Evaluating the Efficacy of Laboratory Ageing of Asphalt Mix Binders as a Prediction for Field Ageing

J. O'Connell
CSIR and University of Pretoria, Pretoria, South Africa

J. Maina
University of Pretoria, Pretoria, South Africa

S. J. Bredenhann
Naidu Consulting, Durban, South Africa

H. Marais
AECI Much Asphalt (Pty) Ltd, Benoni, South Africa

J. Komba
University of Pretoria, Pretoria, South Africa

A Performance-grade Binder Specification (SATS 3208) for South Africa was finalized after CAPSA 2015 and announced at CAPSA 2019. A feature of the performance-graded binder specification is regulation of binder performance after long-term ageing, which is simulated in the laboratory using the pressure ageing vessel. This paper reports how this simulated long-term ageing relates to the ageing of binders in continuous asphalt surfacing mixes in the field.

Samples of asphalt mix surfacing were obtained from 10 sites in Gauteng, South Africa, which were constructed 5 to 30 years ago and selected for the availability of the original binders. An ageing profile was developed for the original binders by characterizing their rheology in the original state, after rolling thin film oven ageing and pressure ageing vessel ageing after 20 hours, 40 hours and 80 hours. The ageing profiles were compared to the corresponding recovered binders. Rheological parameters used for comparison were Softening Point and Flexural Creep Stiffness / m-Value from the Bending Beam Rheometer.

Keywords—pressure ageing vessel, PAV. Field ageing

1. INTRODUCTION

Bitumen or asphalt binder is a crucial component of asphalt pavements that provides durability and resistance to deformation. However, bitumen is susceptible to aging due to factors such as temperature, air, moisture and UV radiation. Ageing leads to reduced flexibility and ductility, thereby increasing the risk of fatigue or environmental cracking, as well as ravelling.

The ageing of asphalt binder consists of short-term ageing and long-term Ageing. Short-term ageing represents the ageing that the asphalt binder in the mix undergoes during the manufacture, storage, transport, and placement on site. Long-term Ageing refers to ageing that the asphalt binder undergoes during the lifetime of the pavement.

In the South African performance-graded binder specification [1], short-term ageing of asphalt binder is simulated in the laboratory using the rolling thin film oven (RTFO) [2]. Long-term ageing is simulated by subjecting residue from the RTFO to the pressure ageing vessel (PAV) [3]. There is debate amongst researchers as to the relationship between the PAV procedure and field ageing [4 - 5]. There are many factors that can bear an influence, including [6]:

- The asphalt mix design (grading, filler, film thickness, design voids, etc);
- Manufacture and construction (time, temperature and construction voids);
- The climate; and
- Geographical location (altitude and UV intensity).

In order to monitor the rate and extent of ageing in an asphalt binder, one or more of the binder properties should be selected for analysis over the ageing period. These properties are named Ageing Index Parameters (AIP's) [7], and the less an AIP changes during ageing, the greater the expected binder durability, under the same conditions of design, construction, and environment.

Monitoring field ageing of binder requires that the asphalt binder in the mix is recovered using a reliable and validated laboratory procedure. This can be the single largest impediment to quality of research results. The recovery process theoretically reduces the repeatability and reproducibility of the results, which should be quantified and considered when evaluating ageing trends and comparisons.

This paper examines the relationship between long-term ageing predicted in the laboratory resulting using the PAV procedure and field ageing for continuously-graded asphalt mixes used as surfacing, located at ten different locations in Gauteng Province, South Africa. The age of the mixes varied between 5 and 30 years, and they were selected based on the availability of the original retained binders used in their construction.

2. METHODOLOGY

A. Investigative Approach

The sites selected for the study are listed in Table 1. The asphalt surfacing from these sites consists of continuously graded mixes, using the following asphalt binder types:

- 50/70 penetration-grade bitumen (50/70);
- Bitumen modified with styrene-butadiene-styrene (SBS); and
- Bitumen modified with Fischer-Tropsch wax (FT wax), well known warm mix additive.

The designation "GFIP" refers to the Gauteng Freeway Improvement Project, which was undertaken in preparation of the FIFA World Cup held in South Africa in 2010.

Table 1:Field Sites Selected for Ageing Evaluation

Site	*Location*	*Binder*	*Age (years)*
1	R104 Experimental section	SBS	5
2	GFIP Package H, : Golden Highway	50/70	8
3	GFIP Package F, N3	SBS	9
4	GFIP Package H, R 21	SBS	9
5	Modderfontein	FT wax	12
6	R50 Bapsfontein	50/70	15
7	Zambezi Road	FT wax	18
8	Eeufees Road	50/70	19
9	N4 Magalies Freeway	50/70	27
10	CSIR Duiker Road	50/70	30

Although asphalt sources in South Africa can currently vary considerably as a result of variations in crude source or importation, this was different 15 to 30 years ago. Asphalt binder composition was relatively consistent at that time, having predictable properties within a narrow band, which depended only on the refinery of origin. Crude sources remained relatively constant and asphalt binder was rarely imported - a legacy of the international crude oil sanctions applied against the Apartheid policies of South Africa. Where a project-specific binder from that period was not available for analysis, a similar binder from that period was used to represent the original project asphalt binder. This applies to Site 7, using the FT wax binder from Site 5, as well as Sites 6, 9 and 10 using the 50/70 penetration-grade binder from Site 8.

Night-time construction was implemented at Sites 2, 3 and 4, due to the high volumes of day-time traffic on these roads. Some asphalt mixes constructed during the day were subjected to increased ageing as a result of mandated construction delays.

Ageing profiles were created for each retained asphalt binder using PAV-simulated ageing for 20 hours, using the standard test procedure [3], as well as extended PAV ageing for 40 hours and 80 hours. The AIP's selected for this investigation were:

- Softening Point [8];
- The Flexural Creep Stiffness (S) at -12°C obtained from the bending beam rheometer (BBR) [9]; and
- The m-Value at -12°C obtained from the BBR [9].

The Flexural Creep Stiffness (S) and m-Value are more relevant than the softening point considering that the former parameters are more closely related to age-related pavement distress than softening point, and that they are specified in the South African performance-related specification [1]. The temperature of -12°C was selected for BBR testing as this is related to the performance grade of PG64X-16 recommended for the Gauteng Province, where X=S, H, V or E as defined by the traffic loading [1].

The binder from the field was recovered using an Abson-based method [10].

B. *Test Methods*

The test methods used in this investigation are listed in Table 2 .

Table 2:Test Methods used in the Investigation.

Property / Procedure	Test Method
Softening Point	ASTM D36 [8]
Flexural Creep Stiffness and m-Value	AASHTO T313 [9]
Rolling Thin Film Oven Test	ASTM D4402 [2]
PAV ageing	ASTM D6521 [3]
Binder recovery from the field	ASTM D1856 [10]

3. RESULTS

A. *Repeatability of Results*

The repeatability of softening points and binder recoveries have previously been determined [“unpublished” 11] and the results are summarised in Table 3.

Table 3:Historical Evaluation of Repeatability for Softening Point [“unpublished” 11]

Property	Coefficient of Variation
Softening Point of 50/70	0.4 %
Softening Point of SBS	3.4 %
Softening Point of 50/70 after binder recovery	0.5 %

The repeatability of the flexural creep stiffness was determined specifically for this investigation, using two different binders, with seven repeats on the Binder 1 and six repeats on Binder 2. Testing was carried out at -24°C, because testing results from laboratory presented a number of anomalies when testing at this temperature. The results are presented in a box and whisker chart in Figure 1 and the coefficient of variation is reported in Table 4. The repeatability of the Flexural Creep Stiffness (S) was determination after PAV. The data were evaluated for outliers by using the interquartile range method, whereby outlier values are defined as values that exceed one and half times the interquartile range beyond the interquartile values.

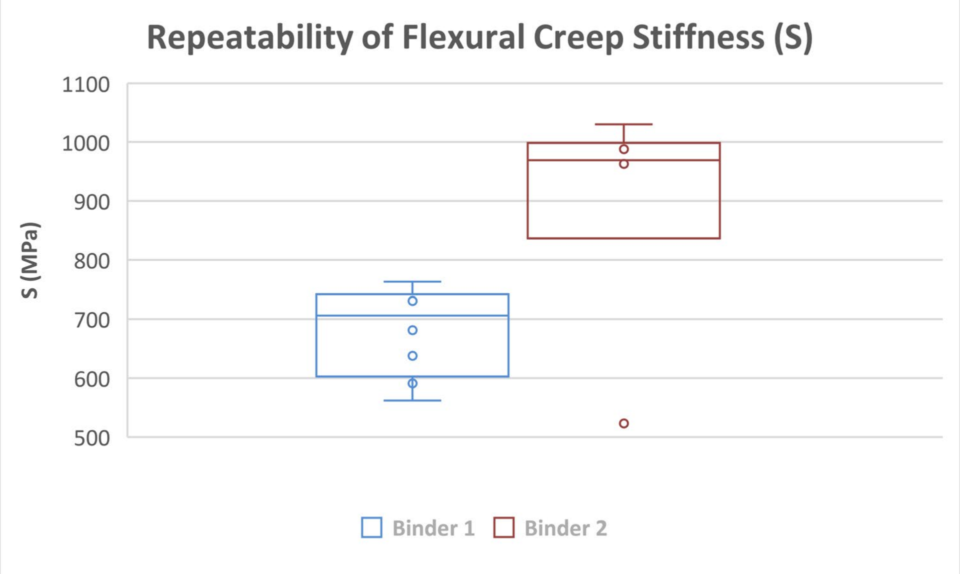

Figure 1: Repeatability of the Flexural Creep Stiffness

Table 4: Repeatability of Flexural Creep Stiffness (S)

Detail	Flexural Stiffness as determined using the BBR (MPa)	
	Binder 1	Binder 2
1st Repeat	562	988
2nd Repeat	763	1030
3rd Repeat	742	975
4th Repeat	731	963
5th Repeat	591	941
6th Repeat	638	523
7th Repeat	742	
Median	731	969
Interquartile range	127.5	38.25
Lower limit for outliers	423	889
Upper limit for outliers	933	1 042
Outliers	none	Value of 523
Average excluding outliers	681	979
Coefficient of Variation (%)	12.1%	3.4%

B. Softening Point as an Ageing Index Parameter

The softening point results for the original binders and recovered binders are given in Table 5 and graphically depicted in Figure 2.

Table 5:Softening Point as an AIP for the Original and Recovered Binders.

Site	*Binder*	*Age (years)*	*Softening Point (°C)*			
			PAV 20	*PAV 40*	*Pav 80*	*Recovered*
1	SBS	5	64.4	66.8	72.0	64.8
2	50/70	8	57.6	61.0	66.0	73.8
3	SBS	9	64.8	66.6	72.4	74.0
4	SBS	9	67	68.2	75.2	64.8
5	FT wax	12	79.4	80.8	82.4	75.6
6	50/70	15	60.4	64	70.4	106.4
7	FT wax	18	79.4	80.8	82.4	84.6
8	50/70	19	60.4	64	70.4	72.4
9	50/70	27	60.4	64	70.4	83.8
10	50/70	30	60.4	64	70.4	78.4

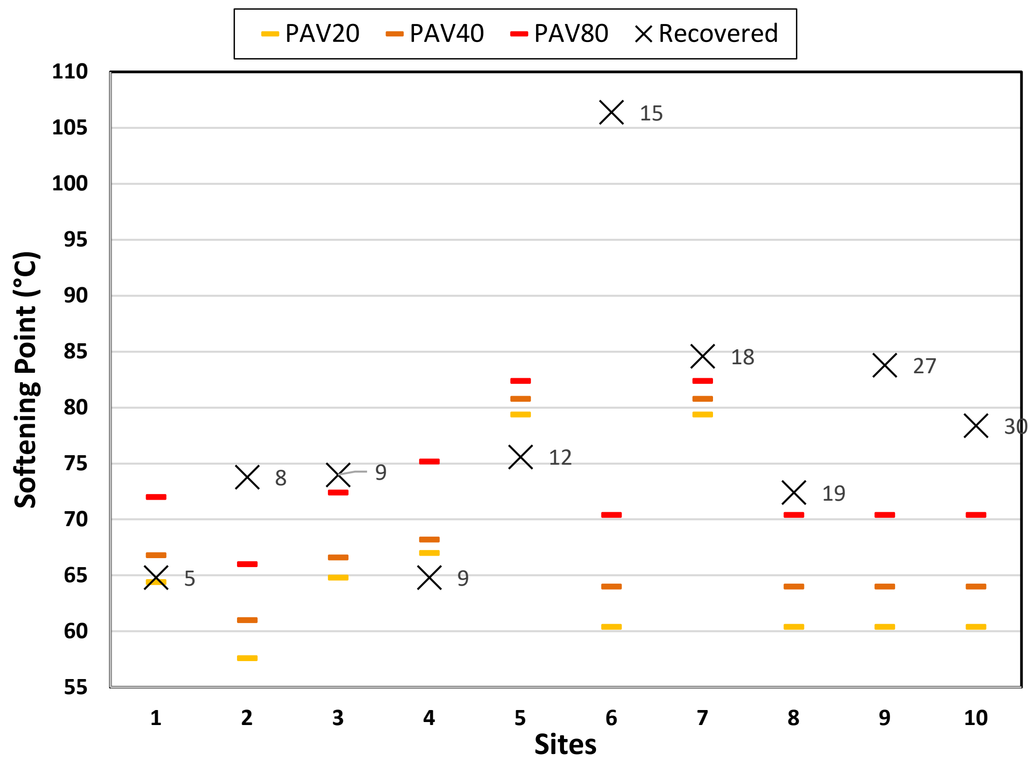

Figure 2: Evaluating Softening Point as an AIP

C. Flexural Creep Stiffness (S) from the BBR as an Ageing Index Parameter

The flexural creep stiffness for the original binders and recovered binders are given in Table 6 and graphically depicted in Figure 3.

Table 6:BBR Flexural Creep Stiffness (S) @-12°C as AIP for the Original and Recovered Binders.

Site	Binder	Age (years)	BBR Stiffness,S (MPa)			
			PAV 20	PAV 40	Pav 80	Recovered
1	SBS	5	186	188	230	253
2	50/70	8	217	257	283	265
3	SBS	9	147	151	161	279
4	SBS	9	110	122	130	239
5	FT wax	12	229	261	300	296
6	50/70	15	171	199	251	503
7	FT wax	18	229	261	300	309
8	50/70	19	171	199	251	163*
9	50/70	27	171	199	251	360
10	50/70	30	171	199	251	340

* The result is lower than expected and is similar to a value only slightly higher than a 50/70 penetration-grade bitumen after RTFO.

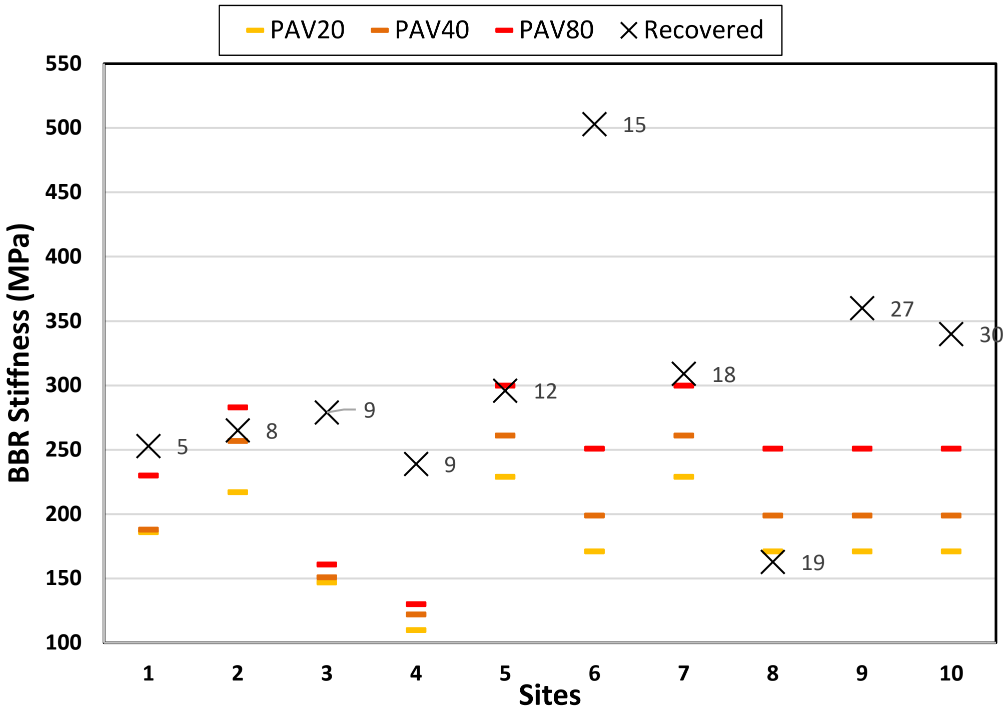

Figure 3: Evaluating Flexural Creep Stiffness as an AIP

The lower-than-expected flexural stiffness obtained for Eeufees Road (Site 8), required further investigation. A photograph of the specimens obtained from Eeufees Road are depicted in Figure 4 and additional binder recovery results are given Table 7.

Figure 4: Cores taken from Eeufees Road (Site 8)

Table 7:Core Properties recovered from Site 8

Property	***Result***
Binder Content	7.2 m/m%
Fibre Content	0.8 – 1.5 m/m%
Grading (% Passing Sieve Size)	
14.0 mm	100
10.0 mm	97
7.1 mm	46
5.0 mm	32
2.0 mm	22
1.0 mm	18
0.600 mm	16
0.300 mm	14
0.150 mm	11
0.075 mm	6.8

The cores in Figure 4 do not appear to be representative of a medium continuous mix, but most likely represent a stone mastic asphalt (SMA) mix (or possibly, an ultra-thin friction course (UTFC)). This is confirmed by the results presented in Table 7, where the high binder content, aggregate grading and presence of fibres are not indicative of a continuously graded mix. The low flexural stiffness is indicative of a newly laid surfacing, but the softening point is high which is a characteristic of a polymer-modified binder. This is confirmed in Table 8, where the m-value is higher than for an unaged 50/70 penetration-grade bitumen.

The composition of the 10 sites were obtained from a consolidated industry database, and the database information was confirmed on site prior to sampling. It is likely that Site 8 was subjected to maintenance activity between the day of inspection of the and the day of sampling.

The results for Site 8 are ignored for future analysis of results.

D. Using BBR m-value as an Ageing Index Parameter

The m-value from the BBR for the original binders and recovered binders are given in Table 6 and graphically depicted in Figure 5.

Table 8: BBR m-Value @-12°C as AIP for the Original and Recovered Binders.

Site	Binder	Age (years)	BBR m-Value (MPa/s)			
			PAV 20	PAV 40	Pav 80	Recovered
1	SBS	5	0.354	0.326	0.301	0.298
2	50/70	8	0.348	0.314	0.284	0.258
3	SBS	9	0.357	0.323	0.275	0.264
4	SBS	9	0.365	0.303	0.288	0.388
5	FT wax	12	0.283	0.253	0.231	0.244
6	50/70	15	0.339	0.311	0.278	0.142
7	FT wax	18	0.283	0.253	0.231	0.201
8	50/70	19	0.339	0.311	0.278	0.262
9	50/70	27	0.339	0.311	0.278	0.209
5	50/70	30	0.339	0.311	0.278	0.245

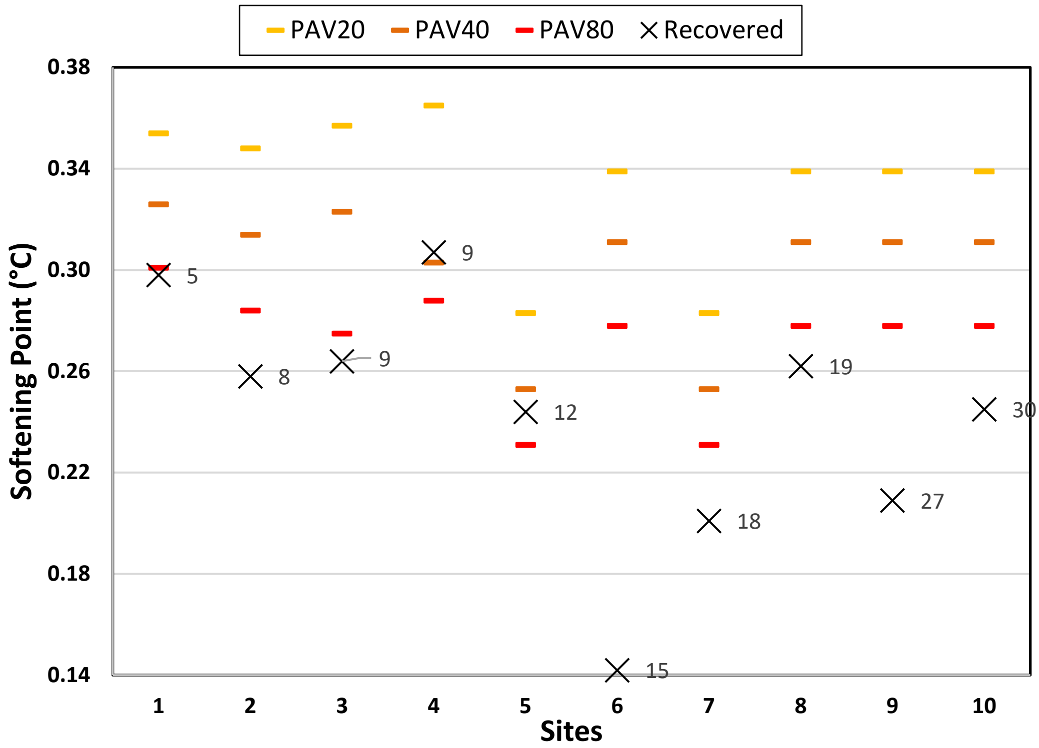

Figure 5: Evaluating m-Value as an AIP

4. Discussion and Conclusion

A. Repeatability of Results

Polymer-modification of bitumen significantly increases the coefficient of variation obtained for the softening point test result test results from 0.4% to 3.5%. The binder recovery process adds an additional element of uncertainty to the testing process and the coefficient of variation increases accordingly from 0.4% to 0.5%.

The coefficient of variation for flexural stiffness is shown to vary from 3.4% to 12.1%, which is higher than that obtained for softening point. The coefficient of variation is expected to increase significantly for recovered samples. No evidence could be found in the literature for the determination of coefficient of variation for flexural stiffness after binder recovery.

The effect of the variability in the results of softening point and flexural stiffness must be considered when interpreting individual values obtained from the sites under investigation.

B. Evaluating Softening Point as an Ageing Index Parameter

The recovered binders were analysed by plotting the value by which the softening point of the recovered binders exceeded the PAV-predicted softening point as a function of asphalt mix age. The standard PAV ageing (20 hours) as well as extended PAV ageing for 80 hours was used in the analysis. The ageing profiles of SBS-modified binders and non-SBS-modified binders are dissimilar [12], and accordingly, the recovered binder analyses are depicted separately. The non-SBS binders are shown graphically in Figure 6.

The effect of a long waiting period during construction is evident for Mix 2 (8 years old), and the softening point exceeds that predicted by PAV significantly. Furthermore, the high softening point obtained for Site 6 (15 years old), is not aligned with the other observations.

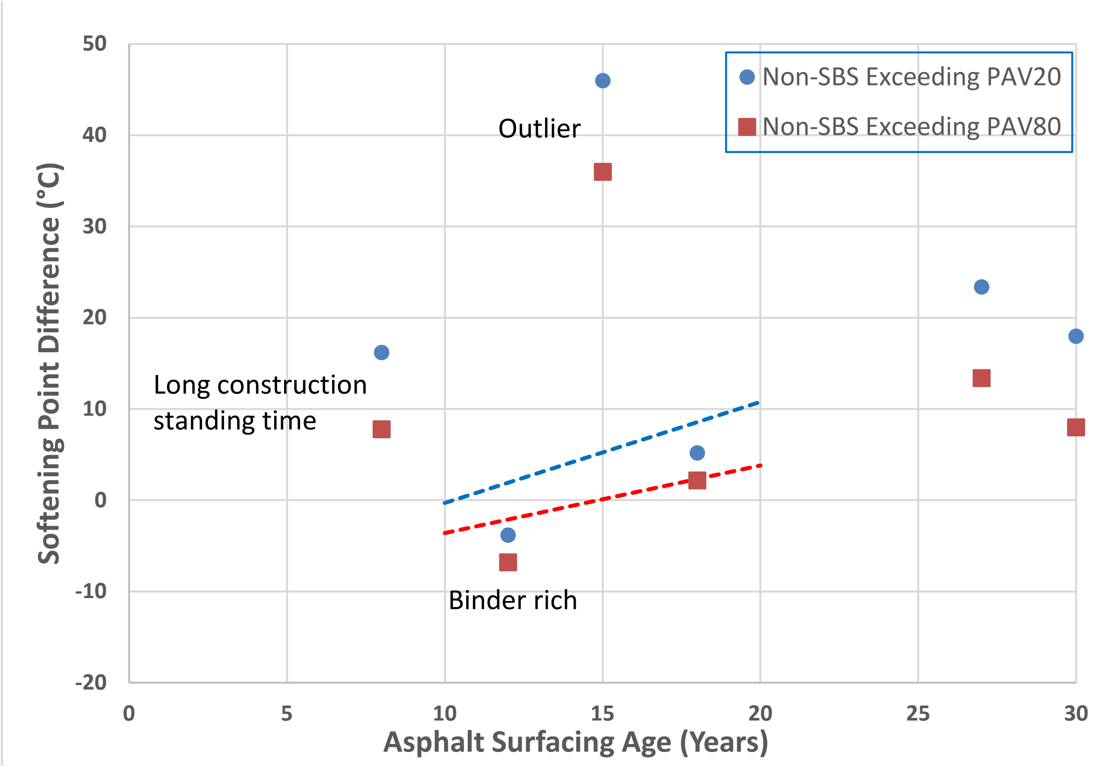

Figure 6: Softening Point Difference between Recovered Binder and PAV Prediction for non-SBS Binders

By omitting the exceptional results, the remaining four results were used to plot trendlines using the least squares method in Excel. The PAV20 trendline implies that the standard PAV ageing represents approximately 10 years of field ageing for continuously graded mixes (where Softening Point Difference = 0°C). The PAV80 trendline represents approximately 15 years of field ageing, implying that there is **not** a linear relationship between length of field ageing and length of time used for PAV ageing.

The non-SBS binders are shown graphically in Figure 7.

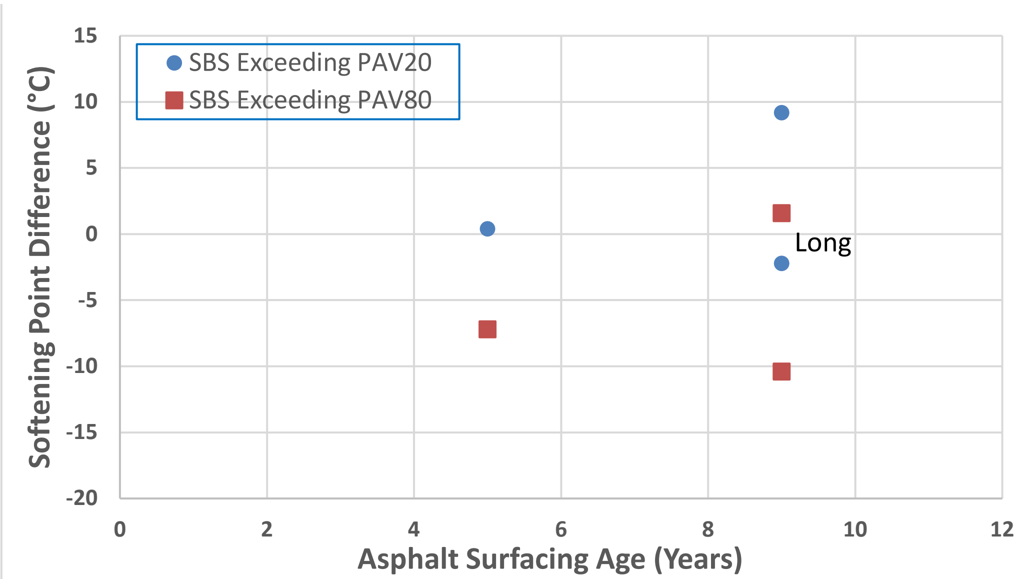

Figure 7: Softening Point Difference between Recovered Binder and PAV Prediction for SBS Binders

The low number of data points and the effects construction waiting times, as well as the non-linear profile for SBS binder [12], prevent an analysis of the data.

C. Evaluating Flexural Creep Stiffness (S) from the BBR as an Ageing Index Parameter

The recovered binders were analysed by plotting the flexural creep stiffness (S) of the recovered binders as a ratio of that predicted by PAV. The standard PAV ageing (20 hours) as well as extended PAV ageing for 80 hours was used in the analysis as shown graphically in Figure 8.

The effect of long waiting period during construction is evident for Mix 3 and Mix 4 (9 years old), and S exceeds that predicted by PAV significantly. The high value obtained for Site 6 (15 years old) is again not align with the other observations. Trendlines were plotted, while omitting these three results. The PAV20 trendline implies that the standard PAV ageing represents approximately 0.5 years of field ageing for continuously graded mixes (where the Stiffness Ratio – 100%). The PAV80 trendline represents approximately 8 years of field ageing, again implying that there is **no** linear relationship between length of field ageing and length of time used for PAV ageing. These trends vary considerably from that obtained from the softening point analysis. However, the correlation for the trendlines were poor for both softening point and flexural creep stiffness (varying from 60 to 80%).

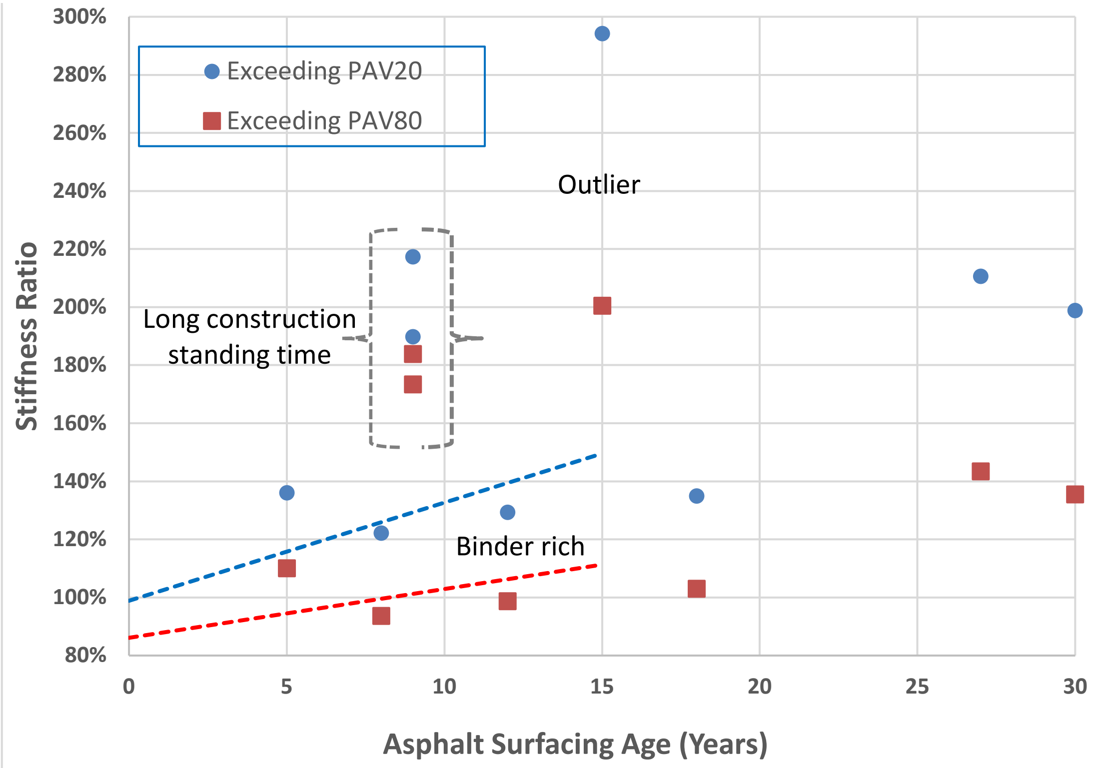

Figure 8: Stiffness (S) Ratio between Recovered Binder and PAV Prediction

D. Analysis of BBR m-value as an Ageing Index Parameter

Finally, the ratio of the BBR m-value to that predicted by PAV was plotted in Figure 9.

The effect of long waiting period during construction is confirmed for Mix 3 to Mix 5 and the deviation for Site 6 remains. Trendlines were plotted, while omitting these results. The PAV80 trendline represents approximately 7 years of field ageing (where m-Value Ratio = 100%), but the PAV20 trendline implies negative ageing is required for the recovered binder to attain equivalency with the standard PAV ageing! This indicates that there is very little correlation between PAV ageing and field ageing when using the BBR m-value as AIP. On the surface, this may be seen to have implications for using m-value as a performance indicator, and by extension, using ΔTc as a performance indicator, as currently presented in the performance-graded specification [1]. However, the recovery process in itself may be playing a role in the anomalies found for the m-value, whereby very small amount of recovery solvent retained by the recovered binder may have a very large effect on the m-value. Overall, it may be premature drawing conclusions based on a limited number of samples, and without fully understanding the effects of the recovery process.

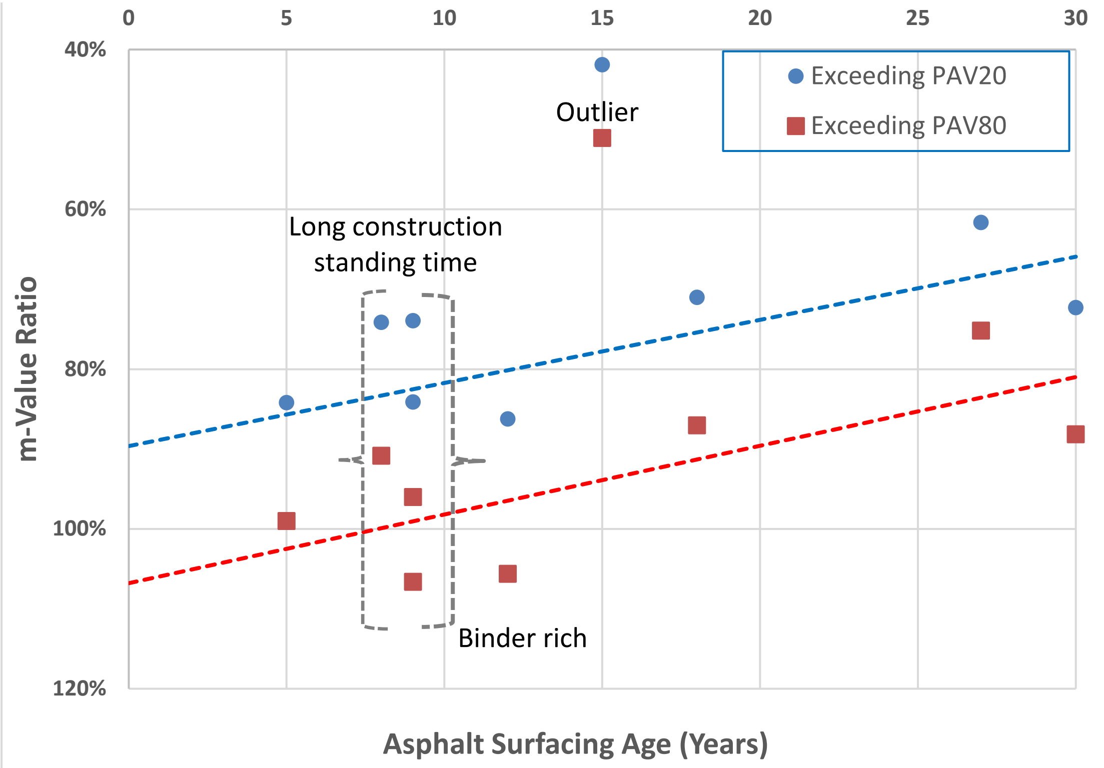

Figure 9: m-Value Ratio (BBR) between Recovered Binder and PAV Prediction

E. *Flexural Creep Stiffness (S) vs Softening as an Ageing Index Parameter*

A clear conclusion can be drawn that not all AIP's are equal and that very different ageing trends can be found depending on which parameter is selected to monitor ageing. The differences between softening point and flexural creep stiffness are highlighted in Figure 10 , where the degree of ageing of the recovered binder relative to the PAV ageing differs depending on the AIP used.

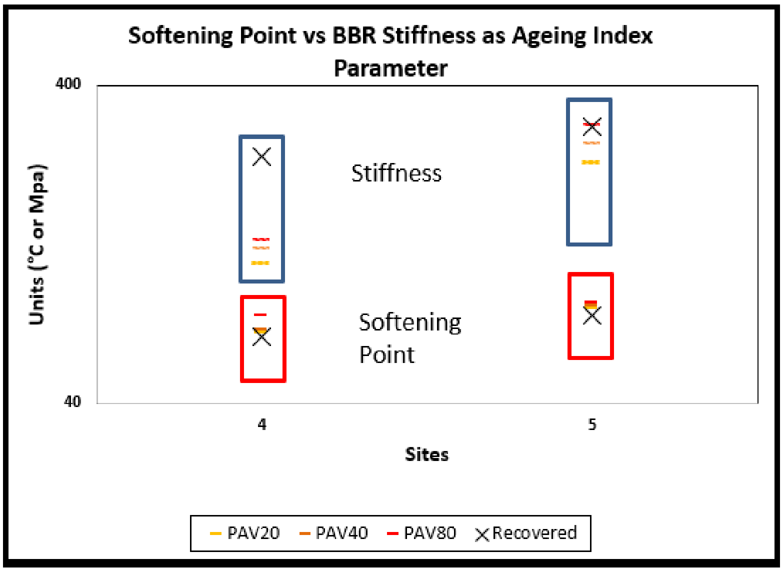

Figure 10: Flexural Creep Stiffness (S) vs Softening as an Ageing Index Parameter

F. Conclusions

This study has shown that:

- The correct choice of AIP used to monitor ageing is critical for obtaining the correct conclusions. The AIP should be most relevant for the performance issue that is being investigated with ageing, whether it be cold temperature cracking, environmental cracking or ravelling. The effects of sampling or sample preparation, e.g. binder recovery, coring, etc, on the AIP that has been selected for the ageing study should be known.
- Ageing studies require a large number of samples, so that statistically valid conclusions can be drawn. From the results obtained in this study, it can be seen that the sample size (10 sites) was insufficient. Three sites experienced extended delays during construction, and this only becomes evident depending on the choice of AIP. One site indicated extensive ageing for unknown reasons, while one more was sampled incorrectly due to possible road maintenance. The remaining five sites were too few to be statistically representative of ageing in Gauteng, South Africa. A similar study undertaken by Khan et al [13] in Canada, employed 54 sites to gain statistical validity. Unfortunately, such large undertakings are expensive and require large resources in terms of skilled laboratory staff and laboratory time.

5. Acknowledgement

The authors express their gratitude to South African National Roads Agency Limited (SANRAL), AECI Much Asphalt (Pty) Ltd and the Council for Scientific and Industrial Research (CSIR) for funding this research."

6. References

[1] SABS Technical Specification SATS 3208, "Performance Grade (PG) specifications for bitumen in South Africa" Pretoria, South Africa, 2020.

[2] ASTM Standard D2872-19, "Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)", ASTM International, West Conshohocken, PA, 2019.

[3] ASTM Standard D6521-19, "Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)", ASTM International, West Conshohocken, PA, 2019.

[4] B.T. Smith, I.L. Howard, W.S. Jordan, C. Daranga, and G.L. Baumgardner, “Comparing pressure aging vessel time to field aging of binder as a function of pavement depth and time”, Transportation Research Record, 2672(28), 2018, pp.223-234

[5] Y. Qian, F. Guo, Z. Leng, Y. Zhang, and H. Yu, “Simulation of the field aging of asphalt binders in different reclaimed asphalt pavement (RAP) materials in Hong Kong through laboratory tests.” Construction and Building Materials, 265, 2020, pp.120651

[6] J. O'Connell and W.J.vdM Steyn, “An overview of the ageing of bituminous binders”, Southern African Transport Conference, Pretoria, South Africa, 2017.

[7] M.D. Elwardany, “Phenomenological Modeling and Laboratory Simulation of Long-Term Aging of Asphalt Mixtures.”, A dissertation submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy. North Carolina State University, 2017.

[8] ASTM Standard D36-14, "Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus)", ASTM International, West Conshohocken, PA, 2014.

[9] AASHTO Standard 313-19, “Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR), Standard by American Association of State and Highway Transportation Officials, Washingtom, DC, 2019.

[10] CSIR Test Method BE-TM-BINDER-1-2006, " Internal Test Method for Determination of Binder Content and Binder Recovery", Revision 3, Council for Scientific and Industrial research, Pretoria, South Africa, 2017.

[11] J.S. O’Connell, Protocol for Softening Point of Bituminous Materials Internal CSIR Report GWDMS: 180012, Council for Scientific and Industrial Research, 2009.

[12] J. O'Connell, G.A. Mturi, and J.W. Maina, “Adjusting the standard rolling thin film oven procedure to improve the prediction of short term ageing”, 10th Conference on Asphalt Pavements for Southern Africa [CAPSA11], KwaZulu-Natal, South Africa, 2011.

[13] A.N. Khan, M. Akentuna, P. Pan, S.A.M. Hesp, “Repeatability, reproducibility, and sensitivity assessments of thermal and fatigue cracking acceptance criteria for asphalt cement” Construction and Building Materials, Vol. 243, 2020