COMPARATIVE EVALUATION OF AN EXPERIMENTAL BINDER IN HOT- MIX ASPHALT: CORRELATING THE PREDICTED PERFORMANCE OF THE BINDER WITH ASPHALT TESTING

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ABSTRACT

The binder is an important constituent of an asphalt mix and it affects the overall performance of the mix, especially with regards to permanent deformation and fatigue cracking. The stiffest binder available from the Chevron refinery in the Western Cape is a 70/100 penetration grade bitumen. This has resulted in numerous role players in the industry developing experimental binders (closer in stiffness to a 50/70 penetration grade binder) to provide an improved performance with regards to asphalt applications.

This paper presents the evaluation of an experimental binder in terms of comparisons with 50/70 penetration grade bitumen of known good performance. Comparative testing was done using the current South African bitumen specification as well as performance grade properties with reference to AASHTO MP19 / M320 and the complex shear moduli. Furthermore, the comparative performance of the binders in identical asphalt mixes containing the same aggregate, grading and binder content were evaluated. The asphalt performance-related tests conducted on the mixes included repeated axial load permanent deformation (rutting indicator), beam fatigue (cracking indicator), dynamic modulus (stiffness indicator) and modified Lottman (durability indicator). The test results were evaluated comparatively to establish whether the performance of the asphalt mixes differed.

The close correlations between some binder tests and the asphalt tests in predicting performance were found to be of interest.

1 INTRODUCTION

Binder or bitumen plays a critical role in the overall performance of asphalt mixes. The properties of binder may be used to get an indication of the expected performance of an asphalt mix. The asphalt mix performance indicators affected by the properties of binder include permanent deformation (rutting), fatigue cracking, stiffness and durability.

The Chevron refinery in the Western Cape did not produce any 50/70 penetration grade bitumen at the time that this investigative work was done. The production of 70/100 penetration grade bitumen was the closest the refinery came in terms of stiffness with regards to a 50/70 penetration grade bitumen.

This has resulted, at the time, in numerous role players in the industry developing experimental binders (closer in stiffness to a 50/70 penetration grade binder) to provide an improved performance for asphalt applications. This paper describes an attempt at evaluating such an experimental binder.

The experimental binder was evaluated comparatively with a standard 50/70 penetration-grade bitumen of known good performance. Comparative binder testing was done in terms of the current South African bitumen specification, performance graded properties with reference to AASHTO MP19 / M320 as well as the complex shear moduli as measured by a dynamic shear rheometer (DSR).

Furthermore, the comparative performance of the binders in identical asphalt mixes containing the same aggregate, grading and binder content were evaluated. The asphalt performance related tests conducted on the mixes included:

- repeated axial load permanent deformation (RLPD) (rutting indicator);
- beam fatigue test (cracking indicator);
- dynamic modulus (stiffness indicator), and
- modified Lottman test (durability indicator).

The test results were evaluated comparatively to establish whether the performance of the asphalt mixes differed significantly.

2 ROLE OF BINDER IN HOT MIX ASPHALT

The binder or bitumen in hot mix asphalt is a thermoplastic glue (adhesion) that binds the remaining constituents (aggregate and filler) together. The binder is hydrophobic, resulting in a water-proofing layer, depending on the design of the hot mix asphalt. The viscosity of the binder is temperature dependant and the desired rheological properties are such that:

- Viscosity should be low enough at handling temperatures (pumping, mixing and compaction)
- Viscosity should be high enough at high pavement temperatures to impart sufficient resistance to deformation of the asphalt mix (high elastic behaviour)
- Viscosity should be low enough at low pavement temperatures to impart sufficient resistance to low temperature cracking (viscous behaviour).
- Furthermore, the binder rheological properties should be such that the binder should impart fatigue resistance over a wide range of pavement operating temperatures.

Raising the viscosity at high pavement temperatures (desirable), often results in higher viscosity at lower pavement temperature too (undesirable), and so the overall effects become juxtaposed. The main goal should be to attain an acceptable balance.

3 MATERIALS, MIX DESIGN AND MIX MANUFACTURE

3.1 Materials

3.1.1 Bitumen binder

Standard 50/70 penetration-grade bitumen (standard binder) was obtained from a commercial asphalt plant in Gauteng, whereas the experimental 50/70 penetration-grade bitumen (experimental binder) was manufactured in a laboratory.

3.1.2 Aggregate

Granite aggregate was sourced from a commercial asphalt plant in Gauteng. The granite aggregate consisting of 9.5 mm stone, 6.7 mm stone and crusher sand, was used routinely in the production of a good-performing medium continuously graded wearing course.

3.2 Mix design

The mix design was sourced from the same commercial asphalt plant in Gauteng and was used routinely in the production of a good-performing medium continuously graded wearing course. The volumetric properties of the mix are summarised in Table 1. The target grading is displayed in Figure 1.

Table 1: Summary of volumetric properties of the medium continuous mix

Mix property	Design value
Binder content (%)	4.7
Design air voids (%), saturation surface dry (SSD)	4.9
Volume of voids in mineral aggregate (VMA) (%)	14.9
Volume of voids filled with binder (VFB) (%)	68.0

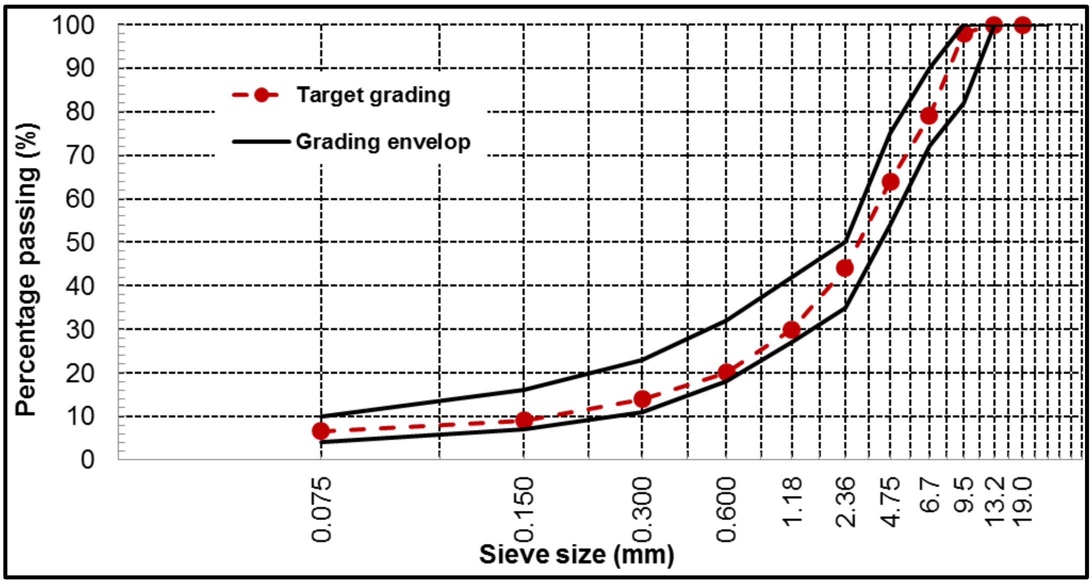

Figure 1: Target grading

3.3 Mechanical mixing and conditioning of asphalt samples

The mechanical mixing and compaction of the asphalt samples were done in accordance with CSIR's test protocols for testing asphalt mixes in South Africa (Anochie-Boateng et al., 2010). Calculated masses of aggregates were blended in accordance with the design grading and pre-heated to the required mixing temperature (145°C). A calculated mass of the bituminous binder and the pre-heated aggregate were placed into a pre-heated mechanical mixer. The materials were mixed until a uniform mixture was obtained (approximately 15 minutes).

After mixing, the loose asphalt material was aged to simulate ageing that takes place during the normal production process in an asphalt plant and transport to site. The ageing of the loose asphalt material was done in accordance with Superpave short-term ageing procedures as described by Von Quintus *et al*., (1991), but slightly modified in the CSIR's test protocol (Anochie-Boateng et al., 2010). The ageing procedures require placing loose asphalt material into an oven set at compaction temperature for four hours before compaction.

3.3.1 Voids of compacted samples

The Maximum Theoretical Relative Density (MTRD) of the asphalt mix was determined by using the standard TMH1 Method C4 A. The average MTRD values of 2.459 and 2.451 were obtained for the Standard Binder and Experimental Binder mixes respectively. Bulk Relative Densities (BRD's) were determined according to TMH1 method C3 (1986). Average voids are reported in Table 2.

Table 2: Summary of volumetric properties of the asphalt samples

Experimental Binder Mix			**Standard Binder Mix**		
Sample Origin	**BRD**	**Air voids (%)**	**Sample Origin**	**BRD**	**Air voids (%)**
Dynamic Modulus	2.285	7.1	**Dynamic Modulus**	2.278	7.1
RLPD	2.288	7.0	**RLPD**	2.289	6.6
Beam Fatigue	2.346	4.6	**Beam Fatigue**	2.349	4.2

4 RESULTS AND DISCUSSION

4.1 Binder test results

4.1.1 Specifications test results

Specification testing was carried out according to SANS 4001-BT1 (2013) and the results are presented in Table 3. At first glance, there does not appear to be much difference between the binder properties, especially if only softening point and penetration are taken into account. If softening point of the binder were to be taken as an indicator of the resistance of a mix to rutting, then similar rut resistance would be expected from both binders, as the softening points are very similar to each other, before and after short term ageing, using the rolling thin film oven (RTFOT).

However, the experimental binder fails the required minimum specification value of 140 Pa.s for viscosity at 60°C. Should viscosity at 60°C be taken as an indicator of the resistance of a mix to rutting, then approximately half the rut resistance would be expected from the experimental binder at 111 Pa.s compared to the standard binder at 217 Pa.s. The dissimilarity between the viscosities at 60°C is unexpected, as it has been the authors' experience that there is close correlation between the softening points of binders and their viscosities at 60°C.

The experimental binder appears to have a greater resistance to ageing, showing an increase of 2.0 °C in softening point compared to the increase of 3.4°C shown by the standard binder. This would retard the experimental binder's ability to improve its resistance to deformation with ageing, but improve its ability to withstand fatigue cracking with ageing.

Table 3: Results of the standard binder tests

Property	Test result		SANS 4001-BT1 Specification	Test method
	Experimental binder	Standard binder		
Original binder				
Penetration (dmm)	66	62	50-70	ASTM D5
Softening Point (°C)	48.0	48.6	46-56	ASTM D36
Viscosity @ 60°C (Pa.s)	111	217	140	ASTM D4402
Viscosity @ 135°C (Pa.s)	0.290	0.390	0.22-0.45	ASTM D4402
Spot Test (% Xylene)	Negative	Negative	30 max	AASHTO T102
After RTFOT (Rolling thin film oven treatment) Ageing				
Mass Change (% m/m)	0.07	0.05	0.3 max	ASTM D2872
Penetration (dmm)	50.0	44.0	N/A	ASTM D5
% Original	76	71	55 min	ASTM D5
Softening Point (°C)	50	52	48 min	ASTM D36
Softening Point increase (°C)	2.0	3.4	7 max	ASTM D36
Viscosity @ 60°C (Pa.s)	193	386	N/A	ASTM D4402
% Original	174	178	300 max	ASTM D4402

4.1.2 Performance graded (PG) binder test results

Performance grade-type tests were carried out according to AASHTO MP19 and AASHTO M320. Results are reported in Table 4. The PG test results indicate that the deformation resistance (as indicated by the J_{nr} value) offered by the standard binder will be approximately twice that of the experimental binder. (A doubling of the J_{nr} value indicates an approximate doubling of the rut rate.) This is in line with what was found with the viscosity @ 60°C.

The fatigue properties (as indicated by G*.sinδ) of both binders are similar, with the standard binder indicating a small advantage.

Table 4: Results of PG tests

Property	Test result		Reference
	Experimental binder	Standard binder	
After RTFOT (Rolling thin film oven treatment) Ageing			
J_{nr} @ 3.2 kPa @ 58°C (kPa^{-1})	3.8	1.9	AASHTO MP19
J_{nr} @ 3.2 kPa @ 64°C(kPa^{-1})	8.8	4.6	AASHTO MP19
After PAV (Pressure Ageing Vessel) Ageing			
Failure Fatigue Temperature (°C), where G*.sinδ ≥ 5 000 kPa	23.7	22.7	AASHTO M320

4.1.3 Rheology test results

The rheological properties were determined by DSR and the results are presented in Figure 2. The results indicate that at 20°C there is little difference between the complex modulus values of either binder after RTFOT. However, at 40 and 55°C the complex modulus values of the experimental binder are significantly lower than those of standard binder after RTFOT, which may be indicative of lower resistance to permanent deformation at these temperatures. After PAV (long-term) ageing, the differences between the binders become less.

The black diagram after RTFOT indicates an increased phase angle for the experimental binder at 40 and 55°C (around 1.59 Hz), imparting a greater viscous nature to that binder at these temperatures – and hence poorer rut resistant properties.

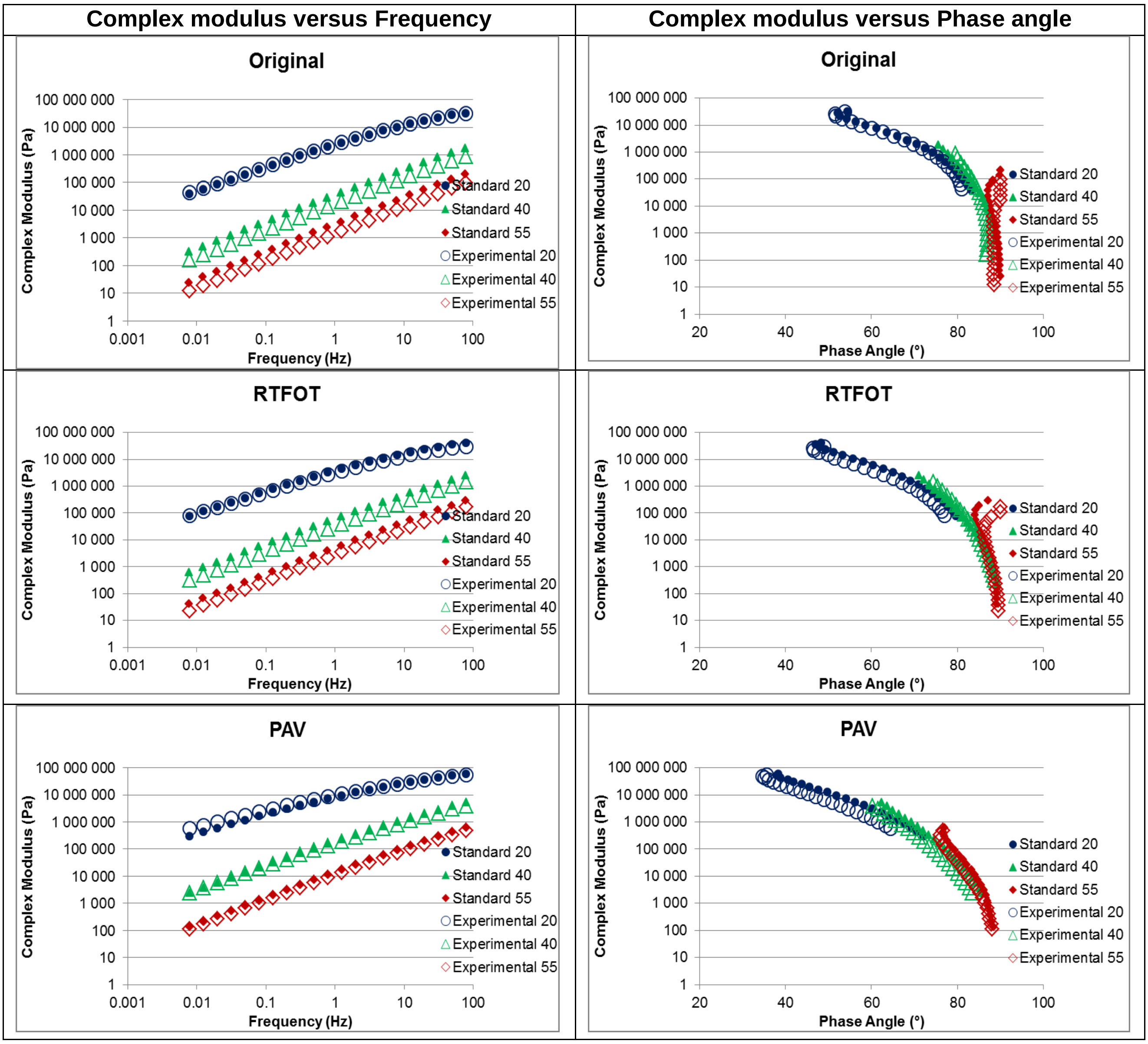

Figure 2: Rheological evaluation of the Standard and Experimental binders

4.2 Asphalt performance test results

4.2.1 Dynamic modulus test results

The dynamic modulus testing was conducted as per CSIR test protocol developed for the South African Pavement Design Method (SAPDM) (Maina and Anochie-Boateng, 2010). A Universal Testing Machine device was used to conduct the dynamic modulus tests on short-term aged gyratory compacted specimens (100 mm diameter x 150 mm high) (Table 5).

As expected, the dynamic modulus of the mixes increased with increasing loading frequency and decreased with increasing temperature. Overall, the dynamic modulus values of the standard binder mix appear to be higher than those of the experimental binder mix. At lower temperature (-5, 5 and 20°C), the dynamic modulus results do not differ significantly. However, at higher temperature (40 and 55°C) there is a significant difference, with the experimental mix having lower values. This would explain the higher permanent deformation obtained later on.

The observed trend of the standard mix with regards to the experimental mix is in agreement with the binder complex modulus results. “The results indicate that at 20°C there is little difference between the complex modulus values of either binder after RTFOT. However, at 40 and 55°C the complex modulus values of the experimental binder are significantly lower than those of standard binder after RTFOT, which may be indicative of lower resistance to permanent deformation at these temperatures.”

Table 5: Dynamic modulus results

Temperature (°C)	Frequency (Hz)	Standard mix				Experimental mix				% Mean difference
		Dynamic modulus of specimens (MPa)			Mean (MPa)	Dynamic modulus of specimens (MPa)			Mean (MPa)	
		C1	C2	C3		C1	C2	C3		
-5	25	25515	30255	27385	27718	25077	28159	25706	26314	5
	10	24852	28994	26361	26736	24275	27239	24805	25440	5
	5	24208	27925	25539	25891	23532	26453	24051	24679	5
	1	22157	25121	23274	23517	21538	24354	22066	22653	4
	0.5	21321	23711	22171	22401	20620	23359	21107	21695	3
	0.1	18832	20202	19405	19480	18285	20803	18700	19263	1
5	25	23227	25398	23841	24155	21967	24784	22429	23060	5
	10	22251	23616	22569	22812	20728	23383	21198	21770	5
	5	21421	22149	21441	21670	19719	22252	20192	20721	4
	1	18800	18588	18550	18646	17202	19452	17653	18102	3
	0.5	17632	16858	17160	17217	16049	18133	16438	16873	2
	0.1	14336	12955	13836	13709	13303	14997	13472	13924	-2
20	25	14463	14260	14936	14553	14081	15190	12836	14036	4
	10	12794	11962	12880	12545	12314	13291	11074	12226	3
	5	11384	10286	11317	10996	10971	11868	9736	10858	1
	1	8091	6728	8005	7608	7955	8777	6827	7853	-3
	0.5	6820	5394	6739	6318	6750	7573	5729	6684	-6
	0.1	4044	2835	4151	3677	4253	5063	3466	4261	-16
40	25	3534	2643	3444	3207	2031	2212	1620	1954	39
	10	2408	1636	2369	2138	1267	1376	952	1198	44
	5	1717	1083	1702	1501	848	919	617	795	47
	1	698	386	699	594	293	325	208	275	54
	0.5	478	258	478	405	197	219	148	188	54
	0.1	209	117	206	177	90	99	78	89	50
55	25	1096	661	1000	919	424	548	729	567	38
	10	643	386	589	539	260	343	427	343	36
	5	448	278	407	377	192	253	298	248	34
	1	207	141	179	176	94	126	164	128	27
	0.5	179	137	154	157	93	129	154	125	20
	0.1	147	131	122	133	88	142	137	122	8

% Mean Difference is the %difference between means

4.2.2 Permanent deformation test results

The permanent deformation testing was conducted as per CSIR test protocol developed for the SAPDM (Anochie-Boateng and Maina, 2012). A Universal Testing Machine (UTM-25) was used to conduct the repeated axial load permanent deformation (RLPD) tests on short-term aged gyratory compacted specimens (100 mm in diameter x 150 mm high) at 40°C.

Figure 3 shows that the standard binder mix had lower permanent axial strain, indicating that the mix had better resistance to permanent deformation. For the RLPD test, the flow number value is an indicator of the permanent deformation behaviour of asphalt mixes. The higher the flow number, the better the resistance to permanent deformation. The flow number can be defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain.

The average flow number value for the experimental binder mix was 311; whereas that of the standard binder mix was 561 indicating that latter mix had better resistance to permanent deformation, almost twice that of the former. These results correlate well with:

- Binder viscosity at 60°C – standard binder is almost twice the value of the experimental binder
- The non-recoverable compliance factor, Jnr @ 3.2 kPa @ 58°C or 64°C – standard binder shows twice the rut resistance compared to the experimental binder. Mturi *et*

al. (2012) have also previously shown the potential to predict permanent deformation resistance of asphalt mixes from creep-recovery testing of South African binders.

- Complex modulus after RTFOT – standard binder is practically twice that of the experimental binder at 40°C after RTFOT.
- Dynamic Modulus at 40°C – The mix with the standard binder is practically twice that of the experimental binder mix at 40°C.

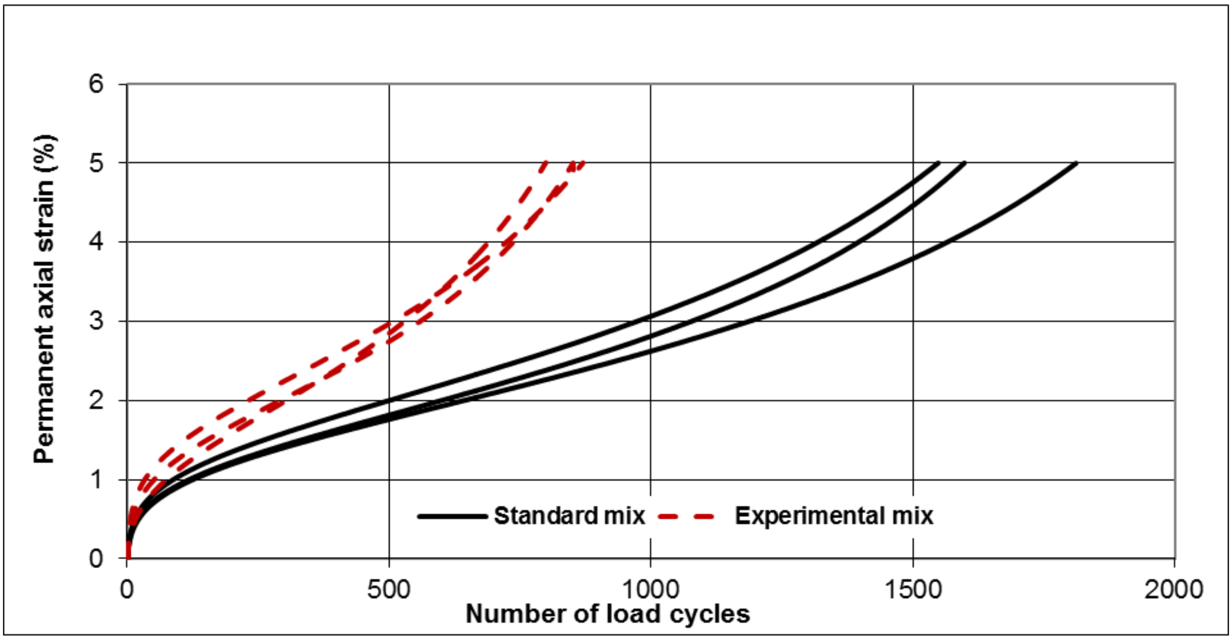

Figure 3: RLPD results at 40°C

Further comparison of the Experimental RLPD test results with results of other medium continuously graded mixes with 50/70pen binder previously tested at the CSIR also indicated that the experimental binder mix has the least average flow number values. The average flow number values for the medium continuously graded mixes with 50/70pen binder tested to date, ranged from 500 to 1100, whereas the average flow number value for the experimental binder mix is 311. The observed differences could only be attributed to the experimental binder itself, which had imparted poor resistance to permanent deformation.

4.2.3 Fatigue test results

Four point beam fatigue tests were conducted on prismatic beam specimens (400 x 63 x 50 mm) under controlled-strain loading conditions at three strain amplitude levels at a frequency of 10 Hz and a temperature of 10 °C (Anochie-Boateng et al., 2010). For each strain amplitude level, three specimens were tested. The failure criterion was defined as the number of load cycles at which the initial stiffness is reduced by 50 % (Figure 4).

At lower strain amplitude level (200 microstrain), the fatigue life of the standard binder mix is slightly higher than that of the experimental binder mix. The results from the two mixes do not differ much from each other, which is in agreement with the values for G*.Sinδ. The lower strain amplitude level is discussed because it is closest in value to the actual strain values experienced by the asphalt surfacing layer.

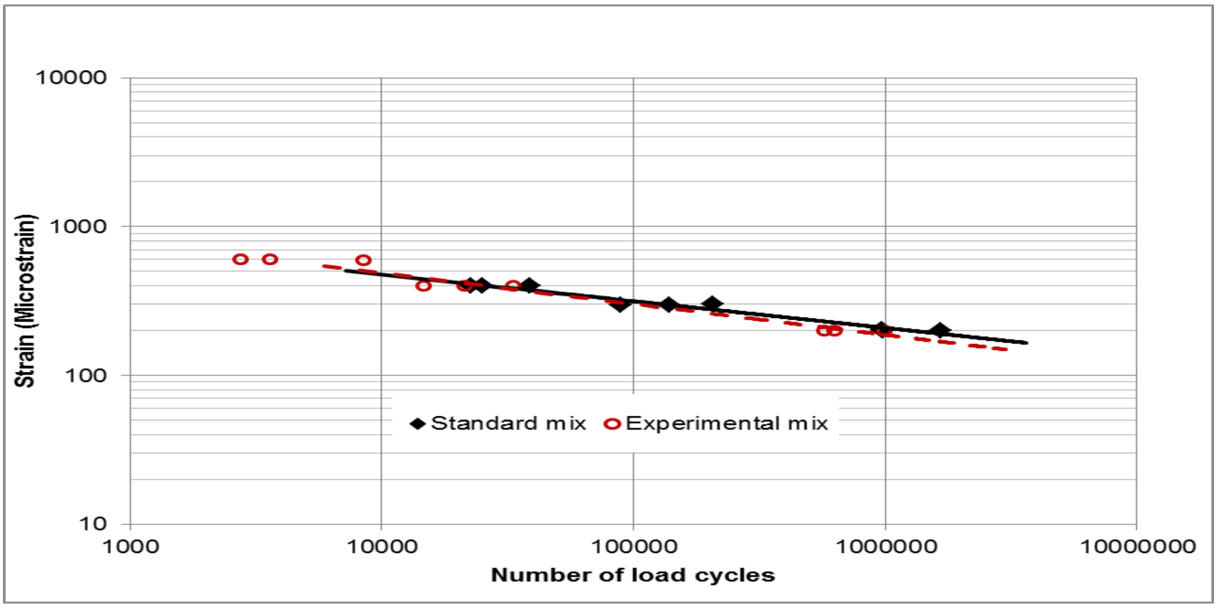

Figure 4: Strain versus number of load cycles at 10°C

4.2.4 Modified Lottman test results

The Modified Lottman test gives an indication of the durability of an asphalt mix in terms of resistance to moisture damage (binder adhesion). Moisture resistance of an asphalt mix is tested in accordance with ASTM D 4867M. The test relies on indirect tensile strength measurements taken before and after conditioning by freeze-thaw cycles. The ratio of the indirect tensile strengths of the conditioned and unconditioned specimens which is referred to as the tensile strength ratio (TSR) is used to get an indication of the resistance of the asphalt to moisture damage (Table 6). Both mixes appears to have good moisture resistance (i.e. TSR greater than 0.8). Although the experimental binder mix had higher average ITS value, the TSR is less than that of the standard binder mix.

Table 6: Modified Lottman Results

Standard asphalt mix					
Treated Briquettes			**Dry Subset**		
Void (%)/Saturation level (%)			Void (%)		
6.8/69.6	6.8/68.3	6.7/69.6	7.5	6.3	6.2
ITS (kN)			ITS (kN)		
1113	1178	1024	1252	1146	1290
Average ITS = 1105			Average ITS = 1230		
TSR = 0.90					
Experimental asphalt mix					
Void (%)/Saturation level (%)			Void (%)		
6.1/56.8	6.7/59.1	6.8/61.8	7.2	6.5	6.0
ITS (kN)			ITS (kN)		
1156	1233	1213	1200	1496	1716
Average ITS = 1201			Average ITS = 1471		
TSR = 0.82					

5 CONCLUSIONS AND RECOMMENDATIONS

The aim of this paper was to describe a process whereby an experimental binder was evaluated with regards to its predicted performance within hot mix asphalt. The laboratory test results showed that the experimental binder gave acceptable performance with regards to dynamic modulus, beam fatigue and durability. Performance with regards to permanent deformation was not acceptable. It is recommended that the experimental binder be reformulated to improve its rutting resistance.

When considering the binder tests, Softening Point and Penetration were poor indications of performance. The following tests, however, gave a very good indication of rutting performance:

- Binder viscosity at 60°C
- The non-recoverable compliance factor, Jnr @ 3.2 kPa @ 58°C or 64°C
- Complex modulus after RTFOT

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REFERENCES

AASHTO MP 19. 2010. Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test. American Association of State and Highway Transportation Officials. Washington D.C

AASHTO MP 320. 2010. Standard Specification for Performance-Graded Asphalt Binder. American Association of State and Highway Transportation Officials. Washington D.C

Anochie-Boateng, J., Denneman, E., O'Connell, J. and Ventura, D. 2010. Test Protocols for determining properties of asphalt materials for SAPDM. TECHNICAL REPORT No: CSIR/BE/IE/IR/2010/0001/B, the CSIR, Pretoria.

Anochie-Boateng, JK and Maina, J. (2012). Permanent deformation testing for a new South African mechanistic pavement design method, Construction and Building Materials 26 pp. 541–546.

ASTM D4867M, 2009. Standard test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures, American Society for Testing and Materials International

Maina, J. and Anochie-Boateng, J.K. (2010). Dynamic Modulus Testing for a New South African Mechanistic Pavement Design Method, Journal of Pavement Engineering, VOL.15, pp 31-39.

Mturi, G.A.J., Nkgapele, M. and O'Connell, J., 2012. Creep recovery behaviour of bituminous binders – relevance to permanent deformation of asphalt pavements. 2nd International Conference on Road and Rail Infrastructure (CETRA 2012). 7-9 May 2012, Dubrovnik, Croatia.

South African National Standard (SANS) 4001-BT1 (2013), "Penetration Grade Bitumens", Standards South Africa, Pretoria, South Africa.

Technical Methods for Highways, TMH1, (1986) Standard Methods of Testing Road Construction Materials, National Institute for Transport and Road Research, Council for Scientific and Industrial Research (CSIR), Second Edition, Pretoria, South Africa

Von Quintus, H.L., Scherocman, J.A., Hughes C.S., Kennedy, T.W. 1991. Asphalt aggregate mixture analysis system. NCHRP report 338. Prepared for Transportation Research Board, Brent Rauhut Engineering Inc, Austin, Texas.