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Case study

Difficulties monitoring short-term ageing in thin surfacing layers using asphalt concrete

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ABSTRACT

Ageing has a profound effect on pavement performance, especially regarding cracking. Due to budgetary constraints, South Africa has pioneered the use of thin asphalt concrete layers. The research described in this paper is based on a short-term ageing study in South Africa, using data generated over a period of 6 years. During this time, polymer modified asphalt binders were increasingly employed in road construction, and rheological analyses from the dynamic shear rheometer were increasingly used to characterize asphalt binders. This study compared the complex shear modulus to the softening point as an ageing index property used to monitor the extent of short-term ageing of the recovered asphalt binder from newly laid asphalt concrete. The asphalt binder properties from 20 constructions sites were evaluated, whereby the recovered binder from the site shortly after construction was evaluated against the asphalt binder properties obtained in the laboratory after the rolling thin film oven treatment. The results indicate that the recovery process leads to a deterioration in the repeatability for the complex shear moduli obtained from recovered asphalt binders. The lower repeatability prevents meaningful conclusions from being made. Furthermore, the work shows that although the Rolling Thin Film Oven Test may be a good predictor of short-term ageing when using softening point as an ageing index property, it is only valid for unmodified asphalt binders in South Africa.

1. Background

1.1. Durability and ageing

One way to address budgetary constraints in developing countries is to use thin asphalt concrete layers between 40 mm and 60 mm thick for road surfacing. Such thin asphalt concrete layers experience different load distributions and rates of ageing compared to the traditionally thicker layers used in Western countries. An asphalt concrete surfacing layer's durability or useful lifetime depends on the rate and extent of ageing to which the layer is exposed. Such a rate and extent can be monitored using either traditional empirical properties such as penetration and softening point, or using more fundamental properties derived from the Dynamic Shear Rheometer (DSR) obtained from the asphalt binder used in the asphalt concrete.

As the stiffness of asphalt binder, and hence the asphalt concrete, increases with ageing, the likelihood of cracking increases, whether attributed to environmental cracking (thermally induced) or traffic-induced fatigue-related cracking [13]. Ageing studies and

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the development of ageing models related to thin asphalt concrete layers may provide a better understanding of the ageing process in thin layers. This could inform economic considerations for pavement maintenance to prevent penetration of water into the pavement structure, a primary cause of pothole formation and pavement damage in South Africa, where granular layers are used extensively in the base of the pavement structure.

The ageing of an asphalt concrete layer can be described in terms of two distinctly different processes, involving very different reaction mechanisms, which can be referred to as short-term ageing (STA) and long-term ageing (LTA):

- STA represents the ageing that the asphalt binder undergoes during the manufacturing, storage, transport, and placement activities.
- LTA is ageing that occurs over the pavement's lifetime.

LTA may represent varying periods of ageing in the field as researchers attempt to reconcile the extent of ageing in the field with the Pressure Ageing Vessel (PAV), a long-term ageing simulation procedure in the laboratory. Various researchers have attempted to quantify the extent of ageing that is predicted by the PAV during LTA [20,22], but the data obtained is affected by the asphalt concrete properties, the location climate, latitude and altitude.

STA is a critical component of any ageing model, even though it is of a short duration (measured in hours) compared to LTA (measured in years). STA has a much higher rate of ageing due to the elevated temperature of the asphalt mix prior to construction. STA of thinner asphalt concrete layers may differ from that of thicker layers in that thinner layers cool down faster during laying and compaction.

1.2. Monitoring STA

Properties selected to monitor changes in the binder during ageing are called Ageing Index Properties (AIPs) [12]. Theoretically, any asphalt binder property can be an AIP. However, selecting an asphalt binder property that is more strongly associated with the performance aspect being evaluated for the asphalt concrete would be more prudent. For example, the softening point or the non-recoverable compliance (J_{nr}) at 64°C would be a better choice as AIP when studying the effects of ageing on rutting than would be the choice of ductility at 15°C or beam stiffness (S) at −12°C. Conversely, ductility and beam stiffness, being associated with cracking, would be a better choice as AIP if studying the effects of ageing on cracking.

Statistical validation of the findings of an investigation into ageing studies is of fundamental importance for international acceptance of the data and conclusions. Some aspects for consideration when pursuing statistically valid results include:

- The use of validated international test methods or validated internal test methods with proven effectiveness;
- The binder properties selected as AIPs should prove to have high repeatability in terms of accuracy and precision;
- Some properties may be expressed in terms of their logarithmic values, thereby concealing their true repeatability, and
- Ageing studies are effectively a measurement of changes. If the range of changes in a AIP is exceed by the range of the repeatability of the AIP, the conclusions obtained from the results cannot be statistically valid.

This paper relates to the second phase of a short-term ageing study conducted in South Africa, whereby data was collected and collated over a period of 20 years. The ageing study was comprised of two distinct phases, with each phase characterized as follows:

- The first phase involved the exclusive use of 50/70 penetration-grade asphalt binder, prior to performance testing in South Africa (2001–2012). Penetration, softening point and penetration index were chosen as AIPs for this phase.
- The second phase (2013–2019) reflected a significant increase in the use of modified asphalt binders. The chief modifiers used in South Africa during this phase included styrene-butadiene-styrene (SBS, a block co-polymer), styrene-butadiene rubber (SBR, a random co-polymer) and ethylene vinyl acetate (EVA). Using recycled asphalt pavement or concrete (RA) was another feature of

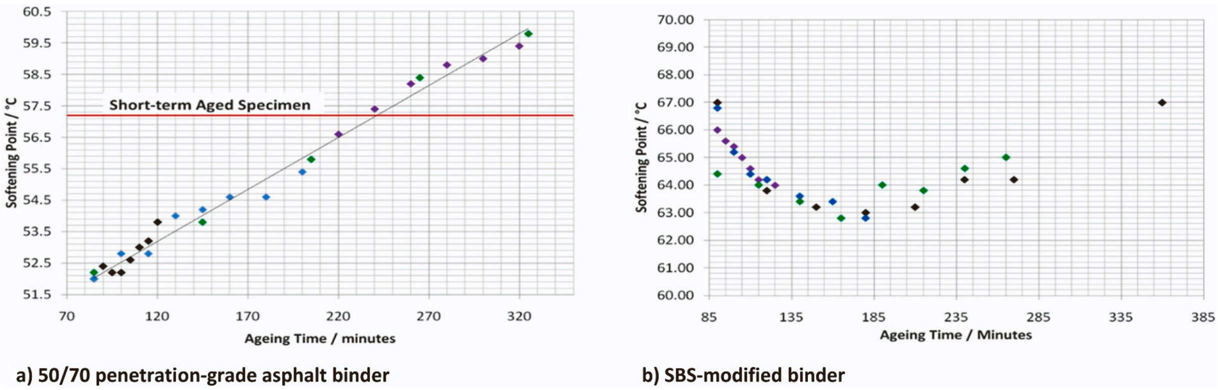


Fig. 1. Monitoring ageing using softening point [17].

the second phase, along with the increased use of performance-related testing. During this phase, rheological data from the DSR, as well as empirical testing, were used as AIPs.

The work from the first phase has been published [19]. This paper focuses on the second phase, 2013–2019, where the objective was to evaluate the ageing reaction kinetics using different AIPs. Whereas the first period employed empirical testing only, the second period under analysis required fundamental rheological analyses because the complex behaviour and characteristics of polymer-modified binders cannot be described adequately by empirical results alone. O'Connell et al. [17] demonstrated that for unmodified binders such as 50/70 penetration-grade asphalt binder, empirical results such as penetration and softening points generate a unique value with ageing. In contrast, the values generated for SBS-modified asphalt binders in South Africa are not unique, depending on the origin of the binder. This is illustrated with softening point data associated with ageing in a rolling thin film oven (RTFO) test in Fig. 1.

Because the softening point values for the SBS-modified binder are not unique, it is impractical to monitor ageing when using an AIP such as softening point. A reduction in softening point was initially observed for SBS-modified binders in South Africa, followed by an increase with continued ageing. This problem can be overcome using rheological data generated by the DSR, as illustrated in Fig. 2.

An additional objective of this paper is to evaluate the effectiveness of the Rolling Thin Film Oven (RTFO) Test in simulating STA. General factors that might affect the rate of ageing during STA within the same location include [18]:

- The chemical and physical characteristics of the asphalt binder;
- The nature of the aggregate and filler;
- Type of manufacturing plant;
- Time taken from asphalt concrete manufacture to compaction;
- The manufacturing temperature of the asphalt mixture;
- The binder film thickness;
- The thickness of the asphalt concrete layer;
- The addition of antioxidants (primarily agricultural lime) or polymer modifiers;
- The weather, which affects the rate of cooling of the manufactured mix; and
- The final voids in the mix after compaction has been completed. This has a small effect on STA, but is a major factor affecting LTA over the lifetime of the pavement.

The data from 2013–2019 was analyzed to determine the effect of factors such as 'mix temperature', 'time to paving', film thickness, and polymer modification of the asphalt binder.

Similar studies have been conducted [1,9,15] whereby the asphalt binder is recovered from the field after STA in the field. Shortcomings evident from these studies include:

- A limited number of sites evaluated;
- Recovery of the binder after manufacture of the asphalt concrete instead of after construction of the asphalt concrete layer;
- No evaluation of the repeatability of the results; and
- Choice of crumb rubber modified binder as a substrate, which cannot be completely recovered.

The literature states that test results on binders are generally more repeatable than using test results on asphalt concrete for ageing studies, because the microstructure of binders are more homogenous compared with asphalt concrete [15].

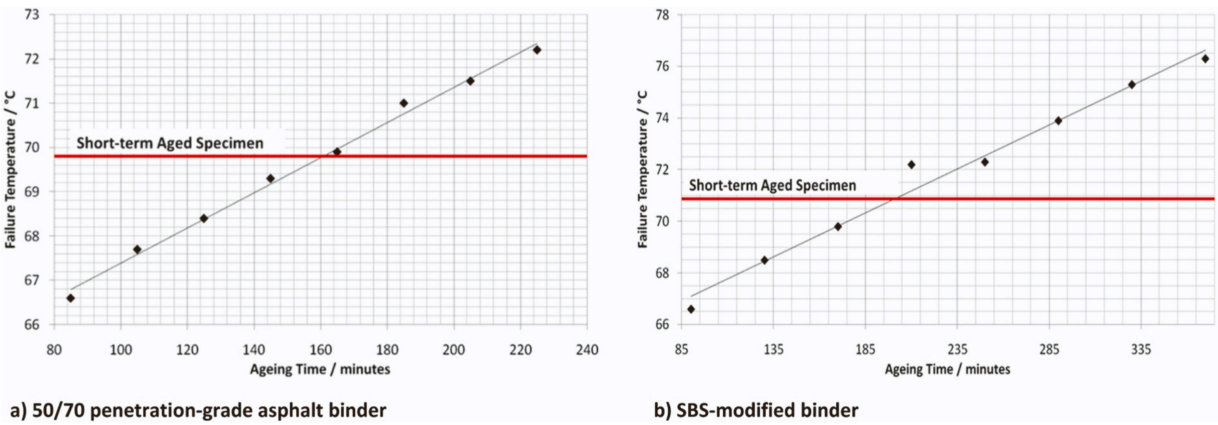


Fig. 2. Measured failure temperature defined by |G*|/sin δ = 2.20kPa [17].

2. Experimental

2.1. Methodology

Three asphalt concrete manufacturing companies in Gauteng Province, South Africa, cooperated in the investigation. The methodology with regards to sampling and data collection is illustrated in Fig. 3.

Establishing the composite binder's initial stiffness before STA requires determining the effect of incorporating recycled asphalt concrete (RA) on the virgin asphalt binder's condition. The following steps were followed to evaluate the effect of adding the RA:

I. The binder from RA was recovered and characterized.
II. The effect of the RA binder on the virgin asphalt binder was determined through a proportional linear calculation using the properties of the RA binder and the virgin asphalt binder, as well as by blending the virgin binder and the RA binder in their design ratios and characterizing the blend.
III. The characteristics of the blended RA binder and virgin binder were deemed to reflect the initial composite binder stiffness of the asphalt concrete before manufacture and were compared to the recovered binder after STA to assess the effect of STA.

2.2. Sites and samples

Unmodified asphalt binder, whether used in its original form or as a base for modification, was primarily produced in four South African crude oil refineries during this investigation period. Modifying asphalt binders also occurred exclusively within South Africa using various imported modifiers and a few proprietary local polymer blends.

The binders evaluated for this period include polymer-modified asphalt binders, containing modifiers such as SBS and EVA, both commonly used in South Africa. Asphalt concrete mixes also commonly contain between 10 % and 20 % RA during this investigation period.

The chronological list of sites which were investigated is listed in Table 1.

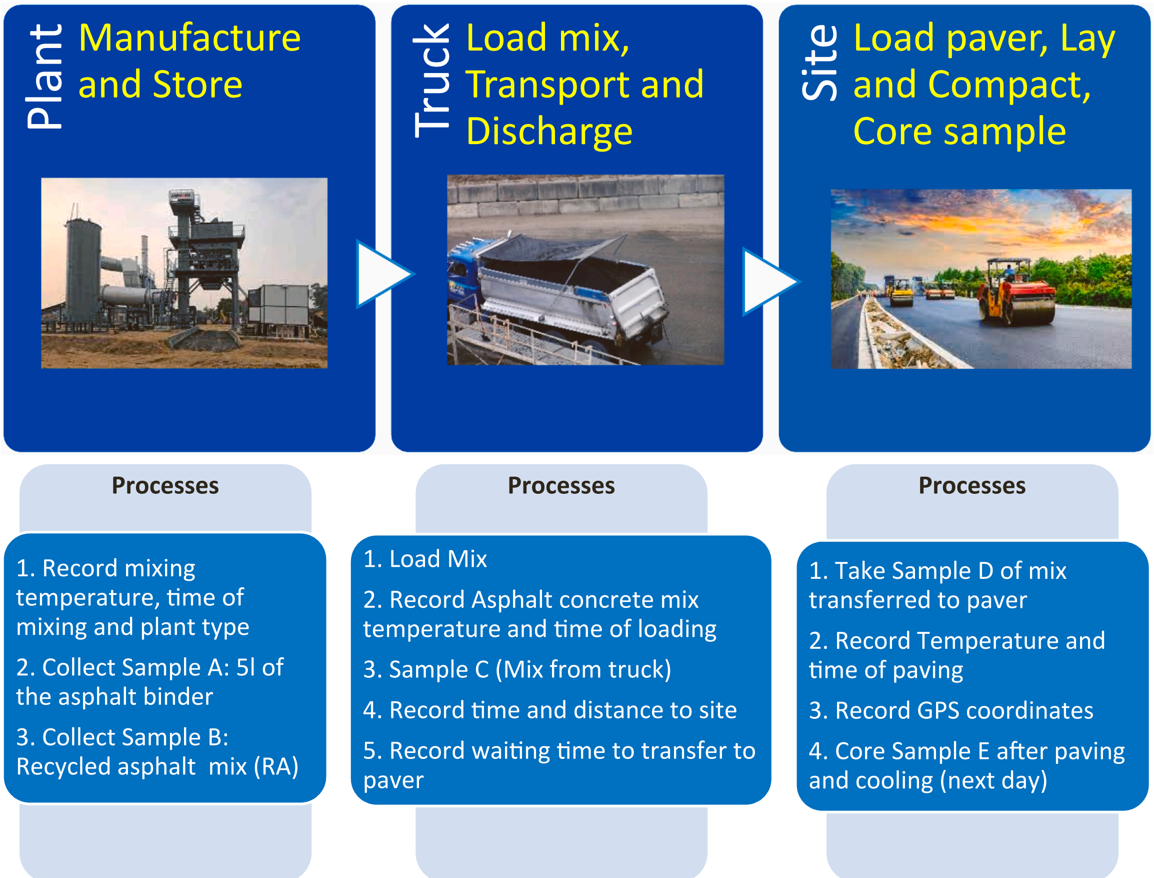


Fig. 3. Methodology for sample and data collection.

2.3. Test methods

2.3.1. Empirical testing

Empirical analyses are limited to softening point only, using ASTM D36 [5]. Polymer-modified asphalt binders are not characterized using penetration in South Africa. Softening point was selected as one of the AIPs for this study because it is a continuation of the AIP used during the first stage of this ageing study. Softening point also has been used extensively from a historical perspective, as it is one of the properties used in the South African asphalt binder specification. The road construction industry can, therefore, interpret Softening Point values more easily than complex modulus values.

2.3.2. Rheological testing using the DSR

Rheological data from the DSR was selected as the second AIP for monitoring ageing because it can overcome unpredictable changes in softening point when evaluating polymer modified asphalt binders. Rheological data was generated using the Smartpave Plus DSR model from Anton Paar using ASTM D7175 [8] as the test method. Rheological data included G' (storage shear modulus), G" (loss shear modulus) and δ (phase angle). The data were generated using frequency sweeps at pre-determined temperatures. All rheological measurements were made within the linear visco-elastic (LVE) region of the asphalt binder under investigation. An example of the determination of the LVE region for the asphalt binder recovered from Site 2 after STA, as generated by the Anton Paar software, is given in Fig. 4.

The LVE limit has been described as strain value where the modulus value attains 95 % of its initial with increasing [3,4]. As expected, the LVE range manifests itself at higher strain values as the temperature increases, considering that the lower stiffness at higher temperatures allows for higher deformation with higher strain values before sample damage occurs. Fig. 4 demonstrates this trend except at 70 °C, where the LVE is presented at a lower strain range. This is a direct consequence of the lower repeatability of G' and G" at higher temperatures, due to the lower precision of the torque application [2]. The expected outcome for using the LVE range at the lower strain range is a lower precision and repeatability for the measurements determined at 70°C.

Because the ageing study occurred over an extended period, a change in testing methodology resulted in two different testing protocols being used in the laboratory during the period under investigation. The two protocols are summarized in Table 2.

Using two different testing protocols made data comparisons difficult, especially when data was generated using different temperatures and frequencies. This problem was overcome by constructing master curves using RHEA™ software, the official rheological analysis software for the Asphalt Institute. The range of frequencies used in the Initial protocol may have been too extreme for the required accuracy of results. Only data from 0.0796 to 20.0 Hz (0.05 Rad/s to 125.7 rad/s) were employed in constructing master curves. The resultant master curve equations were used to compare binder parameters under similar conditions of temperature and frequency (52°C, 10 rad/s).

In the RHEA™ software, the master curves are fitted using a range of models, including relaxation/retardation spectra, the Christensen-Anderson model and the standard and generalized logistic functions [21,25]. For this paper the model used to obtain the master curve was the one which best fit the data. An example of a master curve generated for the 50/70 asphalt binder used on Site 13 is shown in Fig. 5.

To evaluate the quality of the data, the black space diagrams were examined for the extent of data overlap and feathering. An example of the black space diagram for 50/70 binder asphalt on Site 13 is shown in Fig. 6.

An example of feathering (circled) is presented in Fig. 7. Feathering can result from problematic data, as pointed out by the solid circle in Fig. 7, where the data was generated at too high frequencies beyond the range of the DSR equipment. Feathering within the

Table 1
Sites evaluated for the period 2013 – 2019.

Site	Mix	Binder
1	High Modulus Asphalt for base	10/20 + 15 %RA
2	Dense-graded surfacing	70/100 + 4 % SBS
3	Dense-graded base	35/50 + 15 % RA
4	Warm Mix Asphalt: Dense-graded Base	70/100 + 5 % EVA+ 1 % rejuvenator + 40 % RA
5	Dense-graded surfacing	50/70
6	Dense-graded surfacing	50/70
7	Dense-graded surfacing	50/70 +10 % RA
8	Dense-graded surfacing	SBS-modified Binder + 10 %RA
9	Dense-graded surfacing	SBS-modified Binder + 10 %RA
10	Dense-graded surfacing	50/70
11	Dense-graded surfacing	50/70 +20 % RA
12	Dense-graded surfacing	50/70
13	Dense-graded surfacing	50/70
14	Dense-graded surfacing	50/70
15	Dense-graded surfacing	50/70
16	Dense-graded surfacing	50/70
17	Dense-graded Base	Sasolflex (SBS) - modified Binder
18	Dense-graded surfacing	50/70
19	Dense-graded surfacing	SBS-modified Binder
20	Dense-graded surfacing	SBS-modified Binder

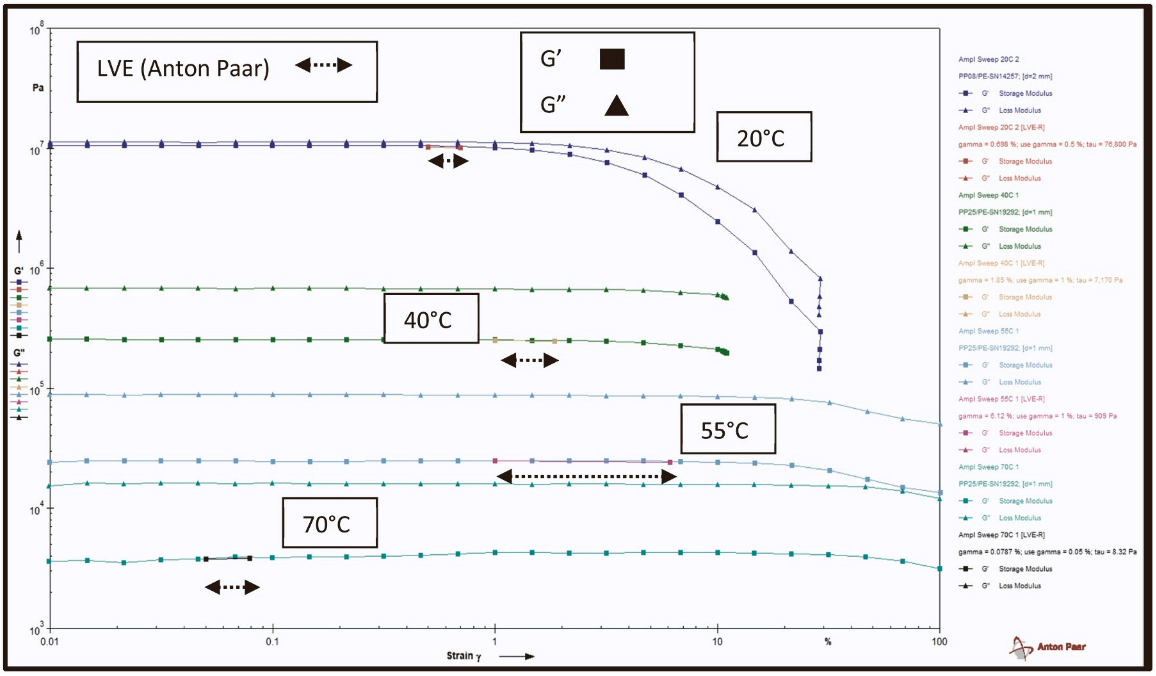
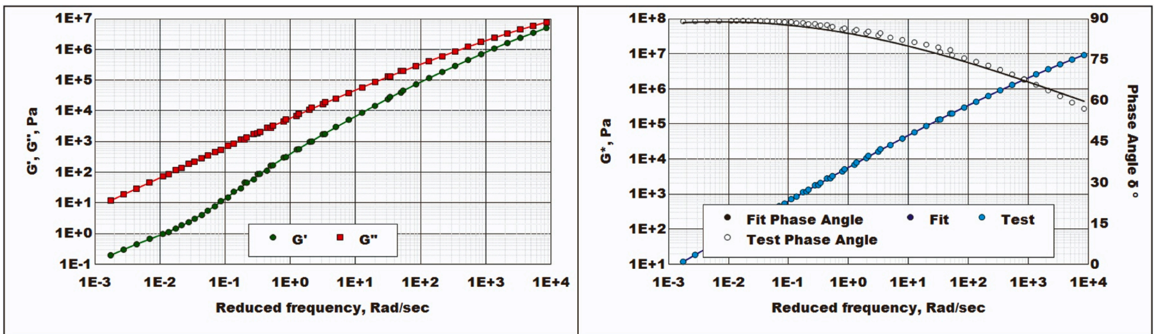


Fig. 4. Determination of the LVE region for the asphalt binder recovered from Site 2 after STA. Showing plots of G' and G'' (log scale) vs % strain (γ) (log scale). Amplitude sweeps were conducted at 20, 40, 55 and 70°C.

Table 2
Laboratory protocols followed during testing.

Protocol Aspects	Initial Protocol (2013 – 2015)	Final Protocol (2016 – 2019)
Frequency sweeps: Frequencies	0.00796, 0.0126, 0.0200, 0.0317, 0.0502, 0.0796, 0.126, 0.200, 0.317, 0.502, 0.796, 1.26, 2.00, 3.17, 5.02, 7.96, 12.6, 20.0, 31.7, 50.2, 79.6 Hz	0.251, 0.398, 0.631, 1.00, 1.58, 2.51, 3.98, 6.31, 10.0, 15.8, 25.1 Rad/s
Frequency sweeps: Temperatures	20, 40, 55, 70°C.	5, 22, 28, 34, 45, 58, 64, 70°C.
Temperature order	Not Defined	From high to low temperature for the 8 mm spindle in case of sample dislodgement at lower temperatures. From low to high temperature for the 25 mm spindle in case of sample flow at higher temperatures.
Sampling	New sample for each temperature	New sample for each DSR spindle
LVE determination	LVE determined at each temperature	LVE determined at the lowest temperature and highest frequency for each DSR spindle size (i.e. 8 mm and 25 mm)



a) Master curves for G' and G'' for 50/70 used in Site 13

b) Master curves for G* and δ for 50/70 used in Site 13

Fig. 5. Master curve generation.

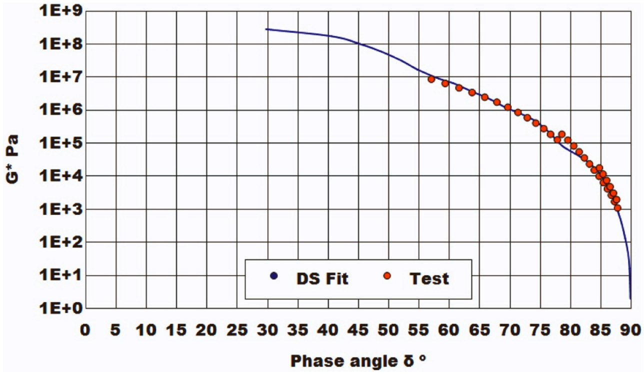


Fig. 6. Black space diagram for 50/70 binder asphalt on Site 13.

dotted circle indicates the disconnect produced by changing from 25 mm parallel plates to 8 mm parallel plates on the DSR. Feathering can also occur with binders exhibiting gel-like behavior associated with elevated asphaltene levels [14], so discretion is required when interpreting feathering on the Black space diagram.

2.3.3. Binder recovery

The in-situ asphalt binder was recovered using ASTM D1856 [6], referred to as the Abson recovery method. The authors have previously published [19] on the importance of the recovery process and how a poor recovery process can result in incorrect conclusions: "The technical performance of the recovery process is a measure of the accuracy (a reflection of how close the properties of the recovered binder compare with the properties of the in-situ binder prior to recovery) and the repeatability of the properties obtained after recovery [16]."

Factors affecting the binder recovery process include:

- Asphalt binder characteristics,
- aggregate characteristics, and
- choice of solvent, which was a solution of 15 % ethanol in toluene for this paper.

Like the first phase of the ageing study [19], gas chromatographic analyses and ash content analyses were employed as measures of quality control. The time from sampling to binder recovery was minimized, with samples being stored at 15°C to delay continued ageing.

2.3.4. RTFO test

The Rolling Thin Film Oven (RTFO) Test [7] is used for the asphalt binder specifications in South Africa and is often considered to be a simulation of STA in the field.

2.3.5. Multiple linear regression analysis [23,24]

Simple linear regression is a statistical model that evaluates the relationship between two sets of variables, i.e. an independent variable (input) and a dependent variable (output). If the variables have a strong relationship, the relationship (or model) can be used to predict outcomes with high accuracy based on the independent variable. This is a bivariate model whereby a relationship is established between one independent variable and one dependent variable, represented by a straight-line equation, also referred to as

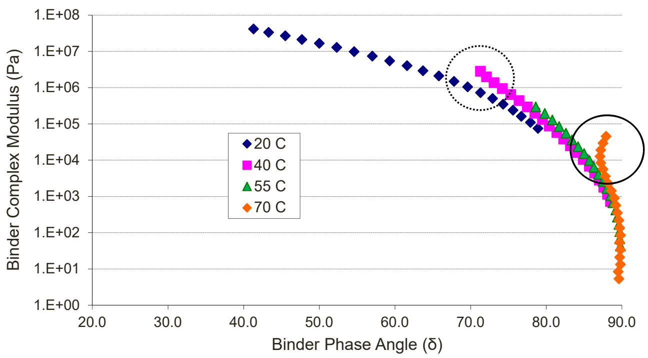


Fig. 7. An example of feathering obtained for 50/70 penetration-grade asphalt binder after RTFO.

the line of best fit. When more than one independent variable is present, the analysis is extended, and a multivariate model is required, which is referred to as a multiple linear regression analysis (Eq. 1)

$$y = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n + \varepsilon \tag{1}$$

Where y = dependent variable
x_i = independent variable
β_i = parameter
ε = error or residual

Correlation coefficients (R-value) and p-values are calculated during the analysis to determine the strength of the relationships between the independent and dependent variables and how statistically significant those relationships are. R-squared (R^2) measures the variation of the multivariate model. R^2 either increases or remains unchanged as additional independent variables are added. An adjusted R2 is calculated to overcome this drawback, which only increases if additional independent variables improve the model's fit. Adjusted R^2 is, therefore, a better indicator of how well the data fits the model.

3. Results

3.1. Repeatability of results

The repeatability of the softening point and rheological data were determined for ten identical samples, as shown in Table 3.

The coefficient of variation (COV) results in Table 3 illustrate that the repeatability decreases for SBS-modified asphalt binders compared to unmodified asphalt binders, which is in agreement with the literature [11]. Furthermore, rheological data show a marked decrease in repeatability of results compared to softening point data.

The softening point COV compares well with the COV of 0.8 % reported for unmodified asphalt binders using a mercury thermometer in ASTM D36/D36M-14, but the repeatability is poorer for modified binders, reported as 1.1 % in ASTM D36/D36M-14. This is likely to be related to the type of SBS polymer used to modify the asphalt binder

The recovery process introduces a further source of variation, resulting in lower repeatability for softening point values and any rheological properties for the asphalt binder after recovery. The repeatability is illustrated in Table 4 after ten separate binder recoveries had been undertaken.

Table 4 indicates that the recovery process has a more significant effect on rheological testing than on softening point data. It is suspected that residual solvents remaining after recovery have a more significant effect on the rheology of a sample than the effect on the softening point values. This is further illustrated in Table 5, where the results for three repeats in this study are recorded.

Where duplicate samples were evaluated, the average result is reported in this paper. Table 5 illustrates poor repeatability for determining complex moduli after asphalt binder recovery. The literature reports similar findings whereby the COV for G* at 64°C (10 rad/s) after the recovery of asphalt binder can be as high as 58 % [26].

Another source of poor repeatability of all results is the presence of RA in the mix (generally 10–20 %). RA is a non-homogenous material with an inherent uncertainty resulting from variations in the RA composition and the degree of stockpile mixing.

Increased uncertainty in results brought about by the recovery process and the presence of RA led to a decision to report softening point values as rounded off to the nearest whole number, compared to the test method requirement for reporting to the nearest 0.2°C. The repeatability of results should be considered when interpreting the results presented in this paper.

3.2. Empirical testing

Fig. 8 illustrates the softening point results obtained from binder recovered from asphalt concrete from Sites 1 – 20 with the

Table 3
Repeatability of binder testing in the laboratory.

Sample	Softening point (°C)		G* @ 52°C, 10 rad/s (kPa)	
	Virgin unmodified	SBS-modified	Virgin unmodified	SBS-modified
Sample 1	48.8	57.4	7.0	10.0
Sample 2	48.8	57.2	6.8	9.8
Sample 3	49.4	57.0	6.6	9.7
Sample 4	48.8	59.0	6.8	9.6
Sample 5	48.8	53.0	6.9	9.5
Sample 6	48.8	55.0	7.2	11.7
Sample 7	48.8	57.4	7.1	11.2
Sample 8	48.8	55.3	7.0	11.1
Sample 9	49.0	58.7	7.1	10.7
Sample 10	49.0	54.8	-	11.5
Average	**48.9**	**56.5**	**6.9**	**10.5**
Coefficient of Variation	**0.4 %**	**3.4 %**	**2.7 %**	**8.1 %**
ASTM reporting	0.8 %	1.1 %	2.3 %	

Table 4
Repeatability of testing of recovered unmodified asphalt binders.

Sample	Virgin unmodified asphalt binder	
	Softening point (°C)	G* @ 52°C, 10 rad/s (kPa)
Sample 1	50.6	8.0
Sample 2	50.4	8.2
Sample 3	50.2	7.6
Sample 4	50.6	8.8
Sample 5	50.4	8.0
Sample 6	50.6	9.2
Sample 7	50.6	7.8
Sample 8	50.5	8.8
Sample 9	50.7	7.7
Sample 10	51.2	8.2
Average	**50.6**	**8.2**
Coefficient of Variation	**0.5 %**	**6.5 %**
Without recovery as a reference	0.4 %	2.7 %

Table 5
Evaluation of binders done after repeated recoveries.

Site	Softening Point (°C)		G* @ 45°C, 25.1 rad/s (kPa)	
	1st Sample	2nd Sample	1st Sample	2nd Sample
Site 1: 10/20 + 15 % RA	72	72	907	748
Site 2: 70/100 + 4 % SBS	65	62	92.1	72.5
Site 3: 35/50 + 15 % RA	58	59	170	-

corresponding original binder results.

The higher original softening point values in Fig. 8 are typical for SBS-modified binders used in South Africa. The average changes in softening point for the sites after STA in the field are reported in Table 6.

The positive increase in softening point after STA for the unmodified asphalt binder can be used to indicate ageing. However, the SBS-modified binders display a decrease in softening point after STA, precluding the use of this parameter as an indicator of ageing for this class of binder. This is unique to South Africa, where the SBS modifier may contain Sulfur-based linking agents, resulting in initial steep increases in softening point, negated over time as the molecular linking breaks down again. The exact mechanism is unknown, but the effect dominates the ageing results as reflected by the softening points. Therefore, the resulting softening point values determined for these sites are not unique, and the softening point, as a binder property, cannot be used to monitor the extent of ageing. The increase in softening points for un-modified 50/70-penetration asphalt binder after STA in this investigation agrees with the results from the first half of the ageing study, which focused on 50/70-penetration asphalt binder and dense-graded surfacing from 2001 to 2012 [19].

The following factors that affect the rate of ageing were specifically investigated to determine their effect on the extent of STA:

I. *The temperature of the mix.*

Manufacturing temperatures of the mix are reported as presented on the asphalt mix batch slips. Initially, additional temperatures were taken on the haulier at the point of loading and the point of arrival at the site. Temperature readings were taken manually using a metal temperature probe, as none of the hauliers was automatically monitored. The temperature readings varied depending on the exact location of the temperature measurement. Some hauliers refused to allow the taking of

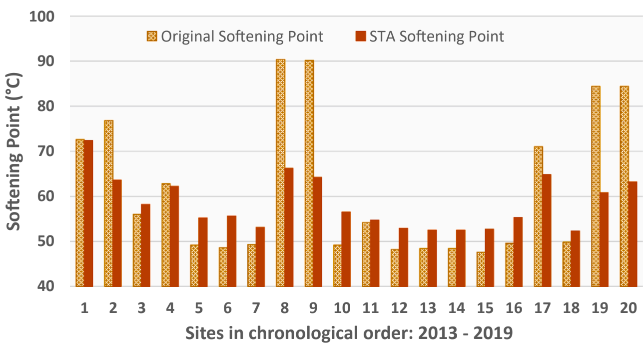


Fig. 8. Softening Points for original asphalt binders and recovered binders after construction (STA).

Table 6
Average changes in softening point after STA.

Binder and Mix Type	All Results	Without RA	With RA
50/70 / Dense-graded surfacing	+ 5°C	+ 5°C	+ 2°C
SBS-modified binder / Dense-graded surfacing	- 19°C	−16°C	- 25°C
Results from the first period, 2001–2012	-	+ 5°C	-

temperature measurements, citing safety concerns. As a result, the manual taking of temperatures in the trucks/hauliers was abandoned.

Asphalt paving is an all-year-round practice in South Africa, and there is no embargo period due to winter temperatures. Accordingly, South African asphalt concrete plants tend to increase manufacturing temperatures by 10–15°C in winter to compensate for additional asphalt mix cooling during transport. Unfortunately, these increased temperatures are not always reflected on the batch slips, as manufacturers are wary that such information may be used as a point of non-conformance for quality requirements. Temperature data is rounded to the nearest 5°C.

II. *The time taken to lay down the mix.*

Time affects the extent of ageing and can be influenced by the distance between the manufacturing plant and the site. Distance within a metropolitan area is less important than slow traffic and breakdowns on site. The time reported in this paper is the time from the collection of the asphalt to the time of laying the mix. Using the time of asphalt mix manufacture would have been more prudent. Still, the exact time of manufacture was not always available, as the asphalt mix collected from the storage silo can be the product of multiple batches manufactured over some time. The reported times have been rounded off to the nearest half hour.

III. *Binder film thickness*.

This is an important parameter affecting binder ageing, as it controls oxygen diffusion throughout the binder. The binder film thickness is a product of the binder content and grading, making this data essential for the ageing study. However, some manufacturers declined to provide this information because they believed that the design sheets constituted confidential intellectual property. The limited data obtained was therefore not included in this paper.

The independent factors associated with the increase in softening point after STA for the asphalt mixes using unmodified asphalt binder are listed in Table 7. The effect of linking agents on the softening point of the modified binders prevented the analyses of these binders using the softening point as a parameter.

A multiple linear regression analysis was performed on the data from Site 5 to Site 18 in Table 8, and the results are summarized in Table 8. Winter and summer were assigned values of 15 and 25, respectively, for the Season parameter to represent the average morning temperatures in °C, typically experienced during construction.

Pearson's r can range from −1–1. A value of 1 indicates a perfect positive linear relationship between variables, and −1 indicates a perfect negative linear relationship between variables. Pearson's r of 0 indicates no linear relationship between variables.

The results from the regression analysis indicate that no statistically significant correlation could be established between the independent factors (time, temperature, season) and the increase in softening point as a measure of STA:

- $R^2 = 0.34$ is low in value, and the adjusted $R^2 = 0.06$ is very low in value.
- The Pearson's r values are significantly low, with the Season parameter having the highest effect on the extent of ageing after STA,
- The p-values of the independent coefficients (0.900, 0.154 and 0.623, respectively) are higher than 0.10, indicating that no statistically significant relationship exists between the extent of STA and these parameters at the 90 % confidence level.

Table 7
Independent factors were evaluated for their effect on the STA of unmodified asphalt binders.

Site	Binder	Mix	Increase in Softening Point (°C)	Mix Temperature (°C)	Season	Time to Paving (hours)
1	10/20 + 15 %RA	High Modulus Asphalt for base	0	170	Winter	4
3	35/50 + 15 % RA	Dense-graded base	2	Unknown	Winter	Unknown
5	50/70	Dense-graded surfacing	6	190	Winter	1.5
6	50/70	Dense-graded surfacing	7	160	Winter	2.5
7	50/70 +10 % RA	Dense-graded surfacing	4	160	Summer	2
10	50/70	Dense-graded surfacing	7	160	Summer	1.5
11	50/70 +20 % RA	Dense-graded surfacing	0	160	Summer	1.5
12	50/70	Dense-graded surfacing	5	140	Summer	1.5
13	50/70	Dense-graded surfacing	4	160	Summer	1.5
14	50/70	Dense-graded surfacing	4	160	Summer	1.5
15	50/70	Dense-graded surfacing	5	160	Summer	4.5
16	50/70	Dense-graded surfacing	6	145	Summer	2
18	50/70	Dense-graded surfacing	3	175	Summer	2

Table 8
Regression analysis for 50/70 binder after STA.

Model		
Increase in softening point = - 0.059 *x* Mix Temperature – 0.329 *x* Season + 0.338 *x* Time to paving +21.06		
R^2	**Adjusted R^2**	
0.34	0.063	
Correlation Matrix		
	Pearson's r	**p-value**
Mix Temperature	−0.043	0.900
Season	−0.458	0.154
Time to paving	0.167	0.623

3.3. DSR testing

Fig. 9 illustrates the rheological data obtained from binder recovered from asphalt concrete and the values representing the initial blended binder conditions before manufacture.

G* increases with ageing, for the 50/70 asphalt binders, as well as for the SBS-modified asphalt binders on Sites 2, 8, 17 and 19. This contrasts with the higher original softening point values presented in Fig. 8 for the SBS-modified binders. G*, therefore, generates unique values over the STA period, allowing G* to be used as an AIP for SBS-modified asphalt binders, enabling a reflection of the rate of ageing during STA. However, this might not be practical because of the large variation and poor repeatability illustrated in Table 9. An anomaly is presented where a decrease in G* is reported for Site 1. This is a direct consequence of a lower repeatability and accuracy associated with the G* for the initial blended binder brought about by incorporating RA for Site 1.

The average absolute increases in G* and the average ratio of G* after STA to initial G* as a percentage are presented in Table 9.

A multiple linear regression analysis was performed on the data, excluding the negative data from Site 1 and unknown data from Site 3. The results are summarized in Table 11 and in Table 12.

The results from the regression analysis indicate that no statistically significant correlation could be established between the independent factors (time, temperature, season) and the absolute increase in G* as an AIP measuring the extent of STA:

- $R^2 = 0.21$ and the adjusted $R^2 = 0.13$ are low in value,
- The Pearson's r values are significantly low, with the Mix Temperature parameter having the highest effect on the extent of ageing after STA, in contrast to the softening point analysis where the Season gave the highest effect.
- The p-values of the independent coefficients (0.494, 0.665 and 0.520, respectively) are higher than 0.10, indicating that no statistically significant relationship exists between the extent of STA and these parameters at the 90 % confidence level.

The results from the regression analysis for the ratio increase in G* are very similar to those obtained for the absolute increase. The results indicate that no statistically significant correlation could be established between the independent factors (time, temperature, season) and the percentage increase in G* as an AIP measuring the extent of STA:

- $R^2 = 0.20$ and the adjusted $R^2 = 0.15$ are low in value,
- The Pearson's r values are significantly low, with the Mix Temperature and Time to Paving parameters having the highest effect on the extent of ageing after STA.
- The p-values of the independent coefficients (0.494, 0.665 and 0.520, respectively) are higher than 0.10, indicating that no statistically significant relationship exists between the extent of STA and these parameters at the 90 % confidence level.

3.4. Extended RTFO

The softening point and G* results for extended RTFO are provided in Fig. 10, and the correlation models for G*are presented in Fig. 11 for the following samples:

- 50/70 penetration-grade asphalt binder.
- 50/70 penetration-grade asphalt binder modified with 4 % SBS.
- 70/100 penetration-grade asphalt binder modified with 4 % SBS and 10 % recovered asphalt binder from RA.

Bearing in mind that the standard RTFO time is 85 minutes and considering the limitations resulting from the lack of repetitions, the following conclusions can be drawn from the single sets of results depicted in Fig. 10 and Fig. 11:

- The SBS-modified binders increase in G* over time while simultaneously decreasing in softening point, in line with the findings for recovered STA asphalt binders.

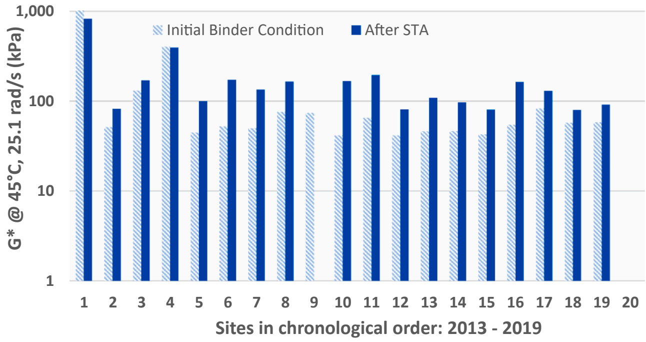


Fig. 9. G* @ 45°C, 25.1 rad/s for recovered binders after construction (STA), with the initial (blended) binder values before construction.

Table 9
Average increase in G* @ 45°C, 25.1 rad/s after STA with the corresponding COV for the data.

Binder and Mix Type	All mixes	*COV*	Mixes Without RA	*COV*	RA mixes only	*COV*
Absolute increase in G* after STA						
50/70: Dense-graded surfacing	74 kPa	*52 %*	67 kPa	*56 %*	107 kPa	N/A*
SBS-modified binder: Dense-graded surfacing	50 kPa	*54 %*	-	-	-	-
Percentage increase in G*after STA						
50/70: Dense-graded surfacing	146 %	*53 %*	139 %	*60 %*	185 %	N/A*
SBS-modified binder: Dense-graded surfacing	73 %	41 %				

*Not applicable as there are only two data points

The independent ageing factors previously discussed and associated with the increase in G* after STA for the asphalt mixes using unmodified asphalt binder are listed in Table 10.

Table 10
Independent factors were evaluated for their effect on the STA of the unmodified asphalt binders.

Site	Binder	Mix	Absolute Increase in G* @ 45°C, 25.1 rad/s (kPa)	% Increase in G* @ 45°C, 25.1 rad/s (kPa)	Mix Temperature (°C)	Season	Time to Paving (hrs)
1	10/20 + 15 %RA	High Modulus Asphalt for base	−193	−19 %	170	Winter	4
3	35/50 + 15 % RA	Dense-graded base	39	29 %	Unknown	Winter	Unknown
5	50/70	Dense-graded surfacing	55	124 %	190	Winter	1.5
6	50/70	Dense-graded surfacing	121	231 %	160	Winter	2.5
7	50/70 +10 % RA	Dense-graded surfacing	85	170 %	160	Summer	2
10	50/70	Dense-graded surfacing	126	305 %	160	Summer	1.5
11	50/70 +20 % RA	Dense-graded surfacing	130	200 %	160	Summer	1.5
12	50/70	Dense-graded surfacing	39	95 %	140	Summer	1.5
13	50/70	Dense-graded surfacing	63	137 %	160	Summer	1.5
14	50/70	Dense-graded surfacing	51	109 %	160	Summer	1.5
15	50/70	Dense-graded surfacing	38	89 %	160	Summer	4.5
16	50/70	Dense-graded surfacing	109	200 %	145	Summer	2
18	50/70	Dense-graded surfacing	22	39 %	175	Summer	2

- Although the two SBS-modified asphalt binders may have different initial binder stiffnesses in terms of G*, their linear rate of increase in terms of change in G* are similar. This endorses the decision to use the absolute linear difference in G* as a parameter for tracking STA instead of using the percentage increase in G* as reported in the literature by some researchers [10].

Table 11
Regression analysis of absolute increase in G* for STA of unmodified asphalt binders.

Model		
Absolute increase in G* = - 1.317 *x* Mix Temperature - 3.702 *x* Season - 10.386 *x* Time to paving + 394.77		
R^2	**Adjusted R^2**	
0.21	- 0.13	
Correlation Matrix		
	Pearson's r	**p-value**
Mix Temperature	−0.230	0.494
Season	−0.147	0.665
Time to paving	−0.217	0.520

Table 12
Regression analysis of percentage increase in G* for STA of unmodified asphalt binders.

Model		
Percentage increase in G* = - 2.415 *x* Mix Temperature - 6.977 *x* Season - 19.88 *x* Time to paving +744.6		
R^2	**Adjusted R^2**	
0.20	- 0.15	
Correlation Matrix		
	Pearson's r	**p-value**
Mix Temperature	−0.214	0.526
Season	−0.150	0.658
Time to paving	−0.217	0.520

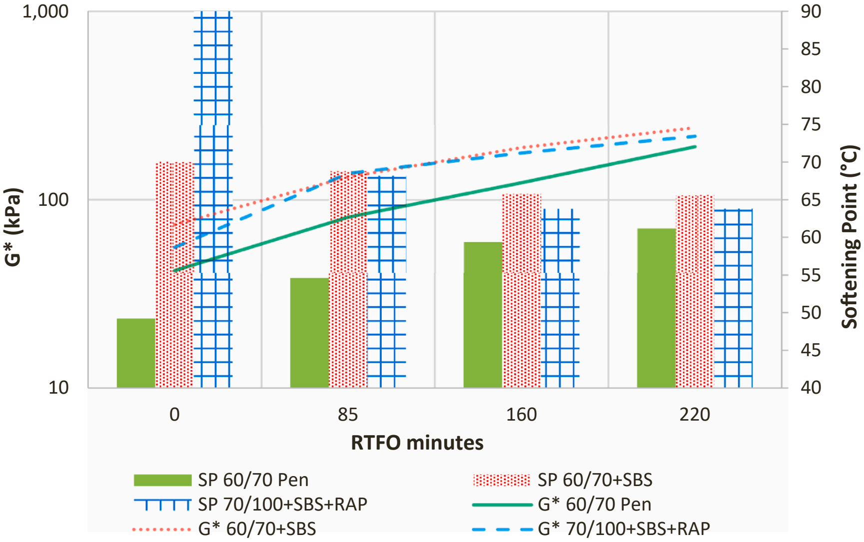


Fig. 10. Extended RTFO ageing.

- The rate of increase in G* for the 50/70 penetration-grade asphalt binder is higher than that achieved for the modified asphalt binders.
- The increase in Softening Point after 85 minutes (Standard RTFO time) for 50/70 penetration-grade asphalt binder is 5.4 °C, a good general representation for STA as indicated in Table 6.
- The increase in G* after 85 minutes for 50/70 penetration-grade asphalt binder is 43 kPa. This is lower than the average increase for STA given in Table 9. However, the large COV exceeding 50 % for this data makes it difficult to form to definitive conclusions. Similarly, the increases in G* after 85 minutes for the 50/70 penetration-grade asphalt binder modified with 4 % SBS and the 70/100 penetration-grade asphalt binder modified with 4 % SBS and 10 % recovered asphalt binder from RA are 58 and 82 kPa, respectively, which are higher than the average increase for STA given in Table 9. Again, no conclusions can be drawn as to whether the conditioning time of the RTFO should be adjusted to align more closely with the results found after STA.

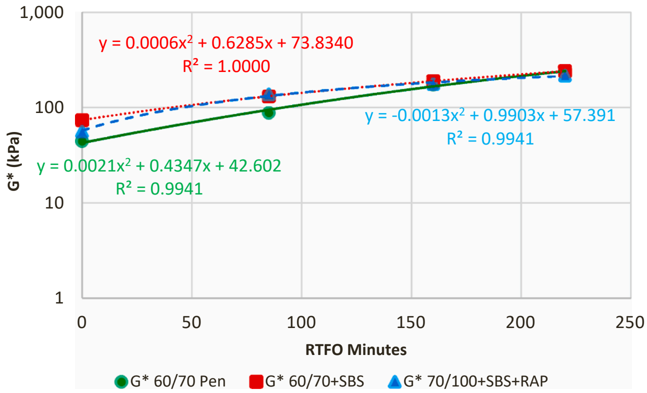


Fig. 11. Extended RTFO ageing.

- There is a strong linear relationship between the value of G* and time in the RTFO. Whether a similar relationship exists in the field remains to be proven.

4. Summary and conclusions

The repeatability of rheological parameters determined for asphalt binders recovered from the road is low, with the COV for the data in Table 9 exceeding 50 %, especially compared to the repeatability for the softening point, which is significantly less. The residual solvent remaining after the recovery process may have a larger effect on rheological properties determined by the DSR than the effect on the softening point. The low repeatability and high uncertainty of the G* results after recovery make it difficult to draw conclusions or establish trends for the rheological data. It is important to discern between the repeatability of G* for standard asphalt binders before mixing with aggregate and the repeatability of G* for the recovered asphalt binders from the asphalt concrete.

For both the softening point and G*, multiple linear regression analyses failed to establish a statistically significant correlation between the extent of STA and such independent factors as the mixing temperature of the asphalt concrete during manufacture, the time taken between mix manufacture and paving, and the season.

The poor repeatability associated with the binder recovery process and the choice of AIP (G*) prevents this binder property from providing guidance for ageing limits during construction. This reinforces the importance of direct asphalt concrete testing as a quality control measure during construction.

An investigation to determine whether the conditioning time of the RTFO should be adjusted to align the RTFO ageing results more closely with those found for STA reveals that:

- The current RTFO conditions gave a good approximation of STA as measured when using the softening point as an AIP.
- Poor repeatability for G* precludes any conclusion regarding changes to the RTFO time for this parameter.
- The presence of RA increases the variability within the results, and it is recommended that ageing studies exclude mixtures containing RA when it is the goal to evaluate ageing mechanisms.

This investigation's final project methodology and site selection differed significantly from the original planning and proposal submitted to the South African National Roads Agency Limited (SANRAL). The main reason for this was a lack of coordination between researchers and contractors/consultants in the field during the planning and proposal stage. It is recommended that future investigations be preceded by the establishing a standard operating procedure (SOP) for site work. Such an SOP should be developed and implemented by all parties involved, including the consultants, contractors and client.

CRediT authorship contribution statement

James Maina: Writing – review & editing, Supervision, Formal analysis. **Wynand J vdM Steyn:** Writing – review & editing, Supervision. **Johan O'Connell:** Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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