymer modification might have improved the ageing characteristics of the mixes where the SBS modified mixes being the least affected by ageing (discussed later in sections 5.2 and 5.3).

The SBS modified base mixes produced better elastic properties at lower frequencies, as shown in Figures 7b and 7d, indicating better rutting resistance of the modified binder mix. Figures 7a and 7c, however, illustrate that the unmodified base course mixes produced a higher shear modulus than SBS modified mixes, indicating better rutting resistance of the unmodified binder mix. Note that both high shear (and/or stiffness) modulus and low phase angle are essential characteristics to enhance resistance of asphalt concrete against rutting. In this case, it could therefore not be explicitly concluded which asphalt concrete is most resistant to rutting. Further analysis was therefore required to understand the effect of the polymer modifiers on rut resistance of the binder mixes. Consequently, the analysis was complemented by determining the viscosity of the mixes. The viscosity of mixes is a crucial factor in evaluation of permanent deformation in asphalt concrete materials [10, 11].

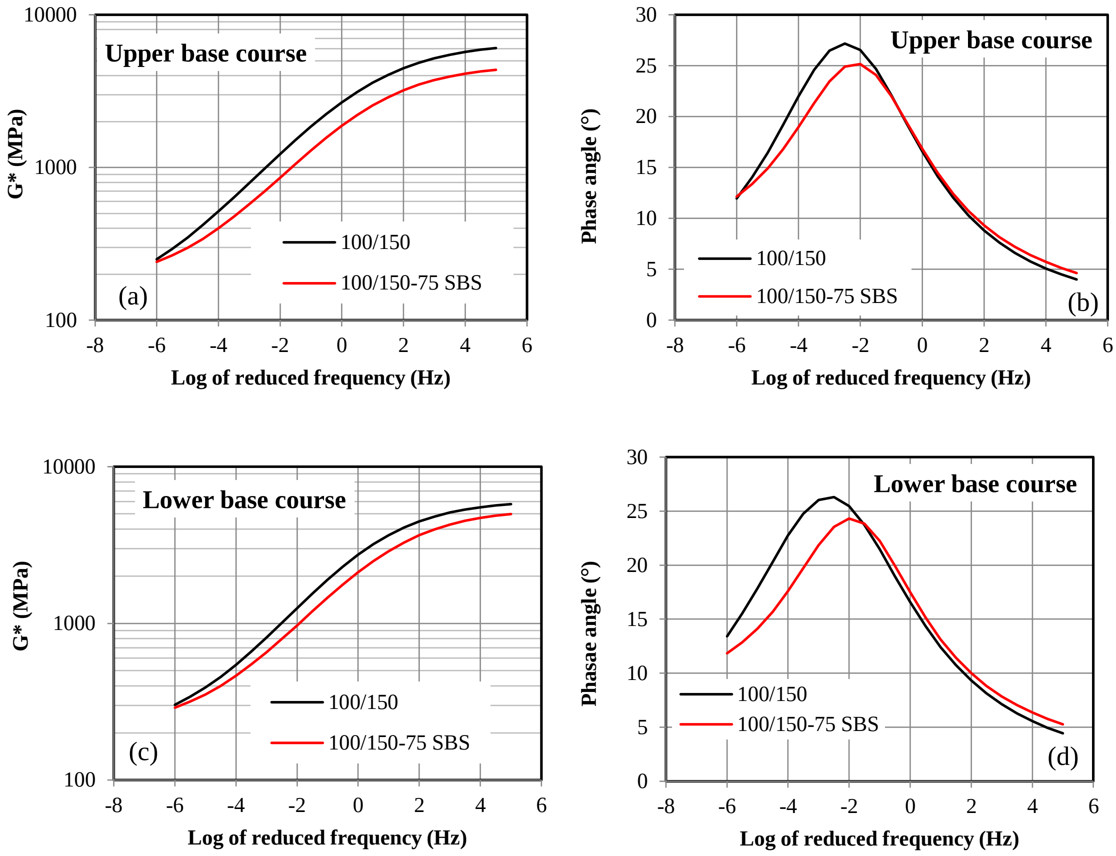

Figure 7: Master curves of (a) Shear modulus upper base course, (b) Phase angle of upper base course mixes, (c) Shear modulus of lower base course and (d) Phase angle of lower base course

The combined effect of shear modulus and phase angle can be shown by viscosity [6].

$$\eta^* = \frac{G^*}{\omega} \tag{4}$$

where η^* is complex viscosity in Pa s, G^* is complex shear modulus in Pa and ω is angular frequency rad/s at maximum value of phase angle when the mix has the least resistance to permanent deformation.

The asphalt binder mix with SBS and EVA polymer modified bitumen clearly shows lower viscosity values, indicating higher rutting resistance of the unmodified mix after six years in situ. This might be attributable to the effect of ageing of the unmodified mix. It can also be observed from Figure 8c that, despite having a higher phase angle, the unmodified base course shows better resistance against permanent deformation, i.e. the influence of the combined effect of shear modulus and location of peak phase angle with respect to reduced frequency was of greater significance than the modified base course mix. Note that the position of the peak phase angle with respect to the reduced frequency in Figures 5 to 7, resulting in ω values, also has an impact on the determined viscosity values. Further discussion on the verification of these findings can be found in sections 5.2 and § 5.3.

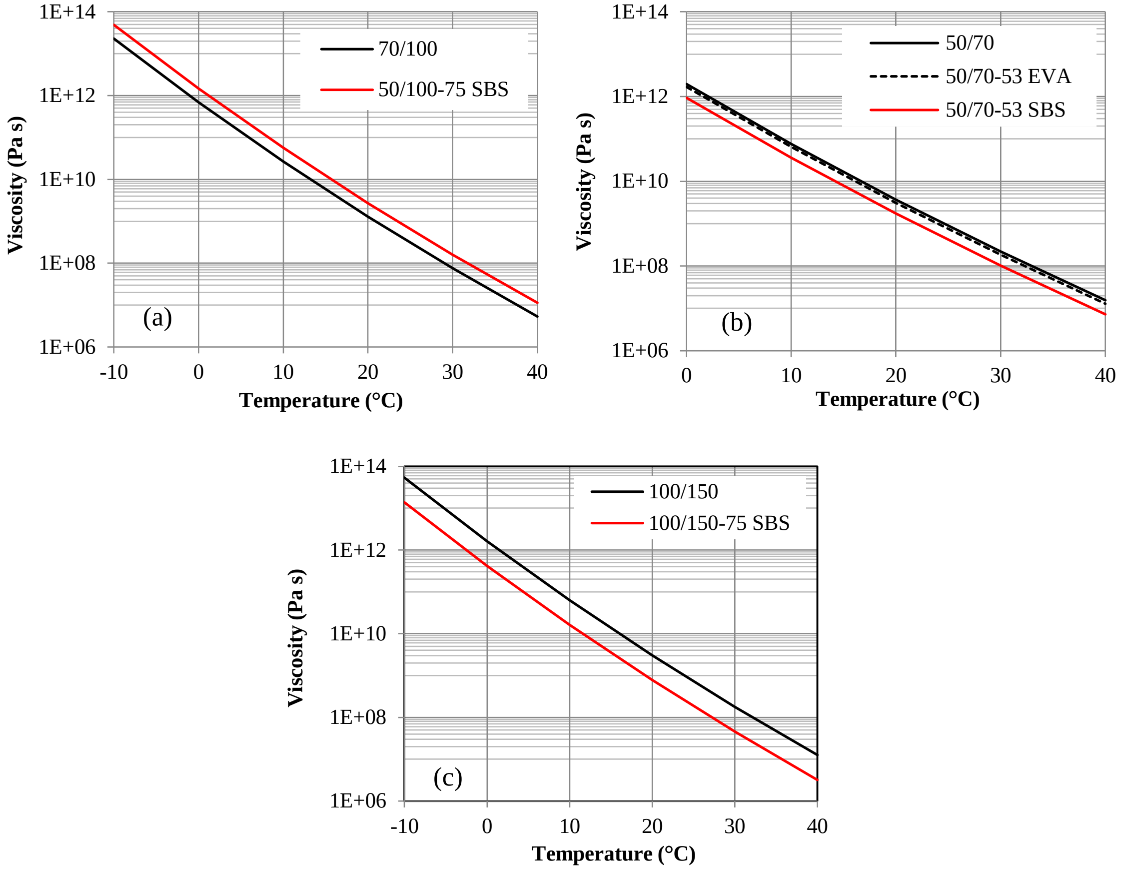

Figure 8: Complex viscosity at peak phase angle in relation to temperature; (a) surfacing (SMA 16), (b) binder course (ABb 22) and (c) base course (AG 22)

5.2. IDT stiffness modulus tests

To further investigate the effect of ageing through mechanical tests, IDT stiffness modulus tests were conducted on field cored samples from 2005/2006 and 2011. The 2005 measurements were performed by the NCC Roads laboratory [8]. The 2006 and 2011 measurements were performed by the VTI laboratory [9] according to European Standard EN 12697-26 Annex C. Figures 9 to 11 present the results of the IDT stiffness modulus test results for the surface, binder and base course mixes. The IDT test conducted in 2011 produced a ranking of the mixes similar to the shear modulus test results for low to intermediate temperature ranges. The effect of ageing was obvious in all the mixes, as indicated by the increase in stiffness moduli with time, but with different rates of ageing.

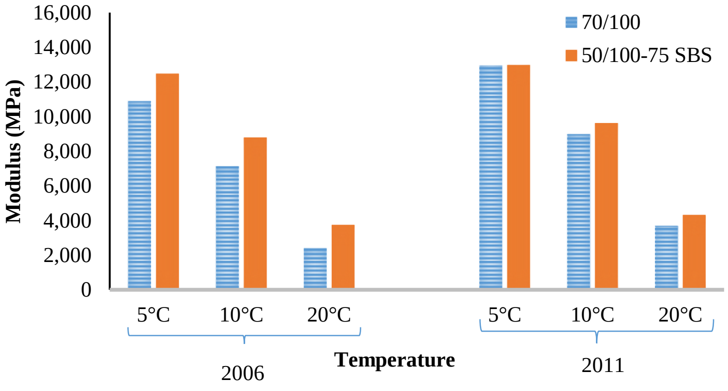

Figure 9: IDT stiffness modulus of the surface course mixes (SMA 16) in 2006 and 2011

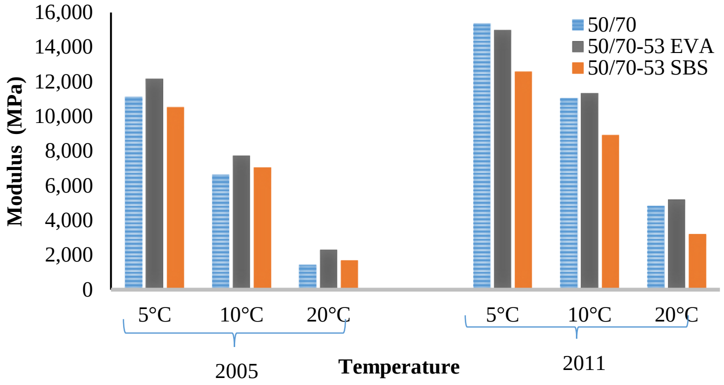

Figure 10: IDT stiffness modulus of the binder course mixes in 2005 and 2011

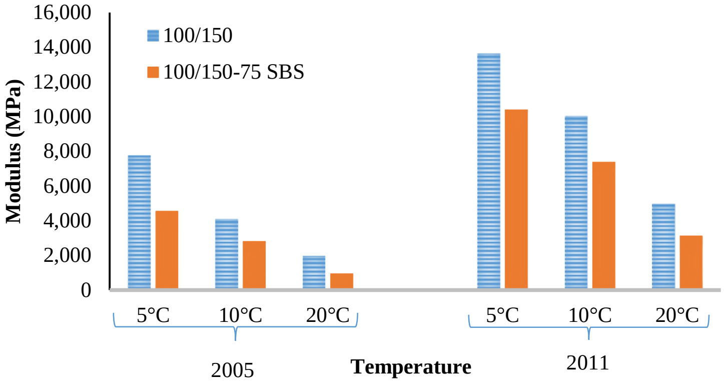

Figure 11: IDT stiffness modulus of the base course mixes in 2005 and 2011

The long-term ageing indices, defined as the percentage of the relative increase in stiffness modulus per year, representing the pavement's ageing after its first year in service [16], were calculated based on stiffness measurements at 10 °C. As shown in Figure 12, the SBS modified surface and binder mixes were least affected by ageing. A similar conclusion was reached based on binder test results reported in [14, 15]. However, unlike the surface and binder mixes, the SBS modified base course mixes exhibited a somewhat higher tendency to age than the corresponding unmodified mix. Note that the base course mixes exhibited higher ageing than the surface and binder mixes. This might be due to the higher air void content (5%), softer binders and thinner binder film of the base course mixes than the surface and binder course mixes (< 2%), thus permitting easier access to oxygen to accelerate the ageing process.

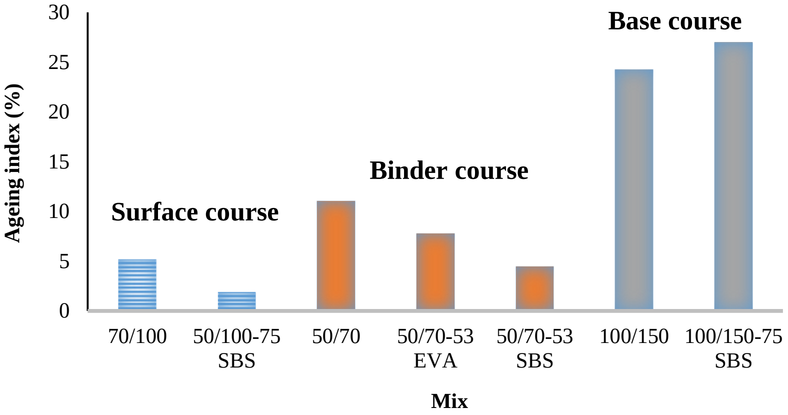

Figure 12: Ageing index at 10°C

5.3. Repeated load creep test

Figure 13 presents the results of the repeated load creep tests conducted on the binder course mixes in 2004 (by the NCC laboratory [8] and 2011 (by the VTI laboratory) according to European Standard EN 12697-25 Method

A. Comparing the creep strains of the binder mixes from 2004 and 2011, a significant difference in creep strain was observed for the unmodified binder mix, indicating that it has exhibited considerable ageing. On the other hand, both EVA and SBS modified binder showed relatively small differences in creep strain for the two measurement years, the SBS modified binder mix being least affected by ageing. Note that, as shown in Figures 6a and 13 (for year 2011), a similar performance ranking of the binder mixes was obtained from both the repeated load creep tests and the dynamic shear modulus tests at higher temperatures. Comparing the effect of ageing from the IDT stiffness tests (Figure 12) and the repeated load creep tests (Figure 13) for the binder layer, similar ageing indices were obtained for unmodified and EVA modified binder mixes. The SBS modified binder mix, however, exhibited 4.4% ageing in stiffness per year (Figure 12) compared with almost no ageing in creep after 6 years in situ (Figure 13). These discrepancies might have occurred due to the differences in test temperatures and testing modes. Further evaluation of the ageing effect on different mixes would therefore be valuable for pavement performance evaluations.

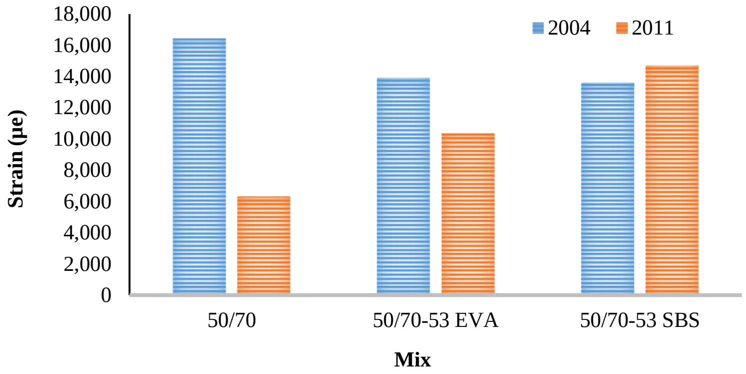

Figure 13: Creep strain of the binder mixes in 2004 and 2011

5.4. DSR, MSCR and Field performance tests

The viscosity ratio of the RTFO-PAV aged bitumen to original bitumen based on DSR tests conducted on surface and binder mix bitumen's is shown in Figure 14. Similar trend ageing was observed for surface mixes from bitumen DSR tests and mixture performance (Figure 12). However, for the binder mix the EVA modification resulted a higher ageing based on bitumen DSR test.

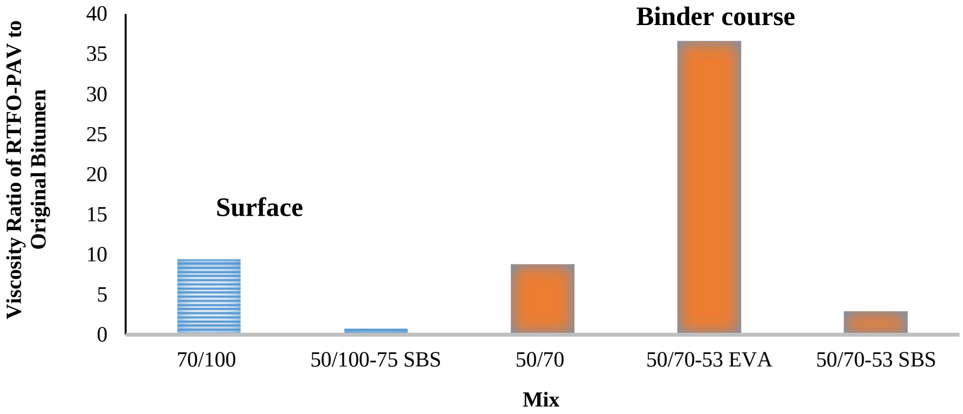

Figure 14: Viscosity ratio of RTFO-PAV aged bitumen to Original bitumen 60°C

Differences in strain recovery at 3.2 kPa and 60°C between the bitumen's and the effect of aging are compared in Table 3 according to the MSCR tests. Obviously, the SBS modified bitumen's show much higher strain recovery compared to others. Considering the effect of aging, the unmodified and EVA modified bitumen's follow the same trend; the increased strain recovery for aged and recovered samples is due to bitumen oxidation that makes the binder more elastic. In the case of SBS modification, aging may reduce strain recovery probably due to oxidation of the polymer. However, even after laboratory or field aging, the SBS modified bitumen's still retain a higher level of strain recovery as compared to other binders.

Differences between the bitumen's, as well as the effect of aging, are also evident when the non-recoverable compliances, Jnr 3200, are compared. Regardless of the sample state, the polymer modifies bitumen's always exhibited lower values of Jnr 3200 than the reference, suggesting higher rutting resistance for the modified binders.

Table 3: Strain recovery and non-recoverable compliance (Jnr) measured at 60°C

	R3200			Jnr 3200, kPa-1		
Bitumen types	Original	RTFOT-PAV	Recovered	Original	RTFOT-PAV	Recovered
70/100	0.0	16.2	5.2	5.2	0.3	0.7
50/100-75 SBS	96.0	70.0	87.1	0.0	0.1	0.0
50/70	0.0	12.6	5.5	3.6	0.4	0.8
50/70-53 EVA	5.8	53.5	34.3	1.8	0.0	0.2
50/70-53 SBS	46.6	50.5	31.9	1.0	0.1	0.3
100/150-75 SBS	98.8	89.6	78.0	0.0	0.1	0.3

Furthermore, to validate the laboratory investigations against the field performance of the test pavement sections, the test road has been monitored since its opening to traffic. Annual field measurements and inspections show that all the sections are in good condition. A rut depth of about 3 mm was measured after 7 years of service and rather small differences (about 1 mm) were observed between the different sections, which is below the measurements' margin of error. Figure 15 shows the surface rut measurements of the different sections measured using the Road Surface Tester (RST). Furthermore, other distress types such as stripping and low temperature cracking have not been observed on the test road. Note that, the measured rutting in Figure 15 for the year 2012 is less from the year 2011, this is due to the different wheel paths the RST vehicle followed. Further follow-up of the test road is obviously needed in order to evaluate the performance of the polymer modified mixes.

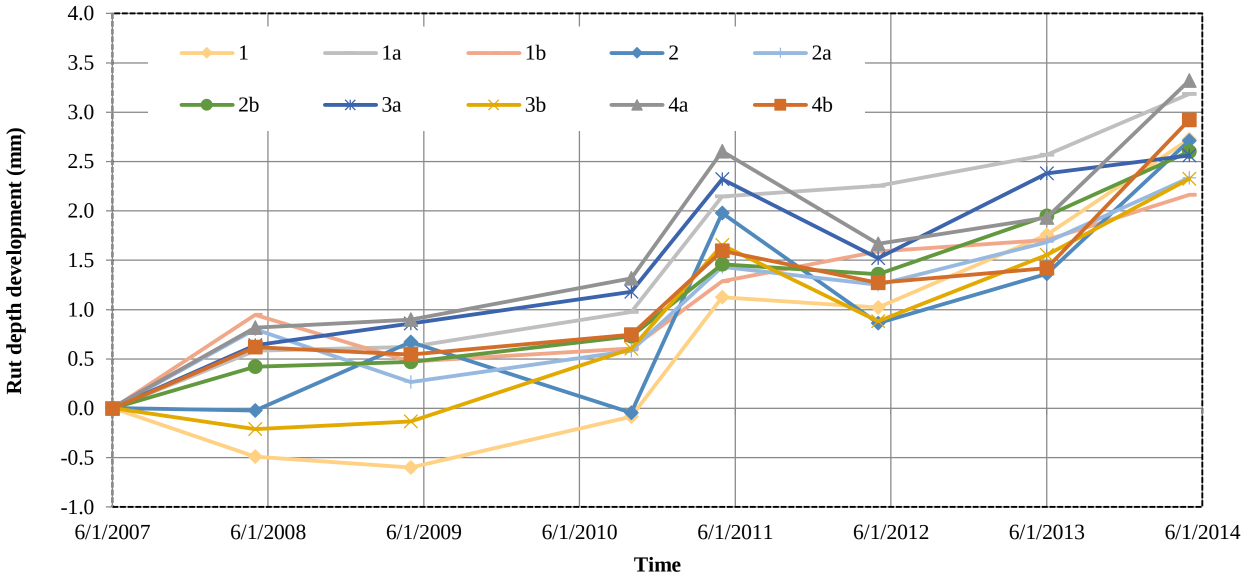

Figure 15: Rut measurements using Road Surface Tester (RST)

6. CONCLUSIONS AND RECOMMENDATIONS

This paper has evaluated the performance of asphalt concrete mixes of an in-service test pavement structure based on the dynamic shear modulus tests conducted on asphalt field cores using the shear box tester. Results of IDT stiffness modulus tests and repeated creep tests were used to verify the ranking of the performance of the mixes based on dynamic shear tests. It was observed that both IDT stiffness tests and the repeated creep tests produced a ranking of the mixes similar to that obtained from frequency sweep shear tests at low to intermediate temperatures and high temperatures, respectively. It can therefore be concluded that the shear box tester and the resulting shear modulus, phase angle and viscosity master curves could be used to evaluate the performance of conventional or modified asphalt concrete mixes over a broader range of loading frequencies and temperatures.

The mechanical tests also indicated that the unmodified mixes exhibited considerable ageing and it was demonstrated that the SBS modified surface and binder mixes were least affected by ageing. The SBS modified base mixes, however, exhibited considerable ageing, as indicated by the ageing indices. This might be due to the relatively higher air void content and the thinner binder films used in the base mixes accelerating the ageing processes. Further investigation of the effect of ageing on different types of asphalt concrete mixes would be valuable to assist the pavement performance evaluations and a longer follow-up period of the test road is needed to validate laboratory investigations.

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