HOT-MIX ASPHALT TESTING FOR THE SOUTH AFRICAN PAVEMENT DESIGN METHOD

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ABSTRACT

As part of the revision of the South African Pavement Design Method (SAPDM), a large scale field and laboratory study into the material response of asphalt mixtures will be undertaken. A first step in this process is to review the state-of-the art of local and international hot-mix asphalt (HMA) test methods and modify or adapt them to suit South African road pavement conditions. This paper presents various laboratory HMA test protocols developed as part of the project to revise SAPDM. Large scale laboratory testing was conducted on a standard South Africa asphalt mix with 60/70 penetration grade binder to develop the test protocols. The protocol development covers bituminous binder tests, asphalt mix preparation and compaction, as well as advanced laboratory tests performed on the asphalt mix. The required modifications to existing protocols are discussed in this paper and some potential challenges with the adoption of the protocols in the SAPDM are addressed.

1 INTRODUCTION

A revision of the South African road Pavement Design Method (SAPDM) is in progress. The revision is funded by the South African National Road Agency Limited (SANRAL) and the CSIR Built Environment Strategic Research Panel (SRP) project. As part of the project, calibrated elastic stiffness (resilient response) models based on monotonic and dynamic loading conditions, and improved damage models for bituminous materials are to be developed for five selected South African asphalt mixes. The revision of SAPDM requires improved and revised test protocols for advanced characterisation of mechanical properties of the asphalt mixes.

Various test methods for resilient response and damage tests for bituminous materials were reviewed as part of the project and used as the basis for developing test protocols to support SAPDM. The review indicated that due to several limitations in some of the commonly used HMA tests methods, road researchers, agencies, and the industry are currently developing and evaluating HMA test protocols for their local use. In this regard, the selected testing conditions for the HMA including temperature and loading rates (frequency) for South Africa were based on actual pavement conditions and testing equipment capability. For instance, the test temperatures were selected based on the actual temperatures experienced in South Africa road pavements. Viljoen (2001) reported that the minimum asphalt surface temperatures in South Africa is generally about 5^oC and in few instances drop below 0^oC, whereas the maximum surface temperature is generally between 45^oC and 55^oC although it can reach close to 70^oC in few days of the year. The tests loading frequencies were selected to cover performance related vehicle speeds to adequately simulate field conditions. This paper focuses on advanced test protocols developed for HMA characterisation in South Africa. This paper also presents test results of a laboratory testing program conducted on a standard asphalt mix with a 60/70 penetration grade binder using the developed HMA test protocols. It is anticipated that the test results generated from the different test protocols will provide the required basis to develop reliable resilient response and damage models for SAPDM.

2 PROTOCOLS FOR MATERIAL SAMPLING, MIXING AND COMPACTION

Standard methods for material sampling, mixing and compaction are observed as much as possible. This section discusses only the parts of the sample preparation procedure, where alterations to the standards method have been made to better suit the requirements of SAPDM.

2.1 Raw materials source

Raw materials (aggregate and binder) are sampled at the asphalt plant in accordance with TMH5: Sampling Methods for Road Construction Materials. At the laboratory, to further ensure homogeneity of the materials sampled, bags of similar aggregate sizes are mixed together by riffling and quartering. Aggregates are oven dried at approximately 140 ℃. After which the materials are split down by riffling to the approximate quantities required for the various compactions. Dry sieve analyses should then be carried out on randomly selected bags to ensure that the material has been adequately riffled (3 bags tested per aggregate size). The required grading (target grading) is made up in triplicate and tested for conformance with the specifications. This was done by wet grading analysis. Obtaining the correct grading from the mix proportions given is also an indication of accurate sample preparation.

2.2 Mix preparation

HMA is produced in accordance with the methods in TMH1: Standard methods of testing road construction materials. The prepared mix is aged to simulate the aging that takes place during the production process in an asphalt plant and transport to site, using the SUPERPAVE short term aging procedure. The method, as described by Von Quintus et al (1991), consists of placing the prepared mix back into the oven and leaving it there for four hours at 135℃ before compaction. A slight adjustment to this method has been made as part of the SAPDM. To allow for mixes with compaction temperature below or above 135℃, mixes will be aged for four hours at the compaction temperature for that particular mix. In reality, ageing occurs whilst the asphalt mix is subjected to a temperature gradient ranging from mixing temperature (145^{o}C) to the compaction temperature (135^{o}C). The rate of change in temperature is dependent on the manner of storage and transport prior to compaction, the volume to surface ratio of the asphalt mix, and the presence and type of insulating materials used (e.g. tarpaulin). Because these conditions vary from contract to contract, the use a fixed temperature for the ageing results in simple reproducible process.

For some of the tests the material behaviour in the later part of the pavement life is of interest. To simulate the aging of the mix over a period of five to ten years, the long term aging procedure recommended by Bell et al (1994) is used. After compaction, specimens made of short term aged mix are put back into the oven and aged for five days at a temperature of 85℃.

In a previous study at CSIR, the ageing of the binder in the short term aging procedure (RTFOT) was found to be similar to the ageing of the binder recovered from cores taken after construction when using softening point as the ageing indicator (Denneman, 2008). The long term aging procedure has not been adequately validated, and validation will form part of the SAPDM project.

Figure 1a shows the Transport Research Laboratory (TRL) slab compactor, and Figure 1b shows an advanced gyratory compactor at CSIR Built Environment road materials laboratory. Cylindrical specimens for dynamic modulus testing were compacted using the gyratory compactor in accordance with AASHTO T 312. Slabs were compacted using the TRL slab compactor in accordance with the CSIR in-house protocol. From the slabs, beams are cut for use in four point bending fatigue and frequency sweep tests. Cores (150 mm diameter) are also cut from slabs to be used in the shear tests at constant height.

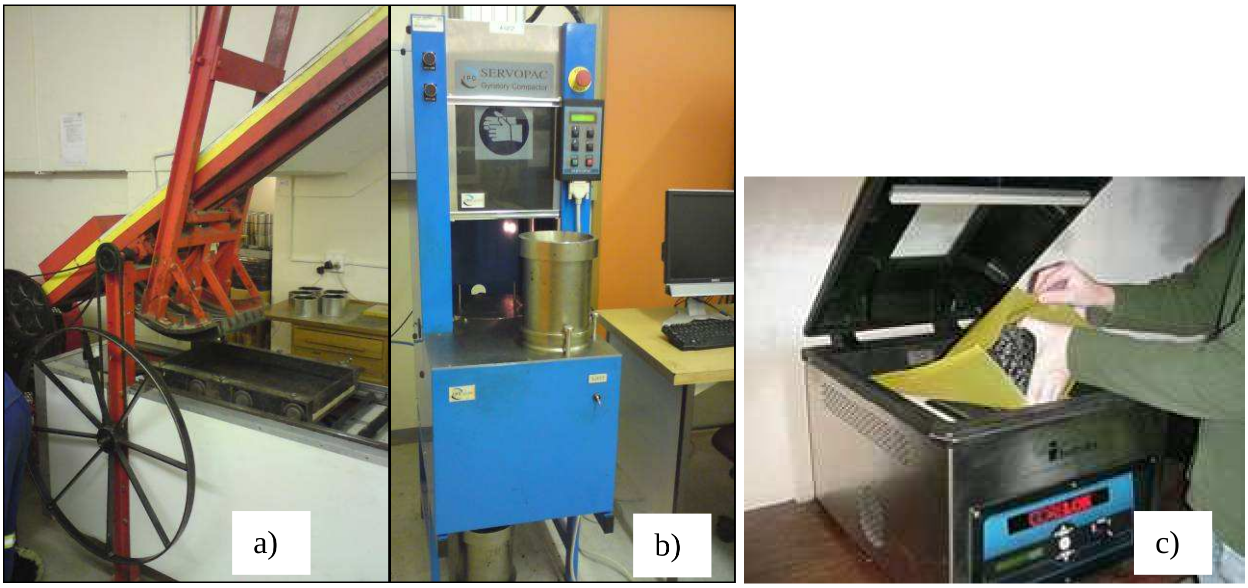


Figure 1: a) TRL slab compactor, b) Gyratory compactor, c) Corelok device

2.3 Density determination

The maximum theoretic relative density (MTRD) of the loose mix and the bulk relative density (BRD) of the compacted mix are determined in accordance with the relevant procedures in TMH1. In addition to the BRD the density of the compacted specimens is also determined using the Corelok device shown in Figure 1c. The Corelok test involves vacuum sealing HMA specimens in plastic bags. The inaccuracies of the conventional BRD method in determining densities of porous samples or samples with interconnected voids (in essence where water absorption exceeds 2%) are avoided by using the Corelok system. The Corelok, has proven to be superior to historical methods such as the parrafin-coated, Parafilm and glass beads methods, exhibiting both greater precision and accuracy (Crouch et al. 2002). However, it has been reported that the Corelok may have an inherent system error at low voids and the ‘true voids” lies between the values obtained by the Corelok and that of the BRD (Xie and Watson 2004, TMH1 1996). The Corelok was developed to replace the saturation surface dry method only in case of porous samples.

Some comparative testing was done to get an indication of the differences between the conventional and CoreLok methods. Table 1 shows the results obtained for the two test methods. Surface roughness (texture) of test specimen appears to introduce some differences in the test results. Thus, the differences in the results for specimens with rougher surfaces were higher between the two test methods than smooth surfaced specimens. Future studies will look at the detailed effect of surface roughness or maximum aggregate size on the results of the two methods.

Table 1: Limited comparison between Standard and "CoreLok" BRD test results

Specimen Compaction	Surface description	CoreLok BRD	Standard BRD	% difference
BTB gyratory	Rough all sides	2.381	2.411	1.2
BTB beam cut from slab	All sides cut except top	2.526	2.530	0.2
BTB slab core	Only top rough	2.568	2.579	0.4
PVC core	Smooth	1.373	1.370	0.2
PVC beam	Smooth	1.431	1.434	0.2

3 DEVELOPMENT OF BINDER TEST PROTOCOL

3.1 Laboratory testing program

The binder testing program involved three empirical tests (penetration, softening point, apparent viscosity), as well as heptane insolubility and dynamic shear rheometer (DSR tests. These tests were conducted on the original binder, binder subjected to the Rolling Thin Film Oven (RTFO – to simulate ageing that occurs during manufacture and laying of the mix) and binder subjected to the Pressure Aging Vessel (PAV – to simulate long term ageing in the field). Binder recovered from asphalt from the plant, cores from site and aged laboratory asphalt mix samples were also tested.

3.2 Sample storage prior to, and after testing

Binder samples received prior to testing were stored in air-tight containers in a store room kept at a temperature of 5ºC. After testing, remaining binder was kept in an air tight container in the binder sample store room for a further period of three years. Tested samples were discarded. Hot mix asphalt samples received for the recovery of the binder were stored in a designated asphalt store room kept at a temperature of 15ºC.

3.3 Sample preparation

For all test protocols, samples were prepared in compliance with the respective test method requirements where such requirements exist within a particular test method. In general, the procedures were:

- 1l sample containers – Containers were placed in an oven maintained at a temperature of approximately 160ºC and the sample was stirred periodically. After one hour, when the sample was sufficiently fluid for thorough mixing (at an approximate sample temperature of 110ºC), the sample container was removed from the oven and an appropriate volume of sample taken for testing. Reheating of the original material for further testing was not allowed.
- 5l sample containers – Containers were placed in an oven maintained at a temperature of approximately 160ºC and the sample was stirred periodically. It takes 2.5 to 3 hours for the sample to attain sufficient fluidity for thorough mixing (approximate sample temperature is 100ºC). This heating time exceeded the maximum heating period required by some test methods. For compliance an oven

temperature at a much higher value (> 220 ºC) would have been required. This was not done because of the risk of local overheating and sample damage.

For modified bituminous binders, sample preparation is in accordance with Method MB-2, of TG 1: “Technical Guideline: The use of Modified Bituminous Binders in Road Construction”, Second Edition, November 2007. For bituminous binders recovered from hot mix asphalt, samples are transferred directly from the round bottom distillation flask to the relevant testing equipment. Based on our own experience, the recovered binder temperature is approximately 150ºC at the time of transfer.

3.4 Binder characterisation test protocol

The rheological properties of selected binders commonly used in South Africa will be used as a direct input into predictive equations to estimate dynamic modulus for asphalt mixes in SAPDM. The dynamic shear rheometer (DSR) is used to determine binder stiffness at intermediate and high pavement temperatures (NCHRP 1-37A 2004, The Asphalt Institute). Currently the American Association of State Transportation Officials (AASHTO) AASHTO T 315 is the standard test protocol used for determining DSR properties of the original as well as short-term and long-term aged binders. The DSR test measures the complex shear modulus (G*) and phase angle (δ) of the binder by subjecting a small sample of binder to oscillatory shear stress while sandwiched between two parallel plates The DSR is used to determine G* and δ by measuring the torque required to obtain a fixed shear strain response of the specimen.

During the protocol development, the DSR was used for strain, frequency and temperature sweeps as well as performance graded (PG) specification tests. The strain sweep tests were conducted to determine the region of linear visco-elastic (LVE) behaviour. The linear viscoelastic behaviour of the binder should be characterized using strains within the LVE region. The strain value targeted for each frequency sweep is the lowest value of the two strain limits determined from the two procedures below:

- Calculate the strain value using Eq. 1 of paragraph 11.3 of AASHTO T 315– 05.

$$y = \frac{12.0}{(G^*)^{0.29}} \quad (1)$$

where; γ = shear strain (%); G* = complex modulus (kPa).

- Obtain the strain limit of the linear viscoelastic range from a strain/amplitude sweep at a particular temperature under investigation. During this procedure the limit of the linear region is defined as the point at which the shear modulus value decreased to 95 percent of the initial modulus (zero-strain value).

Strain/amplitude sweeps were performed at a frequency of 20 Hz. Figure 2 shows an illustration of the concept as an example.

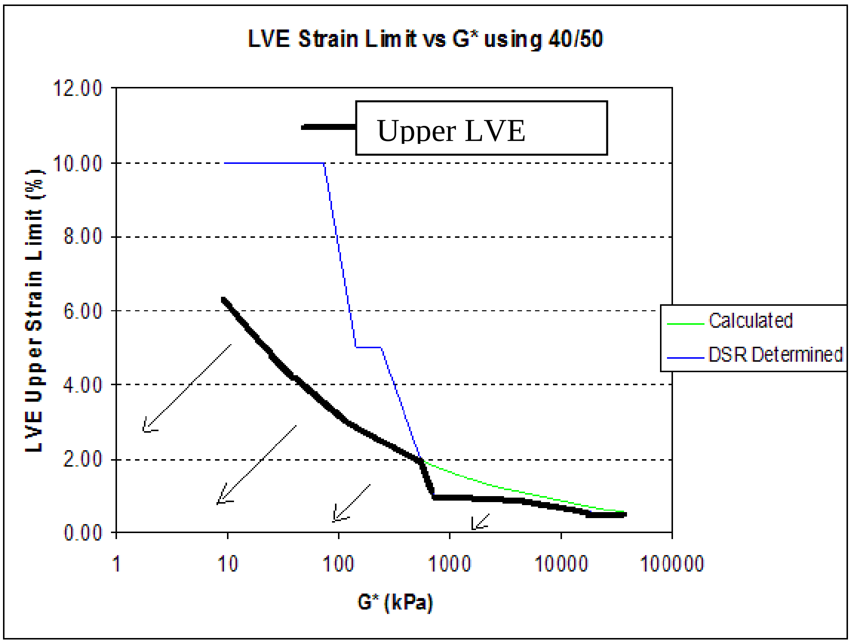


Figure 2: Graphic illustration of measured and calculated

The frequency sweep tests of the binder were conducted at fixed strain levels as indicated in Table 2 at test temperatures of 20, 40, 55, and 70 ℃, and frequencies that covers about four log decades, i.e., 0.0079 to 79.6 Hz. The results of the frequency sweep were used to construct master curves and black diagrams for the binder tested. The following guidelines were established:

- For the determination of G* (complex shear modulus) and δ (phase angle), a temperature equilibrium period of 10 minutes was required before data acquisition commenced. This is in contrast to the standard period of 5 minutes recommended by the equipment manufacturer. Detailed investigations showed that temperature equilibrium could not be reached until at least 8 minutes has passed.
- Frequency sweeps were conducted at 20ºC, 40ºC, 55ºC, 70ºC in a range from 0.0079 to 79.6 Hz in preparation for the master curve.
- The limits of the test temperature and frequency ranges were a function of the binder stiffness (which is affected by binder grade, type of modification, etc) and the capacity of the DSR Model used.
    - Two different plate diameters and sample thickness (gap) were used; (a) 8-mm parallel plates with a 2-mm gap were used when the absolute value of G* ranged from 0.1 to 30 MPa. For unmodified bitumen, this typically applied over a temperature range from 5 to 35℃, and (b) 25-mm parallel plates with a 1-mm gap were used when G* ranges from 1.0 to 100 kPa. For unmodified bitumen, this typically applies for temperatures exceeding 35℃.
- Experimentally determined LVE strain limit from a strain/amplitude sweep at a particular temperature under investigation. The upper limit of the LVE region was defined as the point at which the shear modulus value decreased to 95 percent of the initial modulus (zero-strain value).

Due to the fact that strain limits were determined at 20 Hz, it is estimated that the values for G* obtained at frequencies above 50 Hz may have been obtained at (or just beyond) the upper limits of the LVE region, limiting the accuracy of the results obtained above 50 Hz. A decision was taken not to determine the LVE strain limits at 80Hz as this would have resulted in overall lower LVE strain limits for entire frequency range. Lower LVE strain limits results in lower accuracy for G*. The single operator precision for DSR test established by the CSIR BE test protocol is represented by a COV of 2.3%.

Table 2: Strain limits determined by the DSR and by calculation

Binder Type	Temperature (℃)	Spindle diameter (mm)	G* (kPa)	DSR Recommended Strain (%)	Calculated Strain (%)	Strain Used (%)
Original	20	8	22 300	0.50	0.66	0.50
	40	25	710	1.00	1.79	1.00
	55	25	72.1	10.00	3.47	3.47
	70	25	9.28	10.00	6.29	6.29
RTFO	20	8	29 300	0.50	0.61	0.50
	40	8	1 450	1.00	1.45	1.00
	55	25	140	5.00	2.86	2.86
	70	25	18	10.00	5.20	5.20
PAV	20	8	36 000	0.50	0.57	0.50
	40	8	2 490	1.00	1.24	1.00
	55	25	238	5.00	2.45	2.45
	70	25	29.6	10.00	4.49	4.47

4 DEVELOPMENT OF RESILIENT RESPONSE TEST PROTOCOLS

The current pavement design methods recommend HMA resilient response properties for analysis (SANRAL 2007, NCHRP 1-37A 2004). The dynamic modulus will be used for the resilient response characterisation of asphalt mixes in the SAPDM. This section presents three different elastic stiffness test protocols developed for dynamic modulus, shear dynamic modulus and beam stiffness modulus properties.

4.1 Dynamic modulus testing

The SAPDM requires characterisation of South Africa asphalt mixes by dynamic modulus property. Dynamic modulus values obtained from laboratory frequency sweep test data are usually used to construct master curves to characterize the HMA over ranges of temperature and frequency. Over the years, several test procedures have evolved from the original dynamic modulus test procedure, ASTM D 3497 developed in the 1960s (AASHTO TP- 62 2005, AASHTO T320 2005). In the United States, the National Cooperation of Highway Research Program simple performance test protocols is currently under review (NCHRP 9-29 2004). The recent design guides recommend AASHTO TP 62 to determine dynamic modulus for flexible pavement analysis, and an alternative test method is the AASHTO T320 (NCHRP 1-37A, SANRAL 2007). In this project, the AASHTO TP 62 test protocol was reviewed and modified based on the asphalt road pavement conditions in South Africa. The revised protocol was used to conduct laboratory tests on the standard mix with 60/70 penetration grade binder for verification and repeatability purposes.

For viscoelastic materials, the stress-strain relationship under a continuous sinusoidal (haversine) loading is defined by a complex number called the complex modulus E* (ASTM D 3497, NCHRP 1-37A 2004, AASHTO TP 62. 2005). The complex modulus has real and imaginary parts that define the elastic and viscous behavior of linear viscoelastic materials. The absolute value of the complex modulus is defined as the material's dynamic modulus. Mathematically, dynamic modulus is defined as the maximum (peak) dynamic stress divided by the recoverable maximum (peak) axial strain as presented in Eq. 2.

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \qquad (2)$$

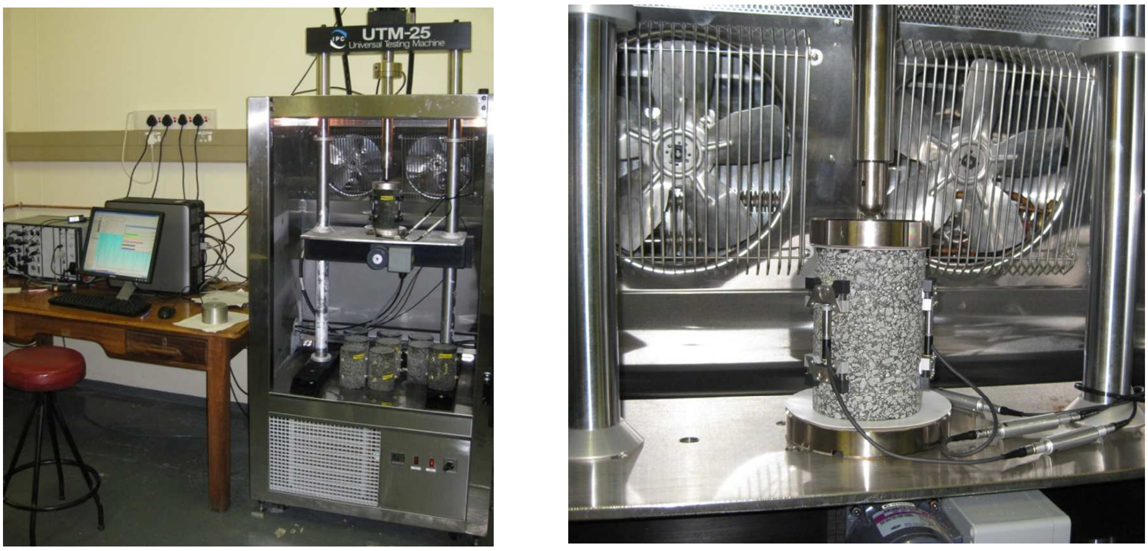
where, |E*| = dynamic modulus; σ_0 = applied stress amplitude (peak stress); ε_0 = measured strain amplitude (peak strain).

4.1.1 *Test protocol and laboratory testing program*

The CSIR BE dynamic modulus test protocol described in this paper is similar to that contained in AASHTO TP62-07, except that strain controlled instead of stress controlled loading is followed in the CSIR protocol. The applied stress is automatically varied in the test software so that the magnitudes of the strains are always kept within the range of 75 to 125 microstrains in order to ensure linear behavior of the sample. The recommended test sequence in the AASHTO TP62-07 protocol consists of testing a minimum of 2 replicate specimens at temperatures of –10, 4.4, 21.1, 37.8, and 54.4 ^{o}C, and loading frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. In the CSIR BE test protocol, a minimum of 5 specimens are tested with test temperatures of -5, 5, 20, 40, 55^{o}C, and loading frequencies of 25, 10, 5, 1, 0.5, and 0.1Hz. That is, a full factorial test matrix of 30 tests is conducted for the dynamic modulus of hot-mix asphalts.

During the dynamic modulus protocol development for SAPDM, 10 cylindrical specimens with dimensions of 100 mm in diameter and 150 mm high were subjected to a sinusoidal (haversine) compressive load pulse. The 10 specimens were tested at the each loading conditions to check variability of test results. The specimens were cored from gyratory compacted sample of dimensions 150 mm diameter and 170 mm high. The axial stresses and the corresponding axial strains recorded for the last five load cycles for each test were used to compute the dynamic modulus of the sample. Figure 3 shows the dynamic modulus testing set up at CSIR BE pavement materials laboratory and a typical instrumented specimen of the standard mix during testing.

The precision of the dynamic modulus test protocol at CSIR BE pavement materials laboratory is not yet established. Repeatability and reproducibility will be determined according to South Africa standards. Currently, no institution or agency in South Africa has dynamic modulus testing equipment for inter-laboratory comparison tests. Additional tests on selected asphalt mix will be needed to establish precision for this test protocol.



(a) Dynamic modulus specimens (b) Instrumentation of test specimen

Figure 3: Dynamic modulus testing setup and instrumentation

4.1.2 *Analyses of dynamic modulus test results*

Table 3 shows the statistical analyses results for the 10 specimens tested. The coefficients of variation (COV) were relatively high for the test temperatures of 40 and 55°C compared with -5, 5 and 20°C. High COVs for dynamic modulus test have been obtained by some researchers including Bhasin et al. (2005), who reported COV values of up to about 31% for different asphalt mixes tested at 10Hz and 54.4°C. The proposed U.S. standard practice for dynamic modulus testing indicated that the COV for properly conducted dynamic modulus test is approximately 13% (NCHRP Report 614 2008).

Table 3: Protocol results for 10 replicate dynamic modulus test specimens

Temp (°C)	Statistic	Frequency (Hz)					
		0.1	0.5	1	5	10	25
-5	Mean |E*| (MPa)	25 438	28 670	29 990	32 934	34 114	35 536
	Stdev (MPa)	1223	1315	1353	1452	1451	2027
	COV (%)	4.8	4.6	4.5	4.4	4.3	5.7
5	Mean |E*| (MPa)	16 958	20 678	22 236	25 963	27 436	29 421
	Stdev (MPa)	1253	1404	1492	1670	1775	2017
	COV (%)	7.4	6.8	6.7	6.4	6.5	6.9
20	Mean |E*| (MPa)	5965	8880	10 369	14 201	16 078	18 304
	Stdev (MPa)	521	615	662	652	656	1123
	COV (%)	8.7	6.9	6.4	4.6	4.1	6.1
40	Mean |E*| (MPa)	673	1161	1550	2933	3942	5563
	Stdev (MPa)	97	188	260	473	605	748
	COV (%)	14.4	16.2	16.8	16.1	15.4	13.5
55	Mean |E*| (MPa)	281	359	419	685	907	1526
	Stdev (MPa)	25	40	51	99	128	258
	COV (%)	8.8	11.1	12.2	14.5	14.1	16.9

4.1.3 *Dynamic modulus master curves*

Master curves are constructed using the dynamic modulus test data to account for the effects of temperature and frequency (or loading rate) on the hot-mix asphalt. Detailed step by step construction of master curves for South Africa asphalt mixes is described in a recent CSIR BE report (Anochie-Boateng et al. 2010). A reference temperature of 20°C was used to construct the dynamic modulus master curves. Figure 4 shows master curves constructed for the ten specimens tested during protocol development, and Figure 5 shows detailed master curve for the average dynamic modulus values of the specimens.

Figure 5 shows that the test data obtained at the low test temperatures were shifted to the right whereas the high temperatures data were shifted to the left to meet the master curve.

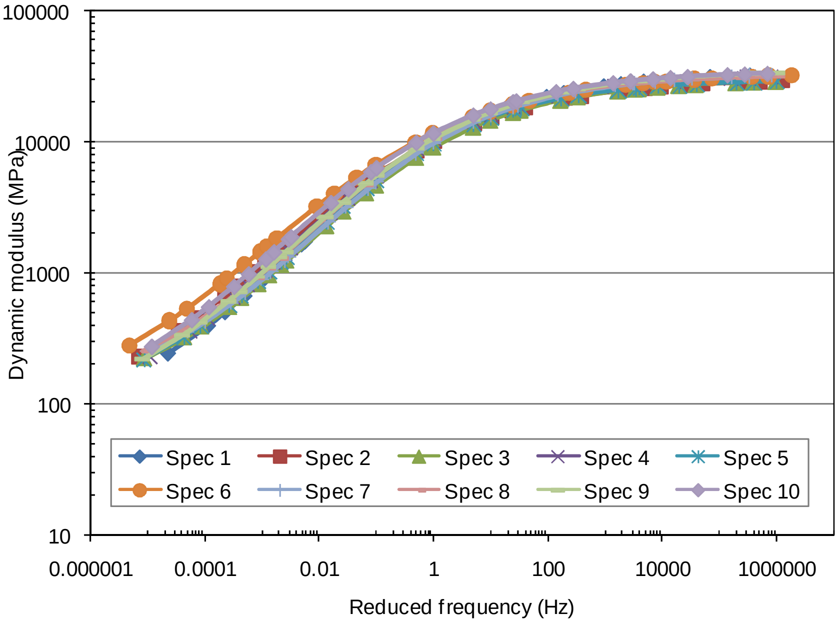


Figure 4: Master curves for 10 replicate specimens

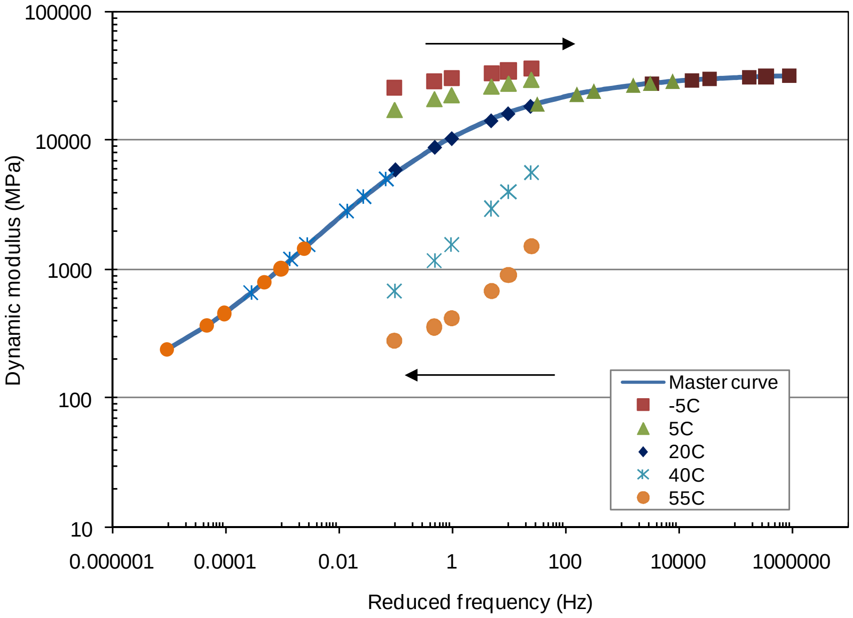


Figure 5: Master curve for average dynamic modulus values

4.2 Shear dynamic modulus testing

As part of the SAPDM project, asphalt mixes are characterized in terms of the complex shear modules G* using the simple shear tester (SST). The standard procedure to obtain the complex shear modulus G* using the SST is contained in AASHTO T320-03. This test procedure is known as the shear frequency sweet test at constant height (SFST-CH). The same equipment is also used for characterisation of the permanent deformation of HMA in the repeated simple shear test at constant height (RSST-CH), which is discussed in Section 5 of this paper. The development of the SST equipment is described by Sousa et al (1994a).

The test procedure for the SFST-CH is based on AASHTO standard test method AASHTO 320-03, with certain alterations and improvement to better suit the requirements of the revision of the SAPDM project. The alterations made to the test methods are discussed below, but first the general concept of the test in simple shear is introduced.

The principle of simple shear is to induce shear strain without volume change. A two dimensional representation of simple shear acting on an object is drawn in Figure 6a. Shear deformation *ΔL* is induced in the horizontal direction. While this load is being applied, the height of the sample *L* is kept constant. The simple shear strain at constant height is calculated using Eq. 3.

$$Shear\ strain = \frac{deformation}{original\ length} = \frac{\Delta L}{L} \qquad [3]$$

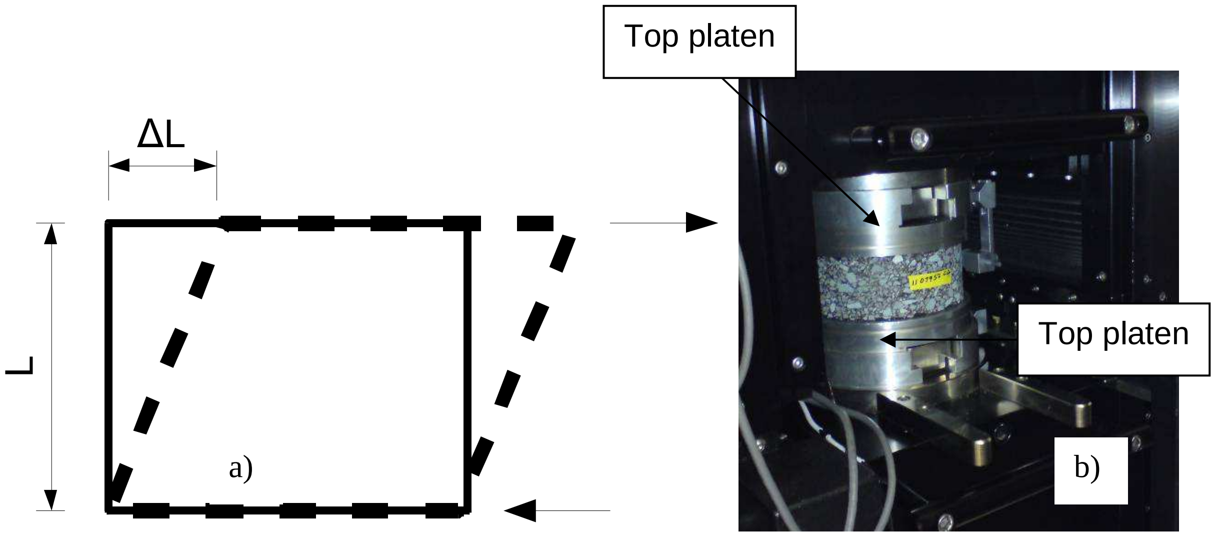


Figure 6: a) Principle of simple shear, b) HMA specimen clamped in SST

To create the situation drawn in Figure 6a the specimen is glued to steel platens at the top and the bottom and then clamped in the SST. An HMA sample clamped in the SST machine during the test is shown in Figure 6b. A horizontal cyclic shear load is introduced to the sample by moving the bottom platen using the shear actuator of the shear tester. The response of the sample in terms of shear displacement is measured using a linear variable displacement transducer (LVDT) mounted horizontally. The horizontal or shear LVDT measures the differential displacement between the top and bottom platens. In the original test method the LVDTs were mounted to the asphalt material itself, but this often leads to LVDTs coming loose during the test (Denneman, 2008). The current AASTHO T320-03 method allows both mounting to the specimen and mounting to the platens. During testing, the sample's height is kept constant by the vertical actuator, and the sample responds to the movement of an LVDT mounted vertically. The range, resolution and accuracy of the LVDTs and the actuators are specified in AASHTO 320-03. The shear LVDT used in the SST setup at CSIR BE has a range of ± 2.5 mm.

The complex shear modulus G* could in principle be used as input for multilayer elastic analysis of pavement structures as well as input for permanent deformation damage models in the same way as E* is used in the new AASHTO 2002 design guide (NCHRP 1-37A 2004). Procedure A of this protocol describes the shear frequency sweep test at constant height. A sinusoidal shear strain of 0.01 per cent is applied at 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz at repeated range of temperatures to determine the G* master curve.

Figure 7 shows an example of a master curve for the complex shear modulus G*. The construction of the master curve is done in the same manner as for the dynamic modulus testing described in a recent CSIR BE report (Anochie-Boateng et al. 2010). The data for the tests performed at temperatures of 40℃ and 55° C were shifted to the left as indicated by the arrows to meet the master curve. Thus, both the master curve and the shift factors are needed for a complete description of the rate of loading and temperature effects on the asphalt materials tested.

The AASHTO test protocol does not contain a statement on the precision of frequency sweep testing using the SST. The testing to determine the precision of the frequency sweep test at CSIR is ongoing. In an extensive study by Anderson et al (2003) found the single laboratory precision to be approximately 10 per cent. Multi-laboratory precision was found to be 38 per cent.

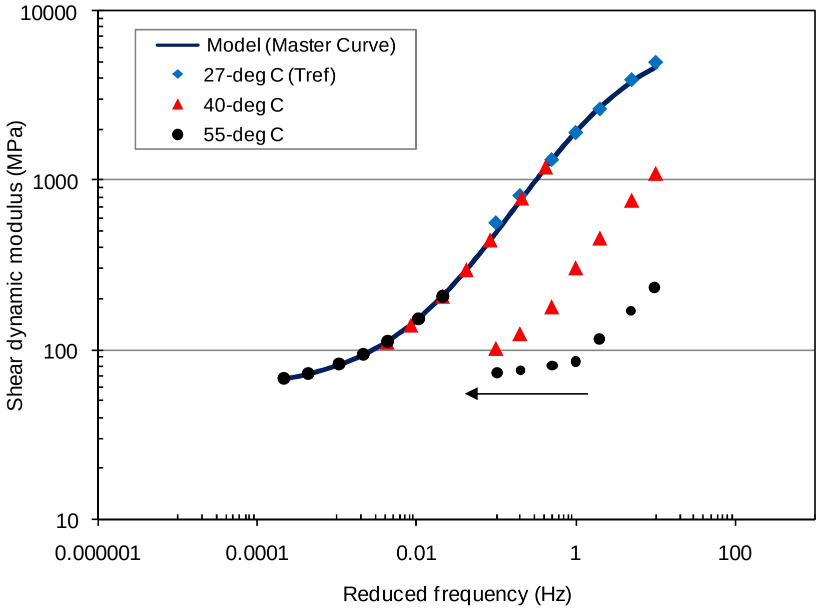


Figure 7: Example of shear modulus master curve for BTB

4.3 Beam frequency sweep

The beam frequency sweep stiffness test is conducted to measure stiffness modulus properties of the beam when subjected to different temperatures and loading frequencies. The test results can be used to construct stiffness master curves to rank the asphalt mixes tested. Three test temperatures of 0, 20, and 40^{o}C and frequencies of 0.1, 1, 2, 5 10, 20 and 25Hz were initially proposed for the beam frequency sweep tests but was later changed. The current CSIR BE test protocol developed for beam frequency sweep test for SAPDM is conducted at test temperatures of 0, 5, 20, 40 and 55^{o}C, and at loading frequencies of 0.1, 0.5, 1, 5, 10 and 25Hz for easy comparison with test results with the dynamic modulus testing.

The beam frequency sweep test is conducted in a servo-hydraulic four-point beam fatigue testing apparatus with environmental controlled temperature chamber available at CSIR BE pavement materials laboratory. Specimens of 400 x 63 x 50 mm are cut from slabs manufactured in the laboratory or obtained from the field to conduct the test. A minimum of 5 replicate specimens are recommended in the CSIR BE test protocol.

4.3.1 *Beam frequency sweep test results*

Five beam specimens of the standard mix were tested with the first protocol (temperatures of 0, 20, and 40^{o}C and frequencies of 0.1, 1, 2, 5 10, 20 and 25Hz). Table 4 shows the statistical analyses results and Figure 8 shows the variation of frequency with beam stiffness modulus at test temperatures and loading frequencies. Currently, no beam frequency sweep test results are available to compare the statistical analyses results obtained from this study. This is perhaps the fact that modulus properties from beam frequency seep test have not been used to characterise HMA in road pavement applications.

Table 4: Statistical analyses results for beam stiffness modulus protocol

Temp (oC)	Statistic	Frequency (Hz)						
		0.1	1	2	5	10	20	25
0	Mean |E*| (MPa)	11851	16661	18252	20238	21504	22552	23109
	STDEV (MPa)	1606	1452	1472	1361	1346	1363	1421
	COV (%)	13.5	8.7	8.1	6.7	6.3	6.0	6.1
20	Mean |E*| (MPa)	1664	4194	5183	6742	7974	9255	9557
	STDEV (MPa)	185	293	374	383	465	515	513
	COV (%)	11.1	7.0	7.2	5.7	5.8	5.6	5.4
40	Mean |E*| (MPa)	165	350	534	842	1161	1491	1609
	STDEV (MPa)	9	43	46	52	60	130	115
	COV (%)	5.6	12.2	8.6	6.1	5.2	8.7	7.1

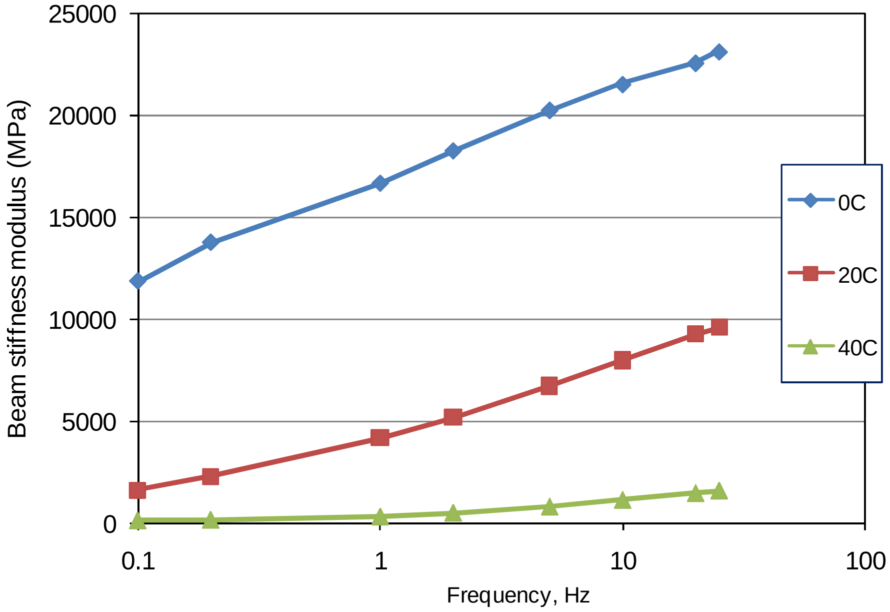


Figure 8: Variation of Frequency with beam stiffness modulus

5 DEVELOPMENT OF TEST PROTOCOLS FOR DAMAGE ACCUMULATION

The main modes of damage to HMA encountered in the field are permanent deformation (rutting) and fatigue cracking. In the SAPDM project the rutting performance of HMA mixes is characterized using the repeated simple shear test at constant height (RSST-CH). The fatigue behaviour of HMA is assessed by means of beam fatigue testing. An addition to fatigue test is a test developed to characterize the fracture behaviour of the material in terms of fracture mechanics properties, which is also perform as part of the project.

5.1 Repeated simple shear test at constant height

The principle of simple shear and the simple shear tester (SST) equipment is already described in Section 4.2. Like the SFST-CH, the RSST-CH is performed in accordance to AASHTO 320-03, with some alterations to suit the requirement of SAPDM. In the RSST-CH a horizontal shear force of 69 kPa is applied to the cylindrical specimen, shown in Figure 6b. The load is applied for 0.1 second followed by a 0.6 second rest period. The horizontal deformation is measured over height of the specimen during the test. The standard procedure AASHTO 320-03 specifies that the test be run for 5 000 repetitions. The reasoning behind the RSST-CH test is that shear deformations rather than compressive deformation dominate rutting development. Mechanistic empirical technology to predict permanent deformation in the field from RSST-CH results was developed at the University of California Pavement Research Center (Sousa et al. 1994b; Monismith et al 2000 and Deacon et al 2002). Further calibration of permanent deformation models is described in Ullidtz, et al (2006a) and Ullidtz, et al (2006b).

During the protocol development stage it was found however that the rate at which permanent deformation accumulates during the test, and the trend in the deformation curve still changes after 5 000 repetitions. It was therefore decided that as part of the SAPDM project the RSST-CH tests will be run up to 30 000 repetitions. Rutting mainly occurs at elevated temperatures; therefore the CSIR BE test protocol recommends tests to be performed at 25℃, 40℃, and 55℃. Figure 9 show s RSST-CH results for a typical South Africa mix tested at different temperatures.

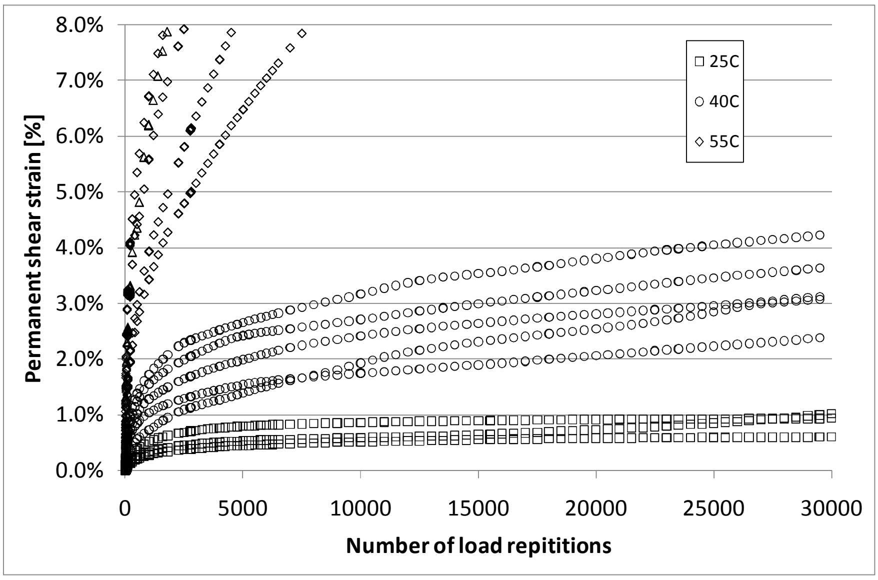


Figure 9: RSST-CH results for typical SA asphalt ix at different temperatures

The AASHTO 320-03 test procedure does not contain a precision statement for the RSST-CH. Anderson et al (2003) found in an extensive study the single laboratory precision of the test to be within 10 per cent. The multi-laboratory precision (reproducibility) was much higher at 70 per cent.

5.2 Repeated axial load permanent deformation test

Permanent deformation properties determined from repeated load uniaxial or triaxial tests are key parameters to model rutting potential in the current pavement design guide pursued by AASHTO (NCHRP 1-37A). In SAPDM these parameters are alternative to shear permanent deformation properties. Permanent deformation properties obtained from repeated load test can also be used to rank asphalt mixes. A major advantage of this test is the ability to measure both resilient modulus and permanent deformation of asphalt mixes in the same test. In addition, the UTM-25 test setup and specimens for dynamic modulus testing are used to conduct the permanent deformation tests.

The repeated axial load permanent deformation test proposed for South Africa consist of applying three deviator stress levels (69, 138 and 207 kPa) at three test temperatures (25, 40, and 55°C) on a minimum of 3 replicate asphalt specimens. During testing, the deviator stresses are repeatedly pulsed in the vertical direction on the specimens using a haversine load of 0.1 seconds and 0.9 seconds rest period. Each stress level is pulsed for 20,000 load cycles to collect permanent deformation accumulation at test loading conditions.

Figure 10 shows typical results of permanent axial strain against number of load cycles for a typical South Africa mix tested at different deviator stress and temperatures.

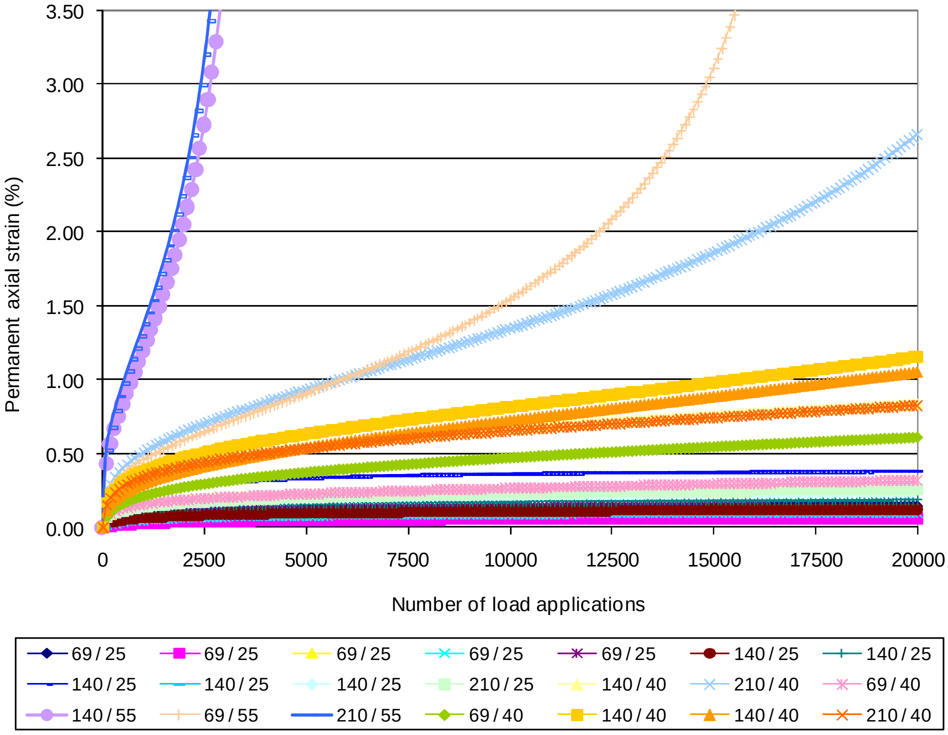


Figure 10: RLPD results for typical SA asphalt ix at different deviator stress and temperature levels

5.3 Flexural beam fatigue testing

Fatigue is a phenomenon in which a road pavement is subjected to repeated stress levels until failure. Fatigue life obtained from prismatic beam test is a key input parameter for flexible pavement design to simulate cracking in hot-mix asphalt. The current road design methods recommend the four point flexural beam fatigue test for characterising hot-mix asphalt mixes fatigue properties (NCHRP 1-37A 2004, SANRAL 2007). The CSIR BE beam fatigue protocol developed for SAPDM establishes comprehensive database including fatigue life, modulus, phase angle and dissipated energy of the asphalt mixes. Based on the database, fatigue characterisation models can be developed for the HMA testes.

5.2.1 *Beam fatigue test protocol and laboratory program*

The CSIR BE beam fatigue test protocol is used for determining beam fatigue characteristics of asphalt mixes in South Africa. The fatigue test is performed at three test temperatures of 5, 10, and 20^{o}C. The AASHTO T321 is the current standard test procedure for determining beam fatigue characteristics. The AASHTO T321 recommends one test temperature of 20^{o}C, whereas the EN 12697-24 recommends selected test temperatures 5 to 25^{o}C.

The stand alone servo-hydraulic testing apparatus used for beam frequency sweep test was mainly designed for beam fatigue testing. A continuous sinusoidal displacement waveform measurement on top of the sample with frequency of 10Hz is applied on a prismatic beam samples of 400 x 63 x 50 mm (length x width x height). The CSIR BE test protocol recommends that fatigue test be conducted at four different strain levels (200, 400, 600 and 800 microstrains). These strain levels are selected to fall within the range specified by the international test protocols (AASHTO T 321 and EN 12697-24), and to cover the strain levels experienced in South Africa pavements. A minimum of three replicate tests are conducted on all samples at each testing condition. The beam fatigue test specimens are obtained by sawing slabs made in the laboratory, or taken from the road.

Figure 10 shows typical beam fatigue test conducted with the CSIR BE test protocol on a typical South African asphalt mix. The figure shows test results at 200 microstrains at temperatures of 5, 10, and 20^{o}C. As expected fatigue life was found to be longer for the sample at 20^{o}C compared to shorter fatigue life at 5^{o}C. Thus, at the same strain level, a lower fatigue life is obtained at high temperatures. This is typical behaviour of asphalt mixes.

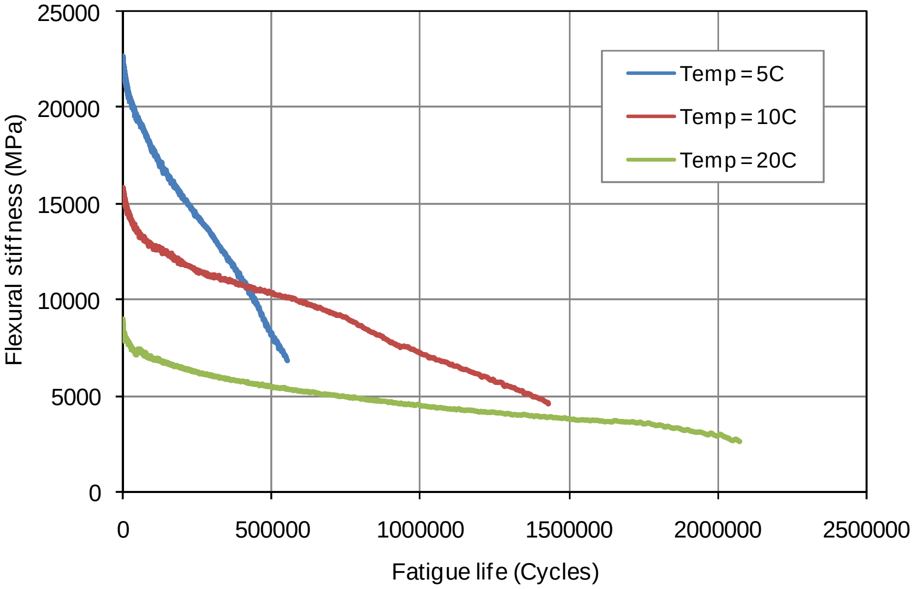


Figure 10: Fatigue curve of the typical hot-mix asphalt in South Africa

6 SUMMARY AND CONCLUSIONS

The South Africa National Road Agency Ltd (SANRAL) has entered into a research and laboratory testing contract with CSIR Built Environment (CSIR BE) to support the new South African Pavement Design Methods (SAPDM). The overall project involves development of test protocols to determine material properties of hot-mix asphalt commonly used in South Africa.

This paper presented laboratory test protocols developed for bituminous binders and asphalt mixes used in South Africa. The test protocols developed were; (a) dynamic shear rheometer protocol for bituminous binders, and (b) stiffness (elastic) modulus, permanent deformation and beam fatigue tests protocols for the asphalt mix. The testing conditions such as temperature and loading frequency were selected based on temperature regimes experience in South Africa road pavements. The required modifications to existing local and international protocols to suit South Africa conditions were discussed, and some potential challenges with the adoption of the protocols in the SAPDM were addressed. The various test protocols were used to conduct a laboratory testing program on standard hot-mix asphalt with 60/70 penetration grade binder for verification purposes. The statistical analyses results presented for some of the test protocols were very promising.

Overall, the developed test protocols will provide the basis to improve and develop reliable resilient response and damage models for SAPDM. Also, the test protocols will enhance consistent and more reliable road pavement analysis for South Africa. The final test protocols will be recommended as technical guidelines or methods for advanced road pavement materials testing in South Africa. The finished protocols are available from www. sapdm.co.za

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