ADJUSTING THE STANDARD ROLLING THIN FILM OVEN PROCEDURE TO IMPROVE THE PREDICTION OF SHORT TERM AGEING

J. O'Connell[1], G.A.J. Mturi[2] and J. W. Maina[3]

[1]CSIR Built Environment, Transport Infrastructure Engineering, Pretoria 0001, South Africa, E-mail: joconnell@csir.co.za
[2]E-mail: gmturi@csir.co.za
[3]E-mail: jmaina@csir.co.za

Abstract

The National Cooperative Highway Research Program (NCHRP 1-37A) promotes the use of the standard rolling thin film oven test (RTFOT) to simulate the short-term ageing (STA) that a binder undergoes during hot mix asphalt (HMA) manufacture, transport, laying and compaction. The properties of the short-term aged binder can then be used in predictive equations to predict HMA performance directly after construction. Also, the residue from the RTFOT is used for the pressure ageing vessel (PAV) in order to simulate long term ageing (LTA) that the binder undergoes in the field over a period of 5 – 10 years.

The authors demonstrate that the standard RTFOT cannot accommodate the wide range of mixing and compaction temperatures of various HMA mixtures used today, ranging from warm mix asphalt (WMA) to high modulus asphalt (HiMA). There is poor correlation between RTFOT values and those obtained from binder recovered from cores after construction. The RTFOT can be modified to predict STA of binders more accurately. Such a modification to the procedure for any particular binder constitutes the first step into the establishment of a modified protocol for a binder type/class. Ultimately data from a number of contract sites would need to be collated, repeatability and accuracy established, before a final protocol is established.

1. INTRODUCTION

The National Cooperative Highway Research Program (NCHRP) has published a mechanistic-empirical framework for pavement design, "Report No. 1-37A: Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures" (NCHRP, 2004). This framework has attracted international interest and in South Africa it is being used as the main reference during the review of the South African Pavement Design Method (SAPDM), which is currently underway.

This framework (hereafter referred to as the MEPDG – Mechanistic-Empirical Pavement Design Guide) has a hierarchical approach with regards to the input requirements for the mechanistic-empirical design method, namely:

- Level 1- Comprehensive laboratory testing required (including dynamic modulus). This is applicable to high value / high volume road construction projects.
- Level 2- Limited laboratory testing required. Binder properties, obtained from laboratory testing, are used in predictive equations to estimate values of dynamic modulus. This is applicable to intermediate value / intermediate volume road construction projects.
- Level 3- Minimal laboratory testing required. Estimated material properties such as dynamic modulus are obtained from predictive equations applied to typical (historical) binder properties values available for a particular binder class. This is applicable to low value / low volume road construction projects.

This paper focuses on the level 2 and level 3 predictive equation used to obtain dynamic modulus values, and specifically on the binder viscosity required as input into the predictive equation. The MEPDG recommends the use of the Witczak model as developed and refined by Witczak and Fonseca (1996) as well as Andrei *et a*l (1999), using a database of 171 conventional asphalt mixes and 34 modified asphalt mixes. Eq. 1 represents the Witczak predictive model.

$$\log\left|E^*\right| = 1.588582 + 0.029232P_{200} - 0.001767(P_{200})^2 - 0.002841P_4 - 0.058097V_a$$
$$-0.802208\frac{V_{beff}}{(V_{beff}+V_a)} + \frac{\left[3.871977 - 0.0021P_4 + 0.003958P_{38} - 0.000017(P_{38})^2 + 0.00547P_{34}\right]}{1+e^{(-0.603313-0.313351\log f - 0.393532\log\eta)}} \quad (1)$$

where:
E^* = dynamic modulus, 10^6 Pa.
η = bitumen viscosity, 10^5 Pa.s
f = loading frequency, Hz.
Va = air void content, %.
Vbeff = effective bitumen content, % by volume.
P34 = cumulative % retained on the ¾ in (19.0mm) sieve.
P38 = cumulative % retained on the 3/8 in (9.5 mm) sieve.
P4 = cumulative % retained on the No. 4 (4.75mm) sieve.
P200 = % passing the No. 200 (75 micron) sieve.
(Please note that the equation has been converted to SI units)

The MEPDG stipulates that the binder viscosity value ***after*** rolling thin film oven test (RTFOT) has to be used for the Witczak predictive equation. The RTFOT (ASTM[1] D2872) is the standard international procedure to simulate the ageing that occurs in a binder during the manufacture, transport, placement and compaction of hot mix asphalt (HMA).

[1]ASTM: American Society for Testing and Materials

2. LIMITATIONS PRESENTED BY THE RTFOT PROCEDURE

Ageing of bituminous binder is an oxidative chemical process that occurs over time, resulting in a loss of flexibility, cohesion and adhesion of the binder, and is generally accompanied by an increase in stiffness of the binder. Ageing of the binder in HMA has a direct impact on the stiffness properties of the HMA, which, in turn, affects the pavement performance.

During the manufacture, transport, placement and compaction of HMA, ageing of the binder is affected by a number of factors including:

- Temperature – The higher the mixing and compaction temperature, the higher the rate of ageing of the bituminous binder. The mixing and compaction temperatures are dependant on the viscosity of the type of bituminous binder used.
- Time – Ageing increases with time. The longer the HMA is maintained at elevated temperatures during manufacture and placement, the greater is the extent of ageing. Construction delays, transport time between the HMA plant and the construction site as well as delays inherent in nocturnal road construction have an effect on the extent to which ageing occurs.
- Oxygen Diffusion Rate – An increased concentration of oxygen will favour an increased rate of ageing. The rate of oxygen diffusion into the binder is determined by the binder film thickness (ignoring factors such as binder viscosity, temperature, partial oxygen pressure, etc). A lower binder film thickness results in an increased concentration of oxygen and an increased rate of ageing.

As part of the revision of the SAPDM, five widely used South African HMA mixes were evaluated based on the MEPDG. Each binder was evaluated and characterised for the following conditions of sample history:

- Binder subjected to the RTFOT to simulate ageing that occurs during manufacture, transport, laying and compaction of the mix.
- Binder recovered from HMA samples manufactured in the laboratory and subjected to short-term ageing (STA). The purpose of short-term ageing is to simulate field ageing – four hours in an oven at compaction temperature prior to sample compaction. This is a modification of the procedure by Von Quintus *et al.* (1991), who prescribed an ageing temperature of 135℃.
- Binders recovered from cores that have been sampled from the pavement after construction.

Results for three of the five binders investigated are presented in this paper as shown in Table 1. The binder properties used for comparison are presented in Table 2.

Table 1: Summary of binders presented in this paper

Binder Presented in Paper	Mix Type	Binder Content (m/m%)	Design Voids (v/v%)	Compaction Temperature (℃)
60/70 penetration-grade bitumen	Medium continuous grading as designated by COLTO (COLTO, 1998). Designated as Mix 5 (Anochie-Boateng et al, 2011a).	5.0	4.9	135
40/50 penetration-grade bitumen	BTB (Asphalt Base, 26.5 mm max) as designated by COLTO (COLTO, 1998). Designated as Mix 1 (Anochie-Boateng et al, 2011b).	4.4	4.5	140
SBS-modified binder conforming to A-E2 (TG1, 2007) classification	Coarse continuous grading as designated by COLTO (COLTO, 1998). Designated as Mix 2 (Anochie-Boateng et al, 2011c).	4.3	4.8	145

Table 2: Binder Properties used for comparison in this paper

Binder Properties	Test Method	Comment
Softening Point	ASTM[1] D36-06	As per SANS 307 (SANS 307, 2005)
Penetration	ASTM D5-06	As per SANS 307 (SANS 307, 2005)
Apparent Viscosity @ 110℃	ASTM D4402-06	As per SANS 307 (SANS 307, 2005). A Brookfield RV model viscometer is used to determine the values

[1]ASTM: American Society for Testing and Materials

The results for 60/70 penetration-grade bitumen, 40/50 penetration-grade bitumen and SBS-modified binder are illustrated in Figures 1a – 1c for softening point, penetration and apparent viscosity, respectively. The results demonstrate that there was poor correlation between the values obtained from binders with different sample histories, even though those sample histories are traditionally thought to present comparable ageing of the binders.

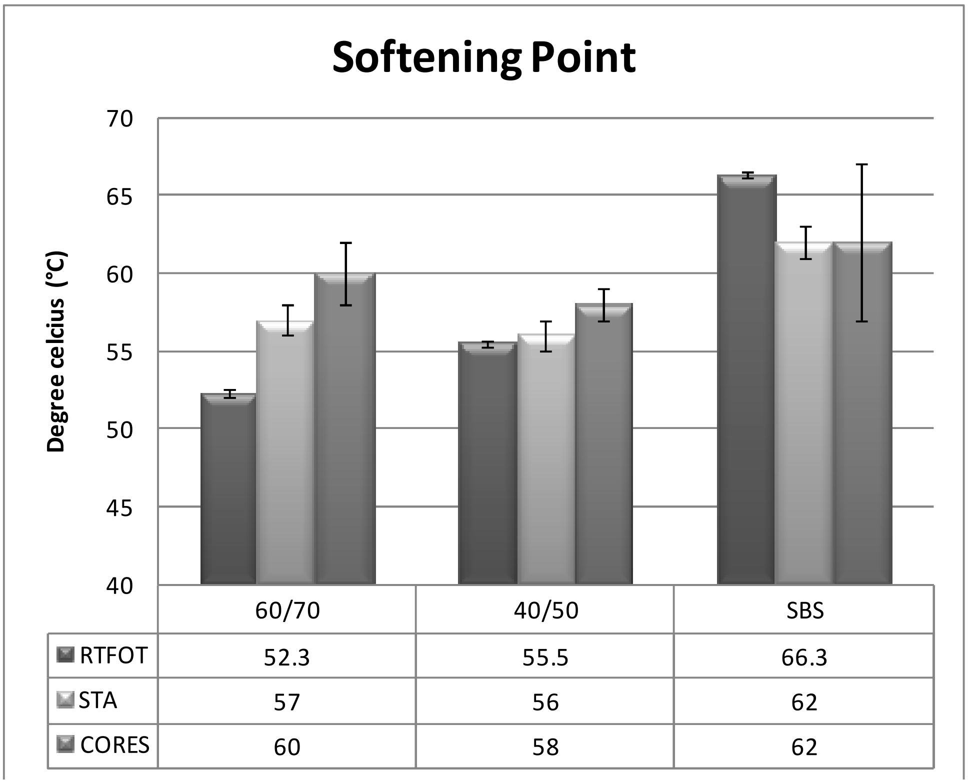

Figure 1a: Softening Point vs Sample History

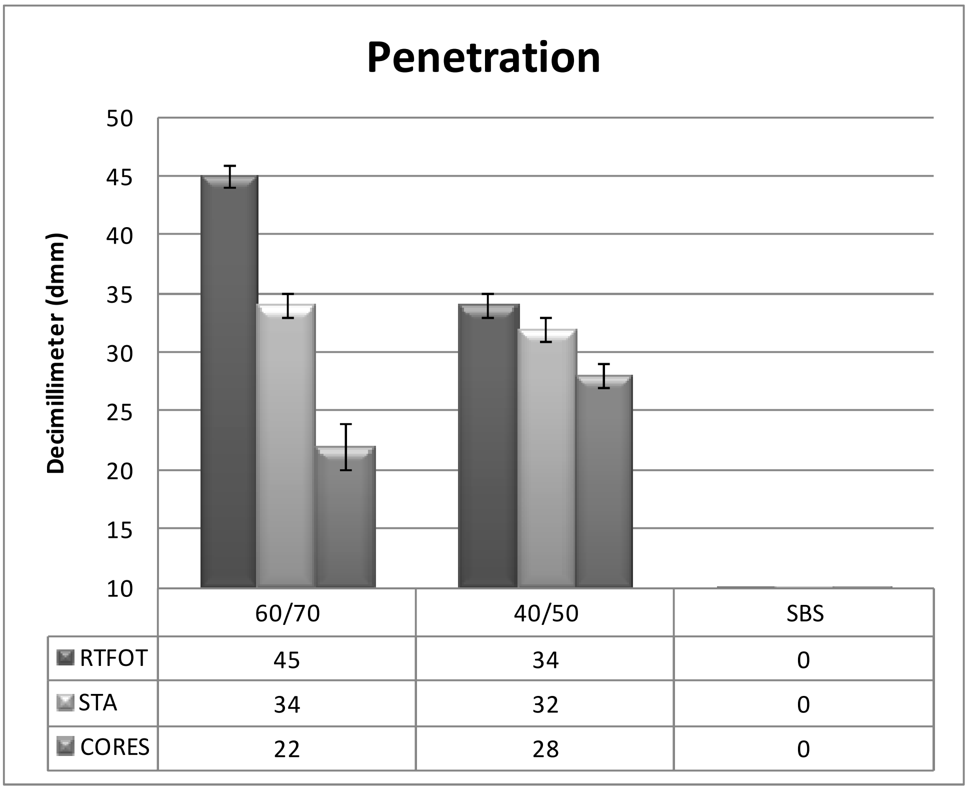

Figure 1b: Penetration vs Sample History

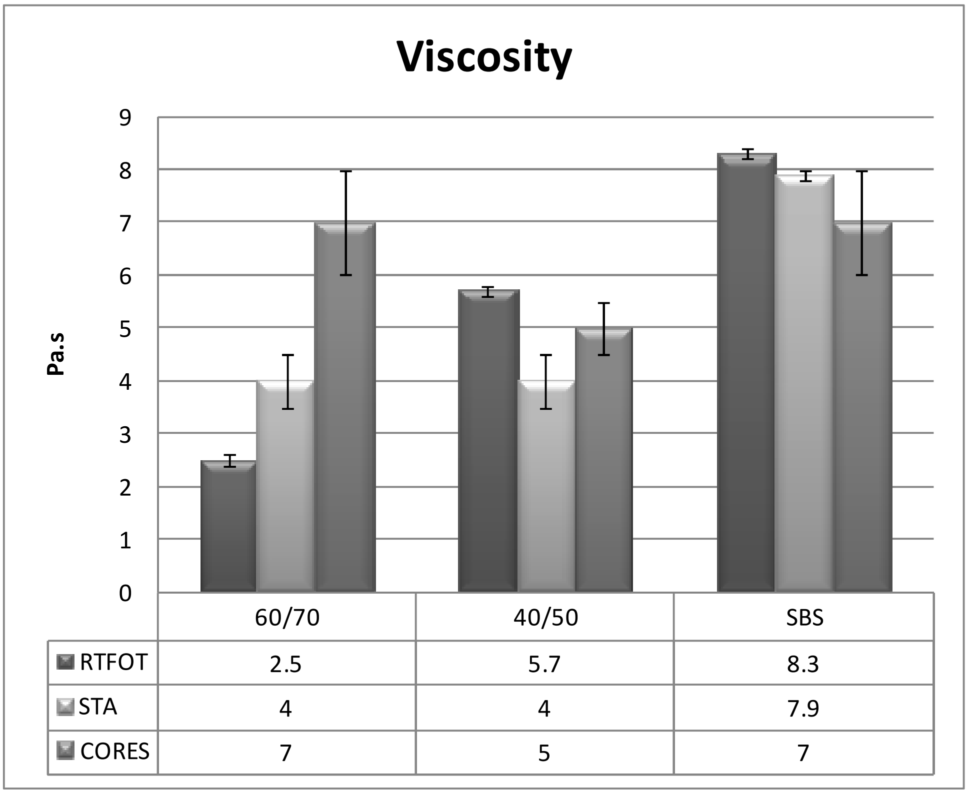

Figure 1c: Viscosity @ 110℃ vs Sample History

The RTFOT ageing procedure was developed in the 1960's for typical unmodified binders used in the production of HMA in batch-type plants. At that time 'non-standard' mixes – e.g. modified binders - were not very common. The RTFOT procedure is, therefore, geared towards simulating ageing that occurs at typical mixing and compaction temperatures of 50 years ago, assuming reasonable compaction times and assuming a standard film thickness. Such a fixed short term ageing procedure ***cannot*** make provision for the wide range of mixing and compaction temperatures used today, ranging from warm mix asphalt (WMA) to high modulus asphalt (HiMA).

These findings have implications for the use of the Witczak predictive equation, or any predictive equation that depends on binder stiffness. The Witczak predictive equation uses the viscosity-temperature relationship of a binder (the so-called A-VTS parameters) to predict the viscosity for any temperature. The relationships for the RTFOT, STA and Core binders are illustrated in Figure 2 and the A-VTS parameters are summarized in Table 3.

Table 3: A-VTS Parameters representing the viscosity-temperature relationships

Ageing History	Regression parameters and coefficients		
	A	VTS	R^2
RTFOT	10.353	-3.4589	0.9997
STA	10.545	-3.517	0.9998
Core	10.523	-3.500	0.9995

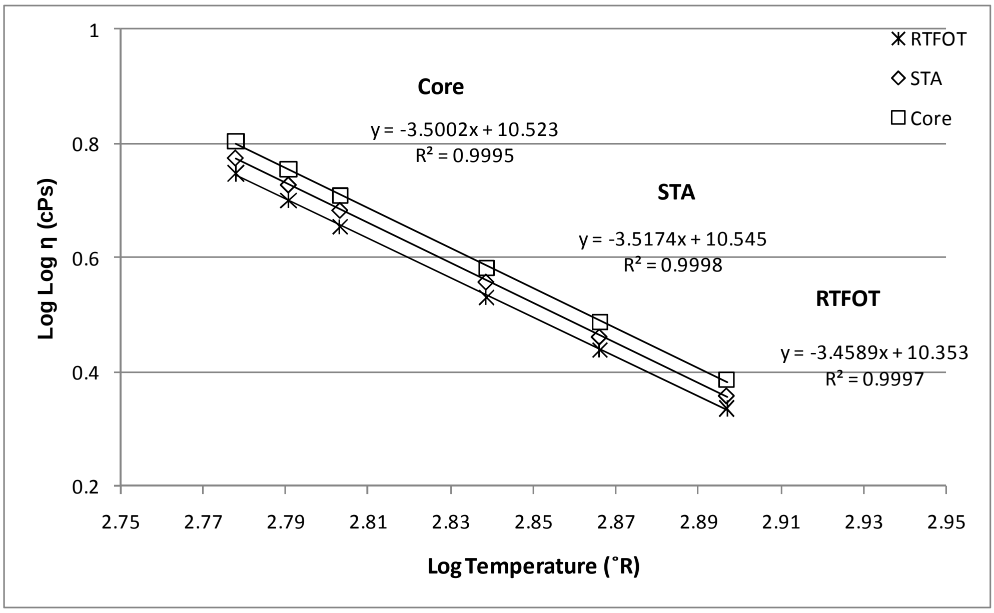

Figure 2: Viscosity-Temperature Relationships

Using the viscosities generated by the A-VTS relationships, the dynamic moduli were generated for 10 Hz at 0˚C and 50˚C by the Witczak model. Results are presented in Table 4.

Table 4: Dynamic Modulus generated at 10 Hz

Temperature	RTFOT	STA	Core
0°C	15 090	19 655	22 965
50°C	740	1 080	1 512

The results in Table 4 indicate that at low temperature (0℃), the predicted value of dynamic modulus can vary up to 50% above that predicted by the viscosity after RTFOT. At high temperature (50℃), the predicted va lue of dynamic modulus can vary up to 100% above that predicted by the viscosity after RTFOT.

The dynamic modulus can, therefore, not be predicted with great accuracy if the binder rheology cannot be estimated accurately after short term ageing. Poor correlation between values after RTFOT and values obtained from field cores has been reported widely (Lee *et al.*, 2008; Davison, *et al*.,1989), and it is noted that most of the international research effort in the past two decades has been directed towards the development of a long term ageing method such as the pressure ageing vessel (PAV). Unfortunately, the PAV method assumes that the RTFOT method is adequate in predicting short term ageing and uses the residue after RTFOT for long term ageing prediction. This has implications for long term ageing prediction.

The limitations of the RTFOT procedure have motivated this investigation into adjusting the current method to more accurately predict short term ageing. It is the long term goal of this investigation to establish adjusted RTFOT procedures for each binder class when statistically sufficient data has been generated and collated. It is hoped that such an adjusted short term ageing method may eventually be refined to include adjustment factors for binder film thickness and travelling time between HMA plant and construction site.

The RTFOT procedure was adjusted in terms of the ageing time parameter (Shalaby, 2002) and for this paper the time was increased to obtain binder properties replicating that which was obtained from specific short-term aged specimens (Von Quintus *et al.*, 1991) produced under controlled laboratory conditions. This investigation includes both empirical (softening point) and advanced rheological testing methods (dynamic shear rheometry) for monitoring ageing.

3. EXPERIMENTAL

The RTFOT procedure is used to simulate short-term ageing of HMA binders in the plant and during paving. It involves the heating of a moving film of binder in a cylindrical glass bottle that is rotated in a carriage inside an oven maintained at 163℃ for 85 minutes, whilst exposed to a jet of ho t air. The effects of heat and air are obtained through the change in physical properties of the binder before and after ageing.

The RTFOT method was in accordance with ASTM D 2872: Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test). Ageing of the binder was monitored by means of:

- Softening point values as per ASTM D36: Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus) and
- G*/Sinδ as per AASHTO Test method T315-05 using a dynamic shear rheometer (DSR). The DSR model was an Anton Paar Physica Smartpave Plus with a Peltier system and a parallel plate measuring configuration.

The binder recovery test method followed in this investigation is an internal CSIR test method (BE-TM-BINDER-1-2006). This test method is a combination of selected parts of ASTM D1856 (1995) “Test Method for Recovery of Asphalt from Solution by Abson Method” as supplied by ASTM International. Benzene (AR) is used as the solvent for binder recovery instead of trichloroethylene (AR). Reasons for the use of benzene rather than trichloroethylene are given in the CSIR Contract Report CR-97-092, “Assessment of Binder Extraction Methodologies” by Van Assen (1997). Results indicated that for South African binders and aggregates, good technical performance was obtained when using benzene as the solvent for binder recovery. In terms of centrifugation during binder recovery, two centrifuge processes were used on the extracted sample using two cups (one cup per centrifuge) to separate the mineral fines effectively from the extracted binder. In other words, each sample was centrifuged twice.

The coefficient of variation (CoV) in the determination of single- and multiple-operator precision for the binder recovery and empirical binder testing was found to be 0.33 - 2.5% and 0.52 - 2.8% respectively for unmodified binders. The CoV for the binder recovery process and testing of recovered modified binders has not yet been determined to date, but is expected to be higher than that obtained for recovered unmodified bitumen.

4. DETERMINATION OF THE TIME EXTENSION FOR THE RTFOT METHOD WHEN USING SOFTENING POINT DATA

Softening point data points for an RTFOT-aged 40/50 and 60/70 penetration-grade bitumen are presented in Figures 3 and 4, for various ageing time intervals. The four different colours in Figure 4 represent four different data sets obtained on separate occasions. For both graphs, the red line represents the softening point of the binder recovered from a laboratory STA sample. This sample was arbitrarily selected for illustrative purposes only. The results from Figures 1a – 1c do not indicate a close correlation between the binder properties obtained from the binders recovered from the STA laboratory samples and the field cores. While we do not have sufficient analyses at this time for statistical confirmation for this observation, the literature reports close correlation between these values (Lee S-J *et al.*, 2008).

From Figures 3 and 4 it can be seen that the extended time requirements to obtain similar softening points as that for the STA samples are as follows:

- 155 ± 10 minutes for the 40/50 penetration-grade bitumen
- 242 ± 10 minutes for the 60/70 penetration-grade bitumen

The significantly longer time required for the 60/70 penetration-grade bitumen is a consequence of the unexpectedly high softening point obtained for the STA laboratory sample (identical to that obtained for the 40/50 penetration-grade bitumen). Such a high value for the 60/70 penetration-grade bitumen may be representative of a particular bitumen/aggregate chemistry, film thickness, etc. In the long term, additional determinations would result in more statistically representative values to represent the time extension goals. The relationships established in Figures 3 and 4 remain valid for the specific binder from a specific refinery as long as no major changes occur in the crude oil selection or manufacturing techniques at that refinery. It would also be a future requirement to establish whether the same binder class from different refineries would essentially have the same relationships.

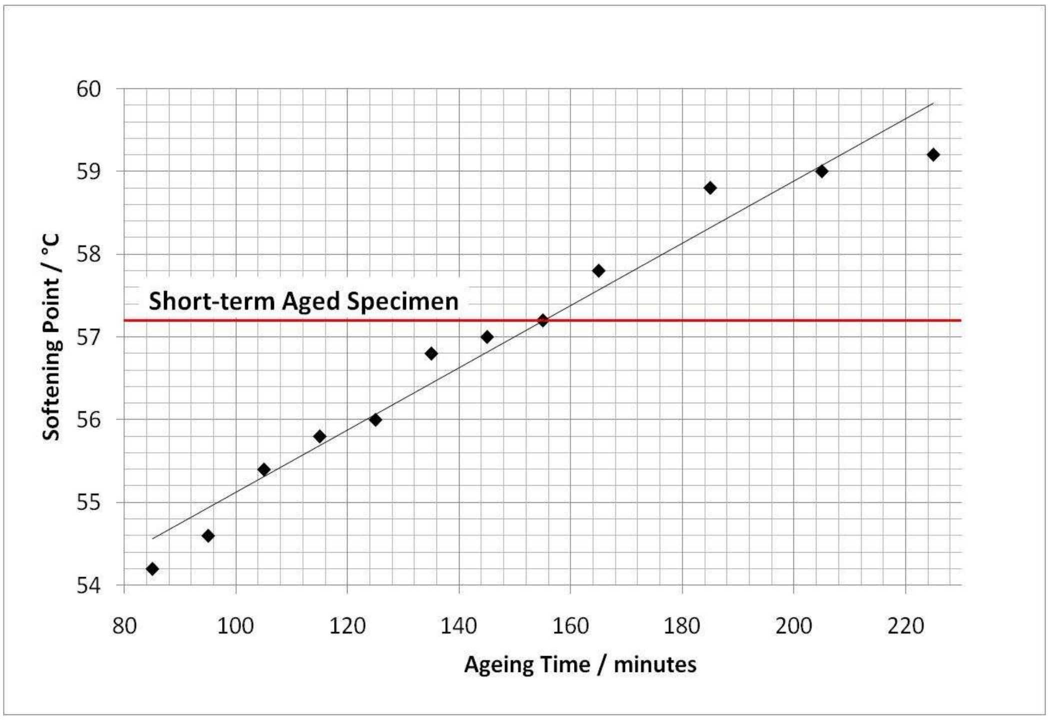

Figure 3: Softening point data for aged 40/50pen grade binder.

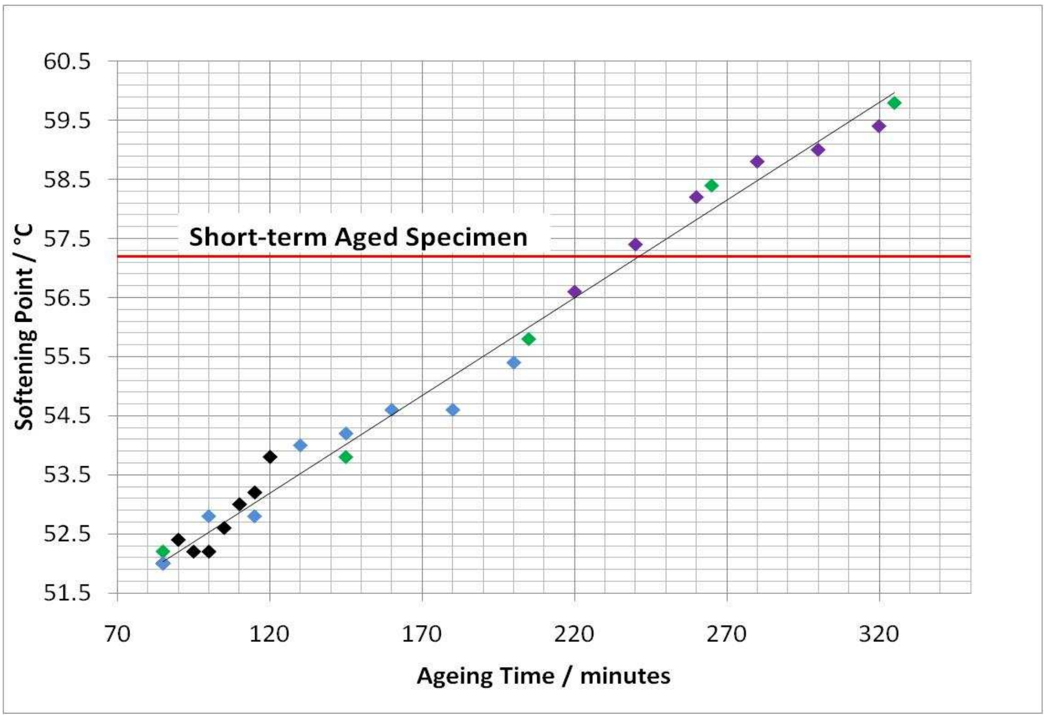

Figure 4: Softening point data for aged 60/70 – separate colours represent four different data sets obtained on separate occasions

For SBS-modified binder, softening point cannot be used as a property to monitor ageing. Figure 5 shows softening point data points with extension time for an SBS-modified binder. The four different colours in Figure 5 represent four different data sets obtained on separate occasions. A linear relationship was not obtained as in Figures 3 and 4. A reduction in softening point is initially observed due to the decrease in strength of the three-dimensional SBS network. Oxidation of the SBS polymer probably interrupts association of the styrene domains. This decrease in softening point occurs up to a point where the softening point of the modified binder increases again. At this stage, the softening point reduction due to the disassociation of the polymer network is overcome by a softening point increase due to the physical hardening of the base binder.

The inability to monitor the ageing of SBS-modified binder using an empirical property such as softening point has been reported previously in the literature (Saleh, 2008).

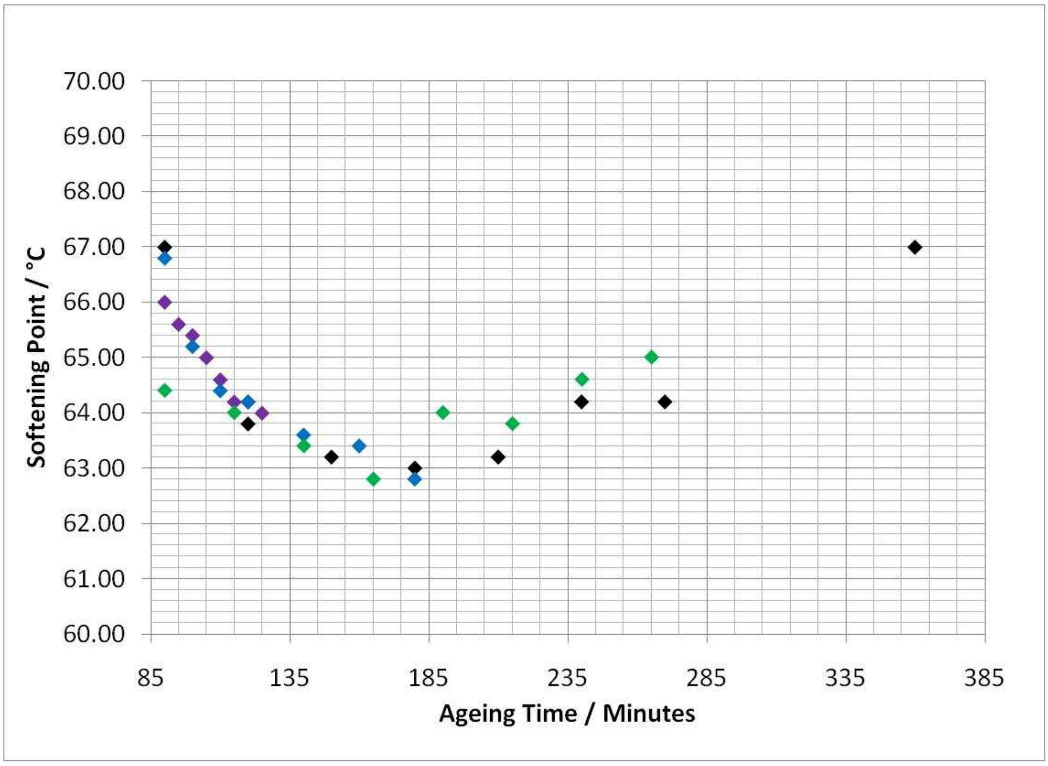

Figure 5: Softening point data for aged SBS-modified binder – separate colours represent four different data sets obtained on separate occasions

5. DETERMINATION OF THE TIME EXTENSION FOR THE RTFOT METHOD WHEN USING RHEOLOGICAL CHARACTERISATION

The effect of ageing unmodified binders occurs in the form of oxidative stiffening at all temperatures, whereas for modified binders, stiffness can vary with time, depending on the stiffness parameter chosen for evaluation (Mturi *et al.*, 2010). Figures 3 - 5 show that an empirical property such as the softening point may be adequate for the monitoring of unmodified bitumen, but it cannot be used to monitor the ageing of modified binders – a different property is required.

Although it has been shown that master curves can be used to model aging effects (Shalaby, 2002), the process remains lengthy and laborious to develop for all binder types displaying different ageing behaviour. The use of the rutting resistance factor (G*/sin δ) at high failure temperature is another possible parameter to use for monitoring ageing, but it has also been shown to produce a non-linear relationship for modified binders (Lee *et al.*, 2008).

Figures 6, 7 and 8 present the Performance Grade failure temperatures (where |G*|/sin δ = 2.20kPa) of samples after RTFOT treatment for varying time periods (referred to as RTFOT extension time) in the oven for the 40/50, 60/70 penetration-grade bitumen and the SBS-modified binder, respectively. A linear relationship was obtained for all the binders evaluated.

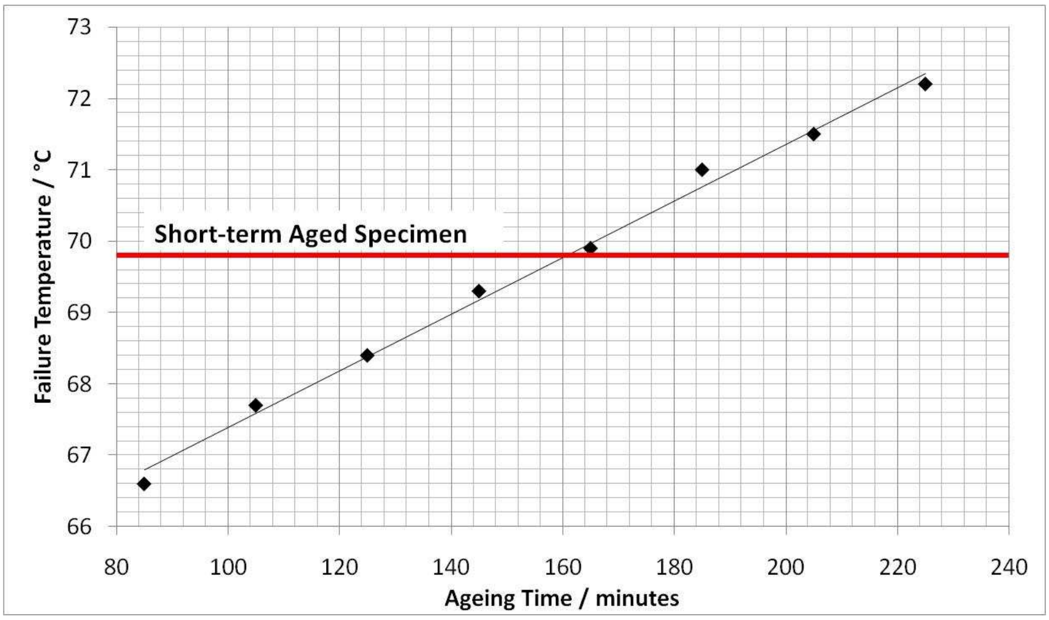

Figure 6: Failure temperature where |G*|/sin δ = 2.20kPa against ageing time for the 40/50 binder.

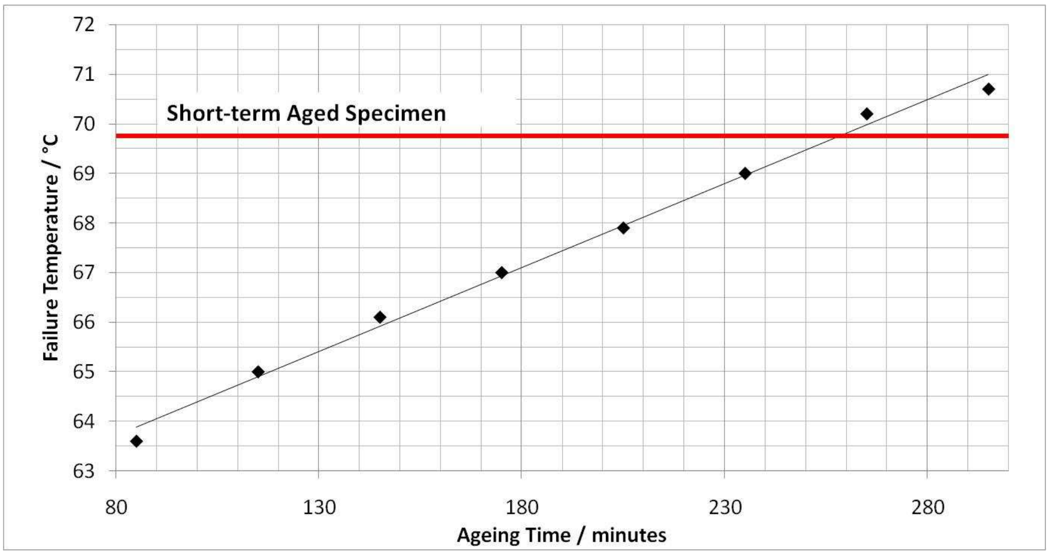

Figure 7: Failure temperature where |G*|/sin δ = 2.20kPa against ageing time for the 60/70 binder.

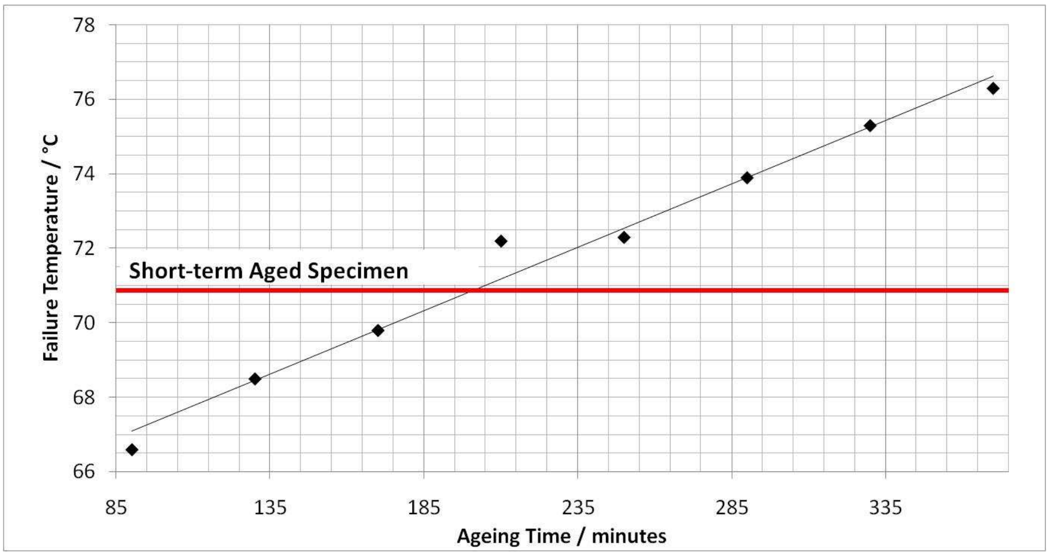

Figure 8: Failure temperature where |G*|/sin δ = 2.20kPa against ageing time for the SBS-modified binder.

From the figures it can be seen that the extension time requirements to obtain similar Performance Grade failure temperatures as that for the STA samples are as follows:

- 160 ± 5 minutes for the 40/50 penetration-grade bitumen (155 for softening point)
- 258 ± 5 minutes for the 60/70 penetration-grade bitumen (242 for softening point)
- 200 ± 5 minutes for SBS-modified binder

Monitoring of the Performance Grade failure temperatures gives a more linear relationship compared to using the softening point property. The extension times obtained for the Performance Grade failure temperatures were similar to those obtained for the softening points, which is expected for unmodified binders.

The relationship established in Figure 7 for SBS-modified binder would only be valid for a specific polymer-binder combination depending on the binder origin, polymer type and concentration. The variability of this relationship for the SBS-modified binder class would need to be established.

6. CONCLUSION

The standard RTFOT method cannot accommodate the wide range of mixing and compaction temperatures of various HMA mixtures used today, ranging from warm mix asphalt (WMA) to high modulus asphalt (HiMA).

If any predictive equation, which depends on binder stiffness, is to be used in a future South African Pavement Design Method, it is a requirement that an adjusted or revised short-term ageing method (as opposed to the standard RTFOT) be established. This paper has demonstrated that this can be achieved by extending the RTFOT time using the current method. However, additional data generation and collation is required to ensure:

- Adjusted RTFOT procedures for each binder class in South Africa. For example, adjusted RTFOT protocols can be developed for warm mixes, where the standard RTFOT could result in an overestimation of STA, and consequently LTA

- Statistically sufficient data is available in order that the extended RTFOT times are statistically representative for each binder class
- Refinement of the ageing model to include adjustment factors for binder film thickness and travelling time between HMA plant and construction site.

Although softening point can be used for determining the RTFOT adjustment for unmodified binders, it is not valid for modified binders, where more sophisticated techniques, such as the use of a dynamic shear rheometer, are required.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts by Mrs Keneilwe Mogonedi and Mrs Santa Conrad in generating the laboratory data.

REFERENCES

Andrei, D., Witczak, M.W., and Mirza, M. W., (1999). Development of a Revised Predictive Model for the Dynamic (Complex) Modulus of Asphalt Mixtures. Interim Team Technical Report. Department of Civil Engineering, University of Maryland, College Park, MD.

Anochie-Boateng, J., Denneman, E., O'Connell and J., Ventura, D., (2011a). Revision of the South African Pavement Design Method. Level 1 Analysis of Medium Continuous Asphalt Mix with 60/70 Penetration Grade Binder. CSIR Contract Report SAPDM-B1B-2010-04. Prepared for South African National Roads Agency Limited, Pretoria, South Africa.

Anochie-Boateng, J., Denneman, E., O'Connell J., and Ventura, D., (2011b). Revision of the South African Pavement Design Method. Level 1 Analysis of Bituminous Treated Base (BTB) Asphalt Mix. CSIR Contract Report SAPDM-B1B-2010-01. Prepared for South African National Roads Agency Limited, Pretoria, South Africa.

Anochie-Boateng, J., Denneman, E., O'Connell J., and Ventura, D., (2011c). Revision of the South African Pavement Design Method. Level 1 Analysis of Coarse Continuous Asphalt Mix with SBS modified Binder. CSIR Contract Report SAPDM-B1B-2010-02. Prepared for South African National Roads Agency Limited, Pretoria, South Africa.

Davison, R.R *et al*, (1989). Development of Gel Permeation Chromatography, Infrared and Other Tests to Characterize Asphalt Cement and Correlate with Field Performance, Volume 1, Research Report 458-1F, Texas Transport Institute, Texas.

Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Report No. 1-37A, Part 2: Design Inputs, Chapter 2: Material Characterization, National Cooperative Highway Research Program (NCHRP), March 2004.

Lee S-J., Amirkhanian S.N., Shatanawi K. and Kim K.W., (2008). Short-term aging characterization of asphalt binders using gel permeation chromatography and selected Superpave binder tests, Construction and Building Materials 22 2220-2227.

Mturi, G., O'Connell, J. and Zoorob, S.E., (2010). Investigating the rheological characteristics of South African road bitumens. 29th Southern African Transport Conference, Pretoria, South Africa

South African National Standard (SANS) 307, (2005). Penetration Grade Bitumens. Standards South Africa, Pretoria, South Africa.

Saleh, A.M., (2008). Comparison Between The Rolling Thin Film Oven Test And The Pressure Aging Vessel Aging Simulation Tests, Master of Engineering Thesis (Civil - Transportation and Highway), Faculty of Civil Engineering, Universiti Teknologi, Malaysia

Shalaby, A., (2002). Modelling short-term aging of asphalt binders using the rolling thin film oven test, Can. J. Civ. Eng., 29, 135-144.

Standard Specifications for Road and Bridge Works for State Road Authorities, Committee of Land Transport Officials (COLTO), subsequently renamed: Committee of Transport Officials (COTO), South Africa, 1998.

Technical Guideline: TG 1, (2007). The Use of Modified Bituminous Binders in Road Construction, Second Edition, Asphalt Academy, Pretoria, South Africa.

Van Assen, E., (1997). Assessment of Binder Extraction Methodologies, CSIR Contract Report CR-97/092, CSIR, South Africa.

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

Witczak, M.W., Fonseca, O.A. (1996). Revised Predictive Model for Dynamic (Complex) Modulus of Asphalt Mixtures, Transportation Research Record 1540, Transportation Research Board, Washington, D.C

KEY WORDS

Mechanistic-empirical, Resilient response, Rolling Thin Film Oven Test, RTFOT, short term ageing, Witczak