CREEP RECOVERY BEHAVIOUR OF BITUMINOUS BINDERS–RELEVANCE TO PERMANENT DEFORMATION OF ASPHALT PAVEMENTS

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Abstract

The increase in traffic loads and loading time in road pavements worldwide has resulted in the widespread usage of polymer modified binders (PMBs) since they offer increased resistance to pavement distresses. The extensive use of inherently different modifiers has expanded the range of PMBs to select from when designing pavements in order to avoid pavement deformation. The new binder selection criterion using the Multiple Stress Creep and Recovery (MSCR) protocol as per ASTM D7405 is meant to differentiate the resistance to permanent deformation of different road binders. The MSCR test is essentially a repeated creep–recovery test at a fixed loading/unloading interval. This paper aims to show how creep tests can differentiate the resistance to permanent deformation for different bituminous binders, whether modified or unmodified. The paper will also illustrate creep as a time–dependent deformation phenomenon that is specific to the rate and magnitude of traffic load.

Keywords: multiple stress creep and recovery, permanent deformation

1 Introduction

Bituminous binders are viscoelastic materials with a time and temperature dependent response to loading. One of the major aims of researchers has been to characterise the elastic response of road binders in order to predict their resistance to permanent deformation. The previous Superpave parameter used for predicting rut resistance had limitations, especially in characterising the performance of polymer modified binders [1]. The new MSCR protocol as per ASTM D7405 measures the non–recoverable compliance of a binder subjected to multiple loads. This test assumes the behaviour of in situ bituminous binders in any pavement structure can be characterised at two stress levels. It also aims to classify road binders based on the extent to which they recover when subjected to the same creep loading/unloading condition. However, the variety of additives used in modifying bituminous binders worldwide has widened the viscoelastic properties of PMBs between viscoelastic liquids and viscoelastic solids at the in–service pavement temperatures. This means that the rate and extent of recovery could differ per binder, per load. This highlights the importance of characterising binders based on a number of loading cycles and loading time, especially when predicting long term permanent deformation [2].
This paper aims to show the challenges of the MSCR concept in predicting rut resistance. It explores the difficulty in characterising binders based on their ability to recover after being subjected to repeated creep loads at a defined rate and magnitude.

2 Experimental

Rheological analyses in this paper were conducted using an Anton Paar Physica Smartpave Plus Dynamic Shear Rheometer (DSR) that uses a Peltier system with a parallel plate measuring configuration. This was consistent with ASTM D7175 (Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer) and ASTM D7405 (Multiple Stress Creep and Recovery of Asphalt Binder Using a Dynamic Shear Rheometer). All measurements were done using the 25–mm diameter measuring spindle at a 1–mm gap setting.

All samples were conditioned at the appropriate test temperature prior to testing. Binders were tested at their SHRP (G*/sinδ = 1kPa) rutting test temperature limit. Five binders were investigated: a 40/50pen grade binder with a SHRP test temperature of 67°C; two SBS–modified binders (SBS at 73°C and SBS at 70°C); waxy HiMA binder at 75°C and a non–waxy HiMA at 82°C.

3 Multiple creep recovery behaviour of viscoelastic material

The MSCR test is meant to analyse the creep recovery behaviour of road binders subjected to multiple loads. The MSCR test involves applying a 1 second creep loading followed by a 9 second recovery over the multiple stress levels of 25, 50, 100, 200, 400, 800, 1600, 3200, 6400, 12800 and 25600Pa. At each stress level, 10 loading cycles are applied. The non–recoverable compliance (J_{nr}) is the measured property, defined as the average non–recovered strain for the 10 creep and recovery cycles divided by the applied stress for those cycles. An accumulation of the non–recoverable compliance will result in permanent deformation of the binder over time.

Fig. 1a shows J_{nr} values at different stresses for an SBS modified binder and a 40/50pen unmodified binder at their SHRP rutting test temperature (where G*/sinδ = 1kPa). The figure shows the modified binder is more stress resilient than the unmodified binder at a range of stress levels up to a certain threshold limit. This is the stress where the % non–recoverable compliance drastically increases and the binder displays reduced resistance to permanent deformation. This happens earlier for the SBS modified binder than for the unmodified bitumen. Fig. 1b shows two HiMA binders (a waxy and non–waxy modified binder) with very different behaviour. The waxy HiMA binder seemed stress sensitive whereas the non–waxy HiMA binder behaved more like an unmodified binder with fixed J_{nr} values up to a certain stress threshold.

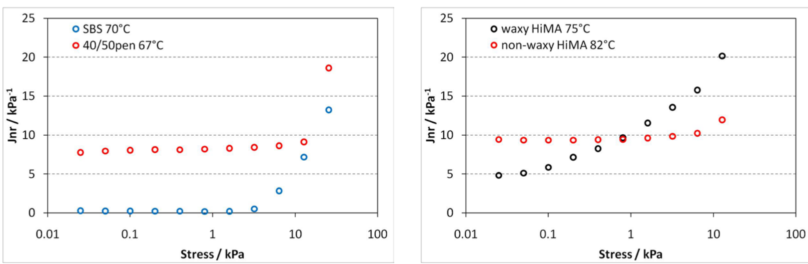

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Figure 1 Comparison of Jnr values at various stresses of (a) an unmodified binder (40/50pen) and a modified binder (SBS–modified), (b) a waxy and a non–waxy HiMA binder at their SHRP (G*/sinδ = 1kPa) rutting test temperature.

The two SBS modified binders in Fig. 2 seem similar in their resistance to permanent deformation up to a certain stress threshold, above which they display different rates of changes, i.e. the two binders exhibit dissimilar non–linear viscoelastic behaviour.

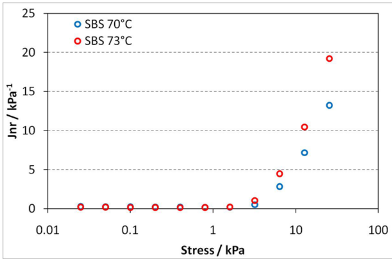
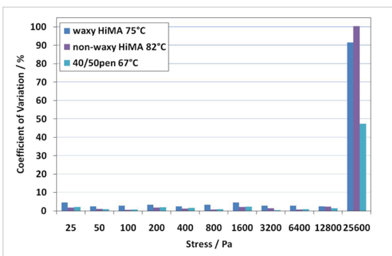


Figure 2 Non–recoverable compliance at various stresses of modified binders at their SHRP (G*/sinδ = 1kPa) rutting test temperature.

Zaoutsos [3] has shown with polymers that the strain of a constant applied stress increases after every successive loading step. Consequently, the reproducibility in the non–recovery compliance values of the binders during the stress/recovery cycles was investigated at different stress levels. The results are displayed in Fig. 3a.
The binders in Fig. 3b only exhibited high coefficient of variation values at the very highest stress level. The source in the poor reproducibility of non–recoverable compliance values after each loading cycle warrants further investigation. But it seems to suggest that non–recoverable compliance values may be affected by the number of loading cycles only at the highest stress level.
The un–recovered strain at the lower stress levels of SBS modified binders decreases with each loading cycle (see Fig. 3b) opposite to what Zaoutros [3] has shown with polymers. Successive cyclic loading simply does not allow these binders to fully recover hence the justification of averaging un–recoverable strain values obtained per loading cycle, as suggested by ASTM D7405, may not hold.



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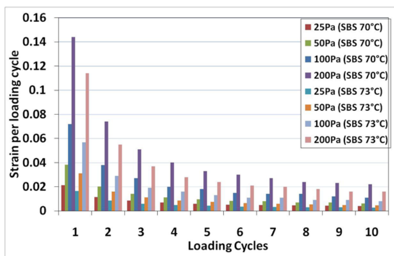

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Figure 3 (a) Coefficient of variation of the strain values for the 10 loading cycles applied at each stress level for the different binders at their SHRP (G*/sinδ = 1kPa) rutting test temperature. (b) Strain values for 10 loading cycles applied at stress levels of 25, 50, 100 and 200Pa for the SBS 70°C and SBS 73°C.

Fig. 4a and 4b reveal the behaviour of the SBS modified binders at loading cycles of different stress and rest phase duration. An increase in the duration of the applied stress shows a notable variation in the non–recoverable compliance values, especially at the non–linear viscoelastic region. Loading times longer than 3 s were not used in order to avoid sample damage and tertiary flow [2], [4]. Fig. 4b shows that a longer rest phase duration results in greater recovery of the SBS modified binders.

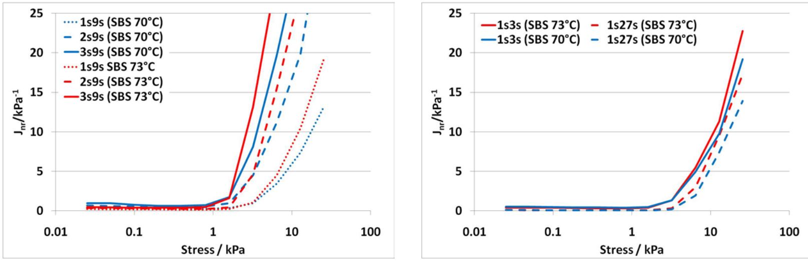

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Figure 4 Loading cycles at different stress (a) and rest (b) phase duration for the SBS modified binders at their SHRP (G*/sinδ = 1kPa) rutting test temperature.

Multiple loads due to moving traffic on a pavement surface will vary with traffic load(stress), speed (loading time or creep time) and volume (recovery time). It remains a challenge to account for all the variations in traffic in a testing protocol.

4 Predicting permanent deformation

The Repeated Simple Shear Test at Constant Height (RSST–CH) was used for the determination of permanent shear strain of asphalt specimens. The shear test was conducted at constant height with a horizontal shear force of 69kPa applied to a cylindrical asphalt specimen in accordance with the standard AASHTO 320–03 protocol but with certain deviations by Denneman [5]. The shear load is applied for 0.1 second followed by a 0.6 second rest period for a defined number of repetitions. The property measured is the permanent shear strain, defined as the horizontal deformation divided by the height of the asphalt specimen. The rate of accumulation of the permanent shear strain in the specimen during the test is used to predict permanent deformation in the field.

Three continuously and similarly graded mix specimens were prepared using the waxy HiMA, non–waxy HiMA and the SBS (73°C) modified binders. The mix specimens were then aged for four hours in an oven at their calculated compaction temperature in order to simulate the short–term ageing (STA) that a binder undergoes during hot mix asphalt (HMA) manufacture, transport to site and laying. Thereafter, the asphalt mixes were compacted to their design densities (approximately 5% air voids). The shear tests were conducted at 55°C and run up to 5 000 repetitions or 5% permanent strain, whichever was reached first. This is because in South Africa, the maximum surface temperature of road pavements ranges between 45°C and 55°C generally [6].

Fig. 5 shows average permanent strain curves, each based on three tested specimens per mix. The use of similar mix designs means that the observed differences in permanent strain measurements between mixes can only be attributed to the in–situ binder performance.

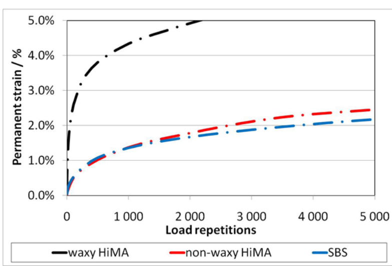

Figure 5 Shear deformation curves for different mix specimens at design density and tested at 55°C (RSST-CH).

The non–waxy HiMA mix exhibited the best resistance to rutting during the early load repetitions. But the SBS modified binder showed better permanent strain resistance beyond 1000 load repetitions. The waxy HiMA mix had the poorest resistance to rutting; accumulating the 5% permanent strain level before the 5000 load repetitions.
The empirical properties would have predicted the HiMA mixes to perform similarly in terms of rutting since the two binders belong to the same specification class. According to the SHRP rutting parameter, the non–waxy HiMA mix should exhibit superior rutting performance compared to the others, which would have been anticipated to perform similarly. Both the empirical test results and the SHRP parameter (G*/sinδ) fails to predict the asphalt performance displayed in Fig. 5.
The RSST–CH test was carried out at the same temperature for the different asphalt specimens. In order to link binder behaviour to mix performance, bitumen samples were re–tested at the same temperature as the mixes. Additionally, the asphalt specimens were subjected to multiple loads. As a result, a better binder test for predict rutting is needed to measure the elastic response of the binder after multiple loads instead of the elastic component of the binder at a fixed frequency.
The MSCR test was used to predict the resistance to rutting of asphalt mixes subjected to multiple stress loads. Fig. 6a contains the non–recoverable compliance curves of the three binders used to make the three mixes at 55°C. The virgin SBS modified binder was the most stress resilient up to a certain stress threshold. The virgin non–waxy HiMA binder showed non–recoverable compliance levels close to the SBS modified binder. Unlike the SBS modified binder though, it showed consistent stress resilience even at high stress levels. The virgin waxy HiMA binder was the poorest in resisting creep stress and it exhibited an increase in non–recoverable compliance values at a much lower stress level compared to both the SBS–modified and non–waxy HiMA binders. This suggested that the binder was stress sensitive.
In order to simulate the properties of the binder in the short term aged asphalt specimens, RTFOT–aged binders were also tested. The results are shown in Fig. 6b. .

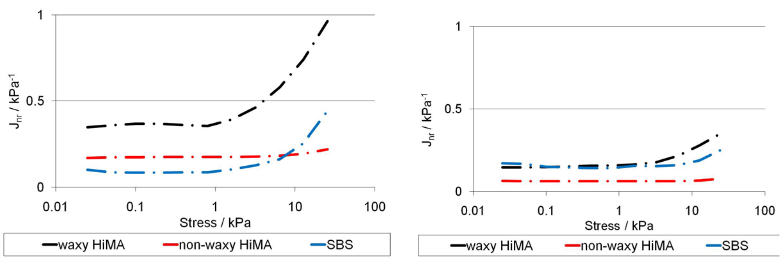

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Figure 6 (a) Non–recoverable compliance at different stress levels of bituminous binders at 55°C. (b) Non-recoverable compliance at different stress levels of bituminous binders after RTFO–ageing at 55°C.

Both the HiMA binders showed improved stress resilience after RTFOT–ageing but the SBS modified binder decreased instead. The non–waxy HiMA binder had the lowest non–recoverable compliance values and would be expected to perform the best in a similar mix. The non–recoverable values of the SBS modified binder and the waxy HiMA binder were similar after RTFOT–ageing, although the latter showed a lower stress threshold i.e. more stress sensitive. Provided the stress of the waxy HiMA binder in the mix does not surpass the stress threshold, the resultant mix was expected to show similar resistance to deformation as the mix with the SBS modified binder. Fig. 5 shows the corresponding mix performance was different to these predictions.

5 Addressing the limitations of the MSCR prediction

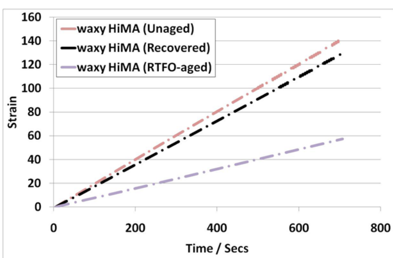
The non–recoverable compliance results of the RTFOT–aged binders failed to accurately predict the rutting performance of mixes made from the different binders. The poor prediction can be attributed to two factors. Firstly, it is due to the incorrect simulation of short–term ageing made by the RTFOT procedure for the waxy HiMA binder. The pseudoplastic nature of the binder means that a much lower mixing and compaction temperature was required to achieve the workability viscosity than that of the non–waxy HiMA binder. Consequently the waxy binder would have aged a lot less during mixing and compaction than simulated by the RTFOT short–term ageing procedure. The non–recoverable compliance behaviour of the in–situ waxy HiMA binder is expected to be between the virgin binder and the RTFOT–aged sample. Secondly, average non–recoverable compliance values of 10 loading cycles are misleading considering the creep recovery behaviour of the SBS–modified binder varies with stress/rest intervals and with loading cycles. A more accurate mix rutting prediction for the RSST–CH test would entail:

- Using the recovered waxy HiMA binder from the mix test specimens.
- Conducting the test as per the creep/recovery cycle times of the RSST–CH test.
- Increasing the number of loading cycles to properly characterise the SBS modified binder performance.
- Performing the creep test at a stress level similar to that experienced by the binder in the mix.

The above recommendations were adopted during further testing, but the stress level experienced by the in situ binder in the mix could not be determined. Therefore, a stress level of 3200Pa was used as recommended by D'Angelo [7].

Lesser ageing of the recovered waxy HiMA binder makes it more stress sensitive and less stress resilient (see Fig. 7a). Fig. 6b had shown the non–recoverable values of the SBS modified binder and the waxy HiMA binder to be similar after RTFOT–ageing (below their stress threshold) but Fig. 7b shows a different picture. The SBS modified binder has poor resistance to initial stress loads but becomes significantly more load resistant (than the RTFO–aged waxy HiMA binder) with increasing loading cycles. This change in creep/recovery behaviour of the SBS–modified binder cannot be predicted with the Multiple Stress Creep and Recovery test since it averages non–recoverable compliance values for 10 loading cycles of each stress load.

The binder strain results in Fig. 8a shows a better rutting prediction of the shear deformation behaviour of the resultant asphalt mixes. Fig. 8a and 8b shows the mix with the SBS modified binder having a reduced rate of strain accumulation with loading cycles compared to the other binders. This may explain why this mix initially looked poorer than the non–waxy HiMA but became more resistant to deformation at increased loading cycles.



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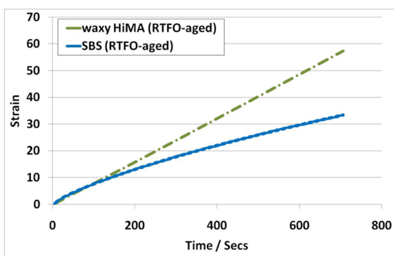

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Figure 7 (a) Strain deformation curves for the unaged, RTFO–aged and recovered waxy HiMA binders at 55°C for 1000 loading cycles at a 0.1 second creep load followed by a 0.6 second rest period at a stress of 3200Pa. (b) Strain deformation curves for the RTFO–aged waxy HiMA and SBS–modified binders at 55°C for 1000 loading cycles at a 0.1 second creep load followed by a 0.6 second rest period at a stress of 3200Pa.

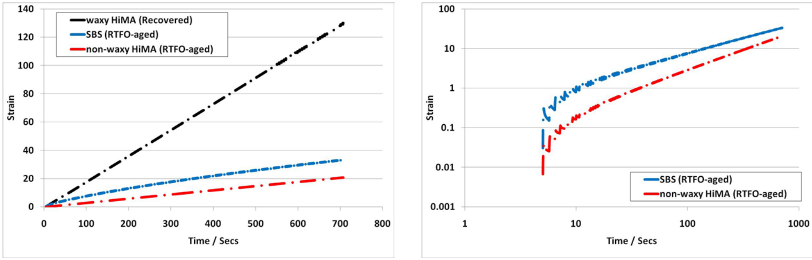

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Figure 8 (a) Strain deformation curves for the binders at 55°C for 1000 loading cycles at a 0.1 second creep load followed by a 0.6 second rest period at a stress of 3200Pa. (b) Log-log plot strain deformation curves for the SBS modified binder and the non-waxy HiMA at 55°C for 1000 loading cycles at a 0.1 second creep load followed by a 0.6 second rest period at a stress of 3200Pa.

6 Conclusion

The Multiple Stress Creep and Recovery test has been developed to predict the resistance to permanent deformation of road binders in asphalt pavements. It is intended to replace both the Superpave PG system and traditional empirical tests. This paper has highlighted the shortcomings of this method. In fixing the number of loading cycles and the stress/rest phase intervals, the method fails to simulate actual pavement loading/unloading conditions. It is also not known whether the stipulated stress levels in the method are representative of actual pavement stress loads experienced by the 'in situ' binder. Consequently, the MSCR protocol may fail to predict actual performance of modified binders whose creep/recovery behaviour varies with loading/unloading conditions. It remains a challenge to predict permanent deformation behaviour of road binders based on traffic conditions.

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