Short term ageing of asphalt binder in thin asphalt layers

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Highlights

- From 2001 to 2012, the prevalent surfacing in South Africa was a dense-graded asphalt mix with 50/70-grade asphalt binder.
- Asphalt binders were consistent over 2001 to 2012, originating from four South African refineries.
- A short-term ageing method in the laboratory cannot emulate the reaction kinetics during manufacturing and placement.
- Binder properties such as penetration and softening are affected to different extents in an oxidation / ageing environment.
- The rolling thin film oven provides a good indication of ageing under typical conditions of manufacturing and laying.

Abstract

The effects of ageing on pavement performance are significant, particularly in terms of fatigue cracking. South Africa has the 10th longest road network in the world, requiring innovative approaches to road construction due to severe budget constraints. Innovative solutions such as thin asphalt concrete layers for surfacing, result in unique ageing rates of the layers, which, in general, have a higher incidence of fatigue cracking than, for example, thicker asphalt concrete layers used in other parts of the world. The objective of this paper is to evaluate how ageing mechanisms affect various asphalt binder properties, and whether they affect them to the same extent or not. Furthermore, the objective of the paper is also to determine the accuracy of the Rolling Thin Film Oven Test (RTFOT) in simulating short-term ageing in the field. The RTFOT provides a relatively good indication of short-term ageing, according to this multi-decade ageing study, and the effect on the asphalt binder properties used as ageing indices depends on the specific property chosen for comparison before and after ageing.

Keywords: Asphalt cement; Bitumen; Asphalt binder; Ageing; RTFOT; Field ageing

1. Introduction

1.1. Hot mix asphalt in South Africa

The total length of South Africa's road network is approximately 750,000 km (Fig. 1), and responsibility for the paved network is divided between (National Treasury, 2021):

- SANRAL (the national road agency), who is responsible for 22,197 km of paved roads. More than 80% of these roads are paved with asphalt concrete;

- Provincial road authorities, who are in charge of 222 951 kilometres of paved roads. More than 80% of these roads have a seal or surface dressing as the surfacing; and
- Municipal authorities, who are responsible for an estimated 275,000 km of paved roads.

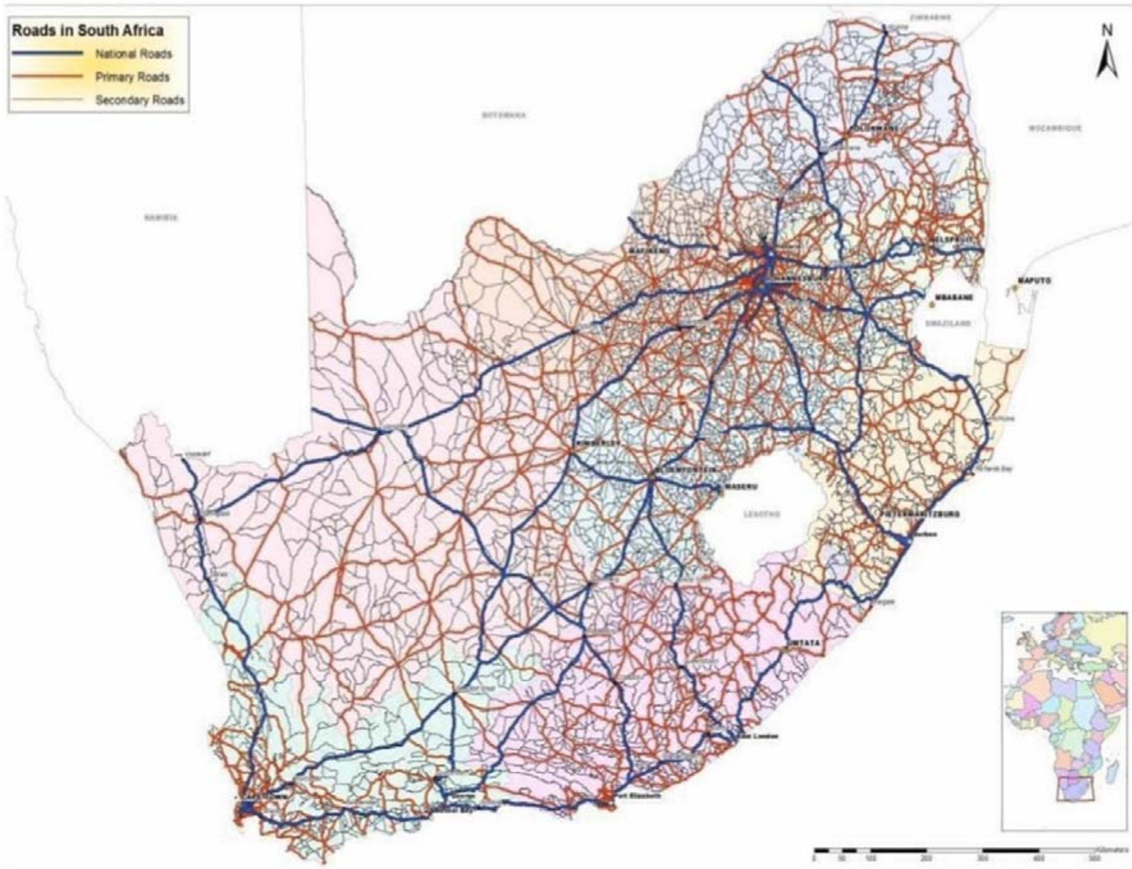

Fig. 1. The South African road network [2].

This represents the largest road network in Africa and the 10th largest in the world (National Treasury, 2021). South Africa is classified as a developing country with budget limitations, requiring innovative approaches to road construction and maintenance. One such innovation was the engineering of thin asphalt concrete layers for surfacing, ranging between 40 mm and 60 mm, compared with international asphalt concrete layers ranging from 80 mm to 120 mm. This implies that asphalt concrete layers in South Africa experience unique conditions regarding load distribution and rate of ageing. Ageing studies of thin asphalt concrete layers have the potential to produce results that are distinct from those obtained for thicker asphalt concrete layers. For example, the main mode of pavement distress in South Africa is cracking, which may be exacerbated by a higher rate of ageing in thinner asphalt concrete layers.

1.2. Durability and ageing

Durability is generally defined as resistance to change during the life of a product. Asphalt concrete is also subjected to change as it undergoes ageing – changes caused by altering the molecular structure of the asphalt cement or binder during oxidative ageing. Such changes can be monitored using both the empirical and fundamental performance properties of the asphalt concrete or asphalt binder. Properties selected to monitor change during ageing are referred to as ageing index properties (AIP's) [9] and the lower the change in the value of an AIP during ageing, the greater the potential durability of the asphalt concrete, under the same conditions of design, construction, and environment.

The stiffness of a road pavement along with its relaxation properties is an important property for input into design and performance prediction models. The stiffness of asphalt concrete layers as part of the pavement structure is affected not only by temperature and traffic speed but also by durability, as the layer ages over time. Generally, the stiffness of asphalt concrete increases with ageing and the relaxation ability decreases, resulting in an increased likelihood of fatigue cracking, as the asphalt loses its strain tolerance [11].

A better understanding of the ageing of asphalt mixes is an important economic consideration in South Africa, where cracking can lead to water ingress into the pavement structure, causing pothole formation, destruction of the granular base, and ultimate collapse of the road structure. The ageing of an asphalt concrete layer occurs during two lifecycle stages, namely Short-Term Ageing (STA) and Long-Term Ageing (LTA). STA represents the ageing that the asphalt cement or binder in an asphalt concrete mix undergoes during manufacturing, storage, transport, and placement on site. LTA refers to ageing that the asphalt cement or binder of an asphalt concrete mix undergoes over the pavement's lifetime. Various researchers have quantified LTA in different ways, depending on the results that they have obtained. Smith et al. [25] quantify LTA as the ageing that an asphalt concrete layer undergoes during a period of 2 to 6.5 years, depending on the depth of the surfacing layer, whereas Qian et al. [23] quantify LTA as less than 4 years.

Previously, ageing studies have been conducted without differentiating between STA and LTA [10], thereby correlating the overall ageing in the field with the original binder properties. STA occurs at higher temperatures, resulting in a more intense rate of ageing compared to LTA. During STA, the asphaltene content of the Asphalt binder can typically increase by 1 to 4 m/m% [13], with an accompanying doubling of the binder viscosity. Some results obtained in South Africa are presented in Table 1.

Table 1. Increases in asphaltene content after RTFOT or STA recorded in South Africa [16], [17], [26].

Sample	RTFOT	STA
50/70 penetration-grade asphalt Cement	2.4 – 3.1 m/m %*	4.4 – 5.3 m/m %**
35/50 penetration-grade asphalt Cement	2.5 m/m %	-
20/30 penetration-grade asphalt Cement	2.9 m/m %	-

* Based on 6 samples
** Based on 3 samples

In South Africa, it is recognized that STA plays a key role in establishing ageing models, and the effects of STA may vary due to factors such as delayed paving or mix temperature variations. This paper relates to an STA study that was conducted in South Africa, evaluating data generated over the last 20 years. The ageing study was conducted in two stages, with each stage focusing on a particular time, namely:

- A period before the introduction of performance testing in South Africa (2001-2012), whereby AIPs were represented by empirical tests such as penetration (Pen), softening point (SP), and penetration index (PI); and
- A period after the introduction of performance-related testing in South Africa, whereby AIP's included Dynamic Shear Rheometer (DSR) data in addition to data provided by empirical testing (2013 to 2019).

This paper focuses on the first period, 2001 to 2012, analyzing absolute values without differentiating between mix temperatures and paving times. The objective of this paper is to evaluate the results from the study to determine how the ageing mechanisms affect different asphalt binder properties when considered as AIPs, and whether different properties change to the same extent or not. Furthermore, the objective of the paper is also to determine the accuracy and relevance of the rolling thin film oven test (RTFOT) in simulating STA.

1.3. Ageing mechanisms

During STA, the asphalt binder can undergo any of the following processes [19]:

- Volatilization: lower molecular mass may dissipate through evaporation (volatilization), a high temperature process;
- Oxidation: incorporation of oxygen into the molecular structure of the asphalt binder;
- External (or internal) oxidative coupling: joining of two different molecules (or two areas within the same molecule) to form a larger heavier (or more rigid) structure;
- Molecular association between asphaltene molecules, aided by complexation or polar bonding, can lead to an apparent increase in molecular weight which will also increase the rigidity of the molecular structure (and an increase in viscosity); and/or
- Exudation: migration of component oils in the maltene phase of the asphalt binder, either into pores/voids in the aggregate or adsorbed at the aggregate surface, resulting in a stiffer asphalt binder.

General factors that may affect the rate and extent of STA include [19]:

- Chemical composition and physical properties of the asphalt binder;
- The temperature of the mix;
- The lapse of time between manufacturing and laying of the asphalt concrete mix;
- Film thickness of the asphalt binder in the mix;
- Presence of antioxidants, or modifiers;
- Aggregate, which may promote exudation or contain oxidation catalysts; and
- Partial pressure of oxygen, which is affected by the altitude.

2. Material and methods

2.1. Samples

Samples were obtained from newly constructed asphalt concrete wearing courses in South Africa on an ad-hoc basis, on behalf of consultants or contractors performing quality control (30 sites); as well as two road sites, which were part of a limited controlled ageing study undertaken by the Council for Scientific and Industrial Research (CSIR). The wearing courses from Sites 1 to 32 consisted of two types:

- A medium continuously graded (dense-graded) mix, which is characterized by relatively low binder film thickness, and
- A Stone Mastic Asphalt (SMA) (gap-graded) mix, which is formulated to be rut resistant by selecting a grading which promotes stone-on-stone contact. SMA is characterized by a relatively high asphalt binder content and high binder film thickness compared to medium continuously graded mixes.

The term 'medium' in South Africa refers to a maximum aggregate particle size of 13.2 mm. All wearing courses were constructed using 50/70 penetration-grade asphalt cement or binder, typically used during that period (2001 to 2012).

A feature of the asphalt concrete industry during that period was that the asphalt binder was very consistent with predictable properties depending on the refinery of origin. South Africa was still a young democracy recovering from a period of international sanctions. Asphalt binder was rarely imported but was mostly produced in four crude oil refineries at the time located within South Africa as shown in Fig. 2. The crude slate feed to the refineries was largely based on Middle Eastern (including Iranian) crude, a situation resulting from a time of crude oil sanctions against the Apartheid government.

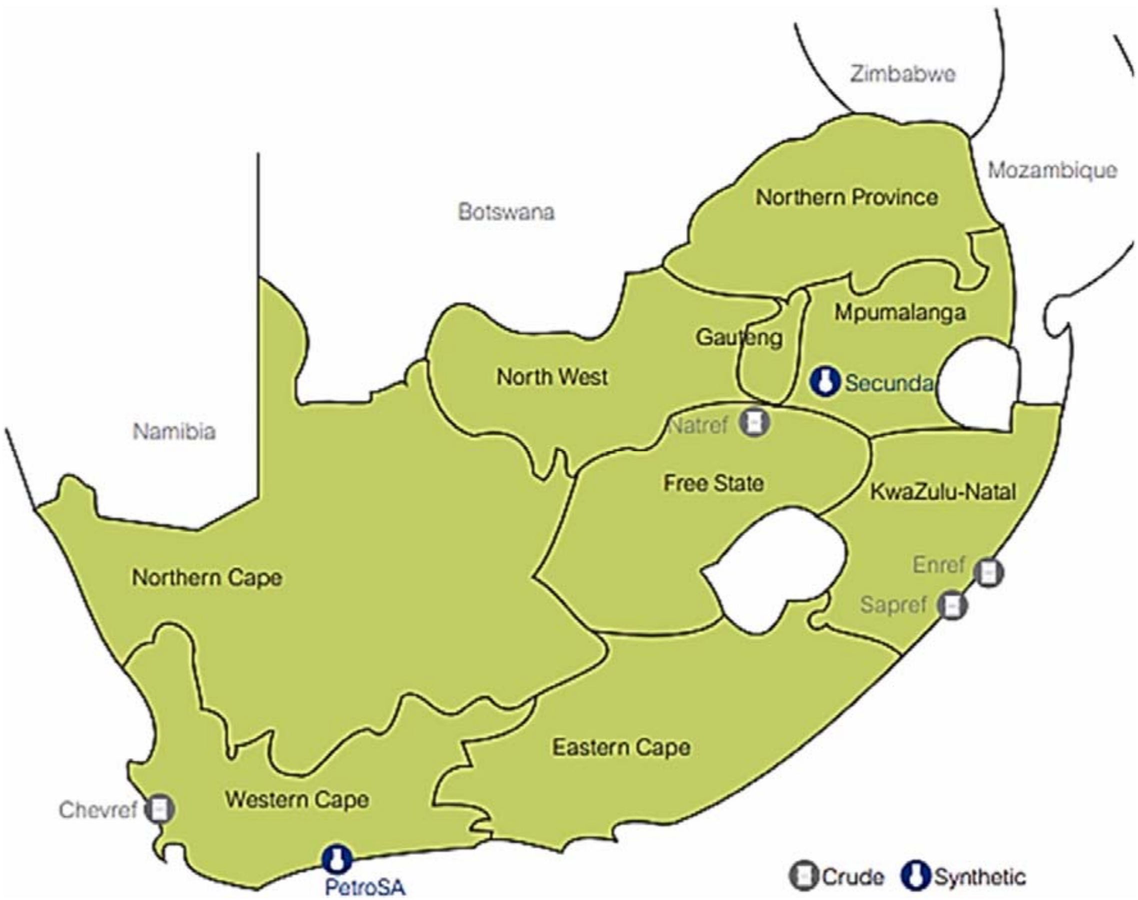

Fig. 2. The four crude oil refineries in South Africa [24].

2.2. Methods

The test methods employed in generating the data for this paper are listed in Table 2.

Table 2. Test methods employed in the laboratory.

Property / Procedure	Method
Softening point (SP)	[6] ASTM D36-9
Penetration (Pen)	ASTM D5-97 [7]
Rolling thin film oven test (RTFOT) – simulation of STA in the field	ASTM D2872 - 04 [5]
Recovery of in-situ asphalt binder from the field	ASTM D1856 - 95 [4]

The recovery of in-situ asphalt binder binder using ASTM D1856, is also known as the Abson method of recovery. It is of fundamental importance that binder recovery process is performed in such a way that the recovered binder properties reflect those of the in-situ binder, or the experimental work will result in compromised results, which would lead to 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 [18].
The technical performance of the Abson recovery can be affected by:

- The type and age of the binder;
- The type of aggregate; and
- The type of solvent used for the recovery process.

The recovery process can result in hardening of the binder, depending on the solvent type, recovery temperatures, duration of the recovery process, exposure to light, and the use of an inert gas [18]. To evaluate the technical performance of the recovery process, the binder was recovered from a standard asphalt concrete sample, which had been specifically manufactured at low temperatures to prevent ageing, using a 15% ethanol in toluene solution as recovery solvent. The standard asphalt concrete sample contained a 50/70 penetration-grade asphalt cement with known properties, which were then compared to the recovered binder properties. By validating the recovery method in this manner, small adjustments can be made to the recovery process parameters (temperature, time), if necessary, to ensure that the recovered field sample properties reflect those of the in-situ binders.

Further quality control measures include:

- Minimizing the time between sampling and binder recovery;
- Storage of samples prior to the recovery process in a sample room at 15 °C to prevent further ageing;
- Gas chromatographic analyses on recovered samples to ensure that no excessive solvent remains in the recovered binder after recovery; and
- Ash content analyses on recovered samples to ensure that fine aggregate material is kept to a minimum in the recovered binder.

Anomaly detection is an important process by which outliers (data far removed from most other data) are identified and removed. Generally, outliers indicate problematic data that do not represent typical outcomes and may skew an analysis of the data. There are various methods by which to detect outliers, and they can broadly be divided into parametric and non-parametric methods [8]. This paper uses the inter-quartile range method for anomaly detection, which is a statistical parametric method. The interquartile range method defines outlier values as those that exceed one and half times the interquartile range beyond the interquartile values [8].

3. Results

3.1. Analysis of penetration as AIP

Fig. 3 illustrates the penetration results obtained from binder recovered from asphalt concrete from thirty-two sites, with the original asphalt binder results (subscript "o"), where available.

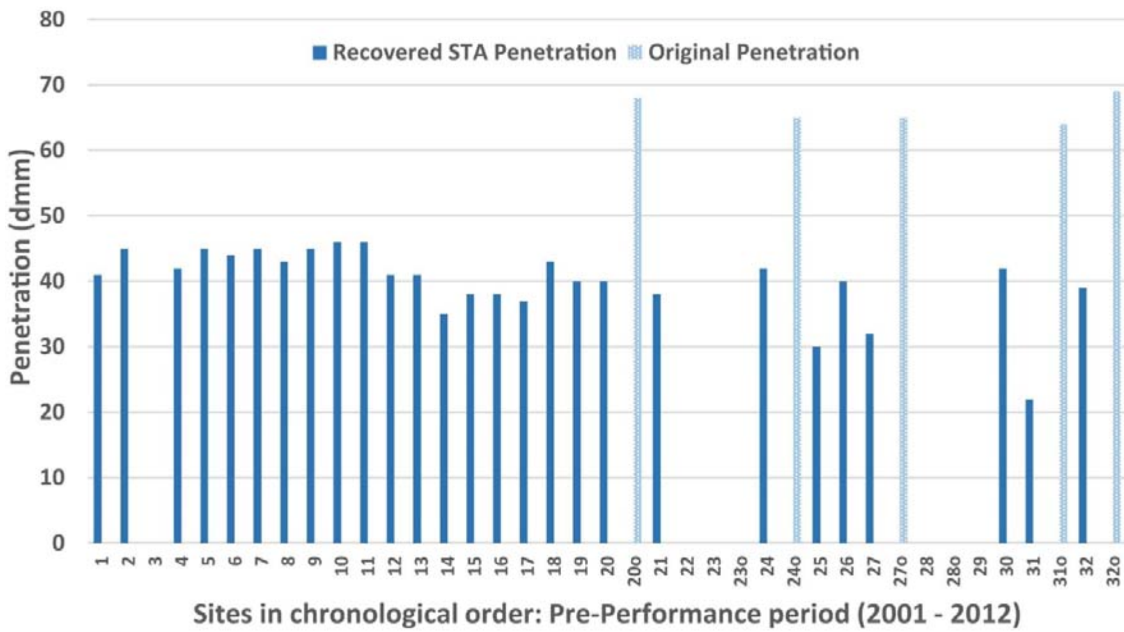

Fig. 3. Penetration values for STA recovered binders after construction with original asphalt binder where available.

Table 3 shows that there is one outlier value present within the data, namely the values for Site 31, which gave an STA penetration value of 22. Further analyses are performed with this outlier removed.

Table 3. Evaluation of the STA penetration data for outliers.

Statistical Parameter	Value
Mean	40.0
Median	41
1st Quartile	38.0
3rd Quartile	43.5
Interquartile Range	5.5
Lower outlier limit	29.75
Upper outlier limit	51.75
Number of data points affected	One point: 22

A histogram of the STA penetration data presented in Fig. 4 gives the sample mean value $(\bar{x})$ for recovered penetration values as 40.7 and the sample standard deviation (s) as 4.0.

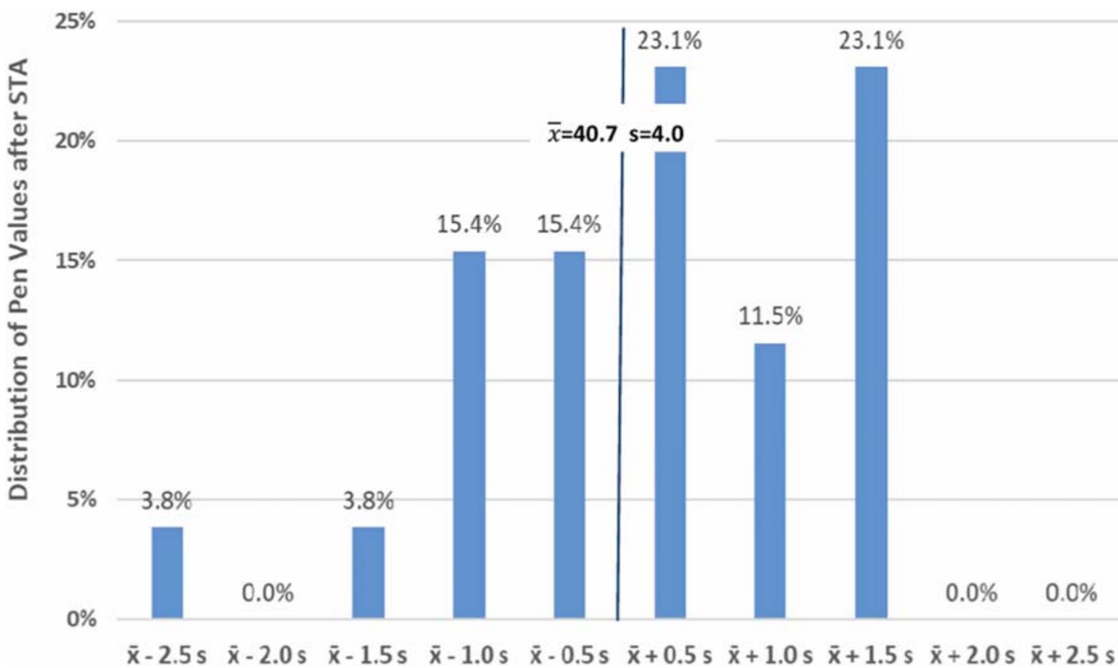

Fig. 4. Histogram representing penetration values after STA recovery.

The histogram does not represent a normal distribution and the mean is affected by lower values which arise where deviation from the norm is represented by lower (harder) values whenever delays in transport or construction result in increased ageing. Under normal conditions, a lower degree of ageing is unusual unless higher penetration values are obtained by using a softer asphalt binder than contractually specified.

This analysis is limited because factors influencing ageing, such as binder film thickness, manufacturing temperature, and time between manufacturing and paving, are unknown, and their effects on the STA recovered results could not be assessed. Significant differences in binder film thickness due to mix-type differences are analyzed further on. Another shortcoming in this initial evaluation is that the original asphalt binders used during the construction contract were available for analysis for only 5 of the 32 sites evaluated in this section. The results are presented in Table 4.

Table 4. Comparing the properties of STA recovered binder with that of the original asphalt binder.

Parameter	Site 20	Site 24	Site 27	Site 31	Site 32
Original asphalt binder					
Penetration of original asphalt binder (dmm)	68	65	65	64	69
Penetration after rolling thin film oven (RTFO) (dmm)	43	42	45	44	45
Retained penetration after RTFO (%)	63	65	69	69	65
Average retained penetration after RTFO (%)	66				
Specification requirement according to the South African Bureau of Standards, SANS 4001-BT1 4001-BT1 (%)	55 min				
Absolute decrease in penetration (dmm)	25	23	20	20	24
Average absolute decrease in penetration (dmm)	22				
Recovered binder					
Penetration of Recovered Binder (dmm)	40	42	32	22*	39
Retained penetration after recovery (%)	59	65	49	34*	57
Average retained penetration after recovery (%)	58				
Absolute decrease in penetration (dmm)	28	23	33	40*	30
Average absolute decrease in penetration (dmm)	29				

* Rejected as an outlier

Although the results in Table 3 only represent a limited number of samples, analyses of asphalt binder samples from 2001 to 2012 are relatively consistent and vary only within a small range [27]. Table 5 and Fig. 5 provide a statistical summary of results obtained on original asphalt binder samples for the period 2001 to 2012, some of which are not associated with the recovered STA binders. This was presented to achieve a more statistically valid representation of binders used during that time.

Table 5. Typical analysis of asphalt binder produced in South Africa (2001 – 2012) compared to recovered binders.

Parameter	Average	Standard Deviation	Coefficient of variation	Specification as per SANS 4001-BT1
Original asphalt binder samples				
No. of samples	12			
Penetration (dmm)	64.6	3.0	4.6%	50 – 70
Penetration after rolling thin film oven (RTFO) (dmm)	43.8	3.0	6.8%	
Retained penetration after RTFO (%)	68			≥ 55
Recovered STA binder samples				
No. of samples	26			
Penetration on recovered binder from site after STA (dmm)	40.7	4.0	9.8%	

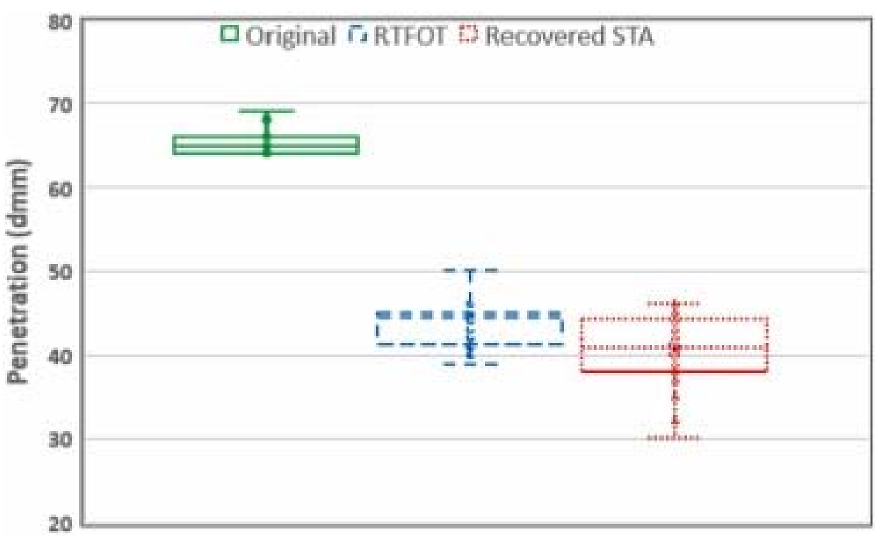

Fig. 5. Box and Whisker Plot of the Original vs RTFOT vs STA penetration values.

The average penetration value after RTFO is higher than that obtained for the recovered binder after STA. The coefficient of variation for the penetration of the asphalt binder after RTFO is higher than that of the original asphalt binder. This is to be expected as there is increased variation introduced by the RTFOT. Similarly, the coefficient of variation for the penetration of the recovered binder after STA is higher than that of the asphalt binder after RTFO due to an increase in variation resulting from the binder recovery process as well as the increased variation in factors such as variation in manufacturing temperature, variation in time to construction, variation in film thickness, and variation in altitude.

At first glance, the difference between the average penetration value after RTFO and that for the recovered binder after STA appears to be insignificant. However, the significance of this difference can be evaluated using the Mann-Whitney U test for independent samples with a non-normal distribution. The Mann-Whitney U test, also known as the Wilcoxon rank-sum test, is a non-parametric test that compares two sets of non-normal samples and evaluates the difference between the two sets of samples using a ranking methodology [15].

The results of the Mann-Whitney U test are summarized in Table 6. The evaluation indicates that the RTFO and STA results differ significantly from each other at the 95% confidence level, but not at the 98% confidence level. A significant difference between the RTFO and STA values is illuminated when evaluating the lowest two individual penetration values for the STA values, namely a penetration value of 30 for Site 25 and *32* for Site 27, which are significantly harder than the values predicted by the average RTFO residue. Although Road 25 reported no premature failures, Site 27 exhibited an early onset of raveling and disintegration of the asphalt concrete mix. Granted, such a perfunctory analysis of penetration values cannot form the basis of a causal relationship between penetration and distress, but such low values can be used to alert the practitioner to the potential of age-related distress such as premature cracking and/or raveling.

Table 6. The Mann-Whitney evaluation of the RTFO and STA penetration values.

RTFO		STA			RTFO		STA		
Penetration Values					Ranking				
44	42	41	46	40	25.5	19.5	15.5	36	11.5
45	45	45	41	38	30.5	30.5	30.5	15.5	6
39	40	42	41	42	8.5	11.5	19.5	15.5	19.5
46		45	35	30	36		30.5	3	1
45		44	38	40	30.5		25.5	6	11.5
45		45	38	32	30.5		30.5	6	2
50		43	37	42	38		23	4	19.5
43		45	43	39	23		30.5	23	8.5
41		46	40		15.5		36	11.5	
Count					Rank Sum				
RTFO		STA			RTFO		STA		
12		26			299.5		441.5		
U		90.5							
U_{crit} @α=0.02		82	98% certainty for rejection of the null hypothesis not attained						
U_{crit} @α=0.05		93	95% certainty that the null hypothesis can be rejected						

The Mann-Whitney evaluation indicates that the following statement is 95% certain, but not 98% certain - *The RTFOT, as an accelerated ageing method, cannot simulate STA when using penetration as an AIP*.

The wearing courses from Sites 1 to 32 are representative of two types of mixes: dense-graded mix and stone mastic asphalt (SMA), which in general has a significantly higher binder content from a design point of view [3]. Fig. 6 illustrates the penetration results obtained for the two types of designs. An analysis of the results is given in Table 7, where the values for penetration of the recovered STA binder from the dense-graded mixes are compared to the values obtained from the SMA mixes.

Fig. 6. Recovered STA penetration results for Dense-graded vs SMA wearing courses.

Table 7. Recovered STA penetration results for Dense-graded vs SMA wearing courses.

Parameter	Dense-graded	SMA
No. of samples	19	7
	2.4	
Average penetration for recovered STA binder (dmm)	39.4	43.9
Standard Deviation	4.0	2.0
Coefficient of variation (%)	10.2	4.6

The average penetration value for the SMA asphalt concrete mixes is higher than that obtained for the dense-graded mixes, indicating that SMA mixes might be undergoing less ageing. This decreased rate of STA ageing is most probably associated with the higher binder film thickness obtained for SMA mixes.

The significance of this difference is evaluated using the Mann-Whitney test for independent samples, the results of which are summarized in Table 8. The evaluation indicates that the Dense-graded and SMA results differ significantly from each other at the 98% confidence level, indicating that it is statistically probable that the binder film thickness influenced the STA.

Table 8. The Mann-Whitney evaluation of the recovered STA penetration values for dense-graded vs SMA mixes.

SMA	Dense-graded			SMA	Dense-graded		
Penetration Values				Ranking			
45	41	43	36	22.5	13	18.5	4
43	45	40		18.5	22.5	10	
45	42	40		22.5	16	10	
46	45	38		25.5	22.5	7	
46	44	42		25.5	20	16	
41	35	30		13	3	1	
41	38	40		13	7	10	
	38	32			7	2	
	37	42			5	16	
Count				Rank Sum			
RTFO		STA		RTFO		STA	
7		19		140.5		210.5	
U		20.5					
U_{crit} @α=0.02		26	98% certainty that the null hypothesis can be rejected				
U_{crit} @α=0.05		32	95% certainty that the null hypothesis can be rejected				

3.2. Analysis of softening point as AIP

Fig. 7 represents the softening point results obtained from binder recovered from asphalt concrete from Sites 1 to 32, with original asphalt binder results (subscript "o"), where available.

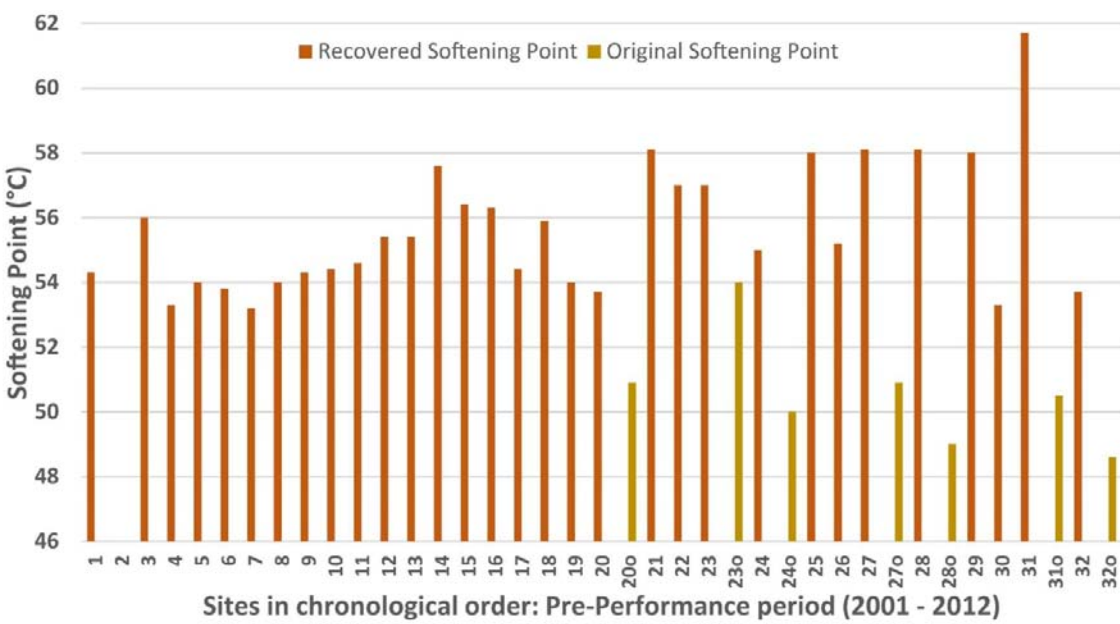

Fig. 7. Softening point values for recovered binders after construction with original asphalt binder where available.

Table 9 shows one outlier value in the data, namely the values for Site 31, which gave an STA softening point value of 61.7. Further analyses are performed with this outlier removed.

Table 9. Evaluation of the STA softening point data for outliers.

Statistical Parameter	Value
Mean	55.6
Median	55.2
1st Quartile	54.0
3rd Quartile	57.0
Interquartile Range	3.0
Lower outlier limit	49.5
Upper outlier limit	61.5
Number of data points affected	One point: 61.7

A histogram of the STA softening point data presented in Fig. 8 gives the mean sample value ($\overline{x}$) for recovered penetration values as 55.4 and the standard sample deviation (s) as 1.6.

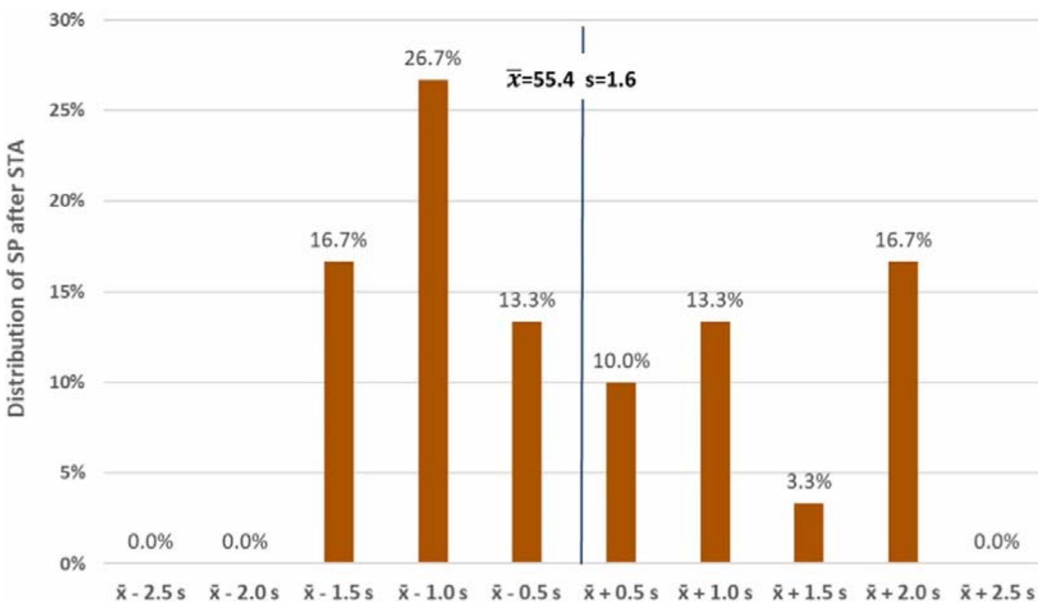

Fig. 8. Histogram of STA recovered softening point values.

The histogram does not represent a normal distribution, and like the distribution of penetration values after STA, the mean is affected by higher values whenever delays in transport or construction result in increased ageing. Very low values are unusual under normal circumstances unless lower softening point values are obtained by using a softer asphalt binder than contractually specified.
The original asphalt binders used during construction were available for analysis for 7 of the 32 sites evaluated in this section. The results are presented in Table 10.

Table 10. Correlating STA Recovered and Original asphalt binder samples.

Parameter	Site 20	Site 23	Site 24	Site 27	Site 28	Site 31	Site 32
Original asphalt binder							
Softening point (°C)	50.9	54.0	50.0	50.9	49.0	50.5	48.6
Softening point after RTFOT (°C)	56.0	60.0	55.0	54.2	55.7	54.1	53.7
Softening point increase after RTFO (°C)	5.1	6.0	5.0	3.3	6.7	3.6	5.1
Specification requirement according to the SANS 4001-BT1	7 °C max						
Recovered binder							
Softening point after STA (°C)	53.7	57.0	55.0	58.1	58.1	61.7*	53.7
Softening point increase (°C)	2.8	3.0	5.0	7.2	9.0	11.2*	5.1

* Rejected as an outlier

Like the penetration analyses, softening points of the original asphalt binder samples vary within a relatively narrow range. The analysis of softening point results for the original asphalt binder samples from this period are given in Table 11 and Fig. 9 compared with the values obtained on binders recovered after STA.

Table 11. Typical Analysis of Asphalt binder produced in South Africa (2001 – 2012).

Parameter	Average	Standard Deviation	Coefficient of variation	Specification as per SANS 4001-BT1
Original asphalt binder				
No. of samples	13 2.4			
Softening point (°C)	50.5	1.4	2.7%	46 - 56
Softening point after RTFOT (°C)	55.1	1.7	3.1%	48 min
Softening point increase after RTFO (°C)	5.4			7 max
Recovered binder				
No. of samples	30			
Softening point after STA (°C)	55.4	1.6	3.0%	

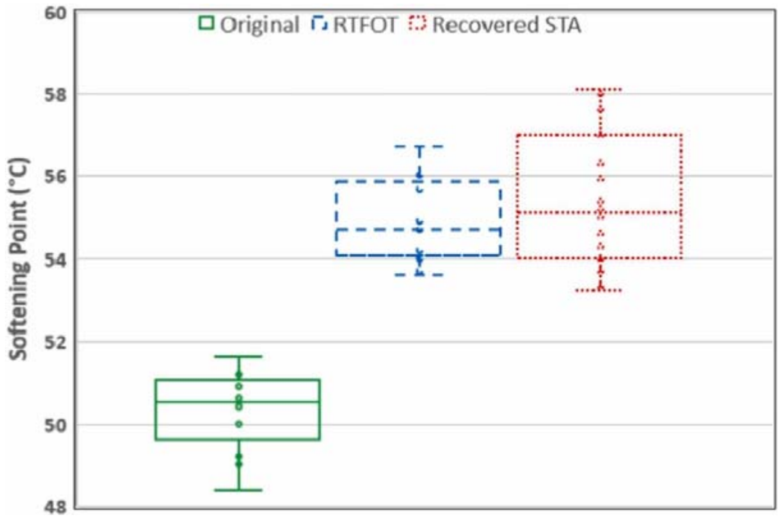

Fig. 9. Box and Whisker Plot of the Original vs RTFOT vs STA softening point values.

Unlike the findings for the average penetration values after RTFOT and STA, the average softening point value after RTFO is closely related to the values obtained for the recovered binder after STA. The coefficients of variation for the softening points are lower than those obtained for the penetration data. This is a direct consequence of the unit used to measure the property (degree Celsius as opposed to degrees Kelvin), as well as the fact that the percentage increase in value after ageing (whether after RTFO or STA) is significantly lower for softening point than for penetration.

Also, unlike for the penetration data, the coefficient of variation values for the softening point data, are similar irrespective of whether obtained for the original, RTFOT or STA data. This could imply that softening point, as an empirical property, is less variable than penetration and less sensitive to processes like ageing and the binder recovery process which allows for the retention of small, but variable amounts of solvent in the recovered binder.

To evaluate the significance of the differences between the softening point data obtained after RTFOT and STA, the data is subjected to the Mann-Whitney test for independent samples, summarized in Table 12. The evaluation indicates that the RTFO and STA results are not significantly different, and the null hypothesis cannot be rejected at the 90%, 95%, or 98% confidence levels.

The Mann-Whitney evaluation indicates that the following statement cannot be rejected with 90%, 95% or 98% certainty: *The RTFOT, as an accelerated ageing method, accurately simulates the STA in terms of softening points as an AIP*. We can conclude that RTFOT simulates softening point increase for STA to a better extent than penetration decrease. This is an important indicator that accelerated ageing methods can affect different AIPs differently compared to field ageing. This is to be expected considering that the two ageing processes, RTFOT and STA in the field, involve different chemical oxidation mechanisms [20]. Laboratory simulation of STA does not emulate differing mix temperatures, varying film thicknesses, UV radiation and mineral catalysts found in the field. Simulated ageing can, therefore, never be an 'exact science' and will affect various AIPs differently.

Table 12. The Mann-Whitney evaluation of the RTFO and STA softening point values.

RTFO		STA				RTFO		STA			
Softening Point Values						Ranking					
54.3	55.7	58.1	56.3	54.4	53.3	16	28	41	32	18.5	2.5
53.6	54.1	58.1	56	54.3	53.3	4	13	41	30.5	16	2.5
56.7	53.7	58.1	55.9	54.3	53.2	34	6	41	29	16	1
54.9	54.7	58	55.4	54		22	21	38.5	26.5	10.5	
56		58	55.4	54		30.5		38.5	26.5	10.5	
54		57.6	55.2	54		10.5		37	25	10.5	
60		57	55	53.8		43		35.5	23.5	8	
55		57	54.6	53.7		23.5		35.5	20	6	
54.2		56.4	54.4	53.7		14		33	18.5	6	
Count						Rank Sum					
RTFO		STA				RTFO		STA			
13		30				265.5		680.5			
U		174.5									
U_{crit} @α=0.02		107		98% certainty for rejection of null hypothesis not attained							
U_{crit} @α=0.05		120		95% certainty for rejection of null hypothesis not attained							

As with the penetration results, the recovered STA softening point values are evaluated in terms of the two mixes used at the 32 sites under investigation, namely the medium continuous grading (dense-graded) and the SMA mixes. Fig. 10 presents the softening point results obtained for the two types of mixes.

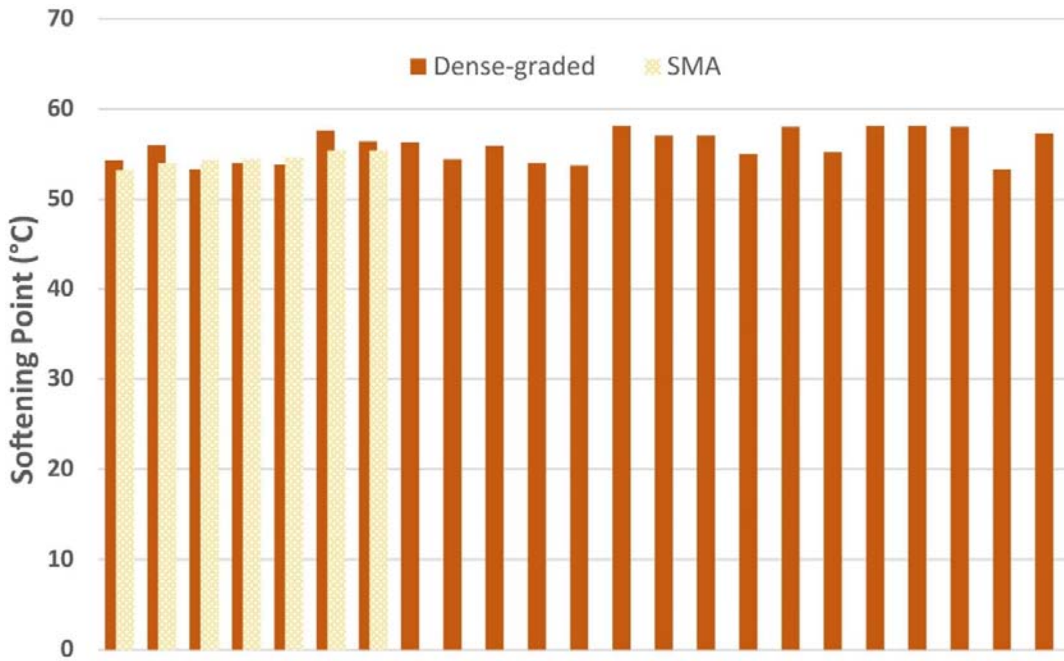

Fig. 10. Recovered STA penetration results for Dense-graded vs SMA wearing courses.

A summary of the results is given in Table 13, where the values for softening point of the recovered STA binder from the dense-graded mixes are compared with those values obtained from the SMA mixes.

Table 13. Recovered STA softening point results for Dense-graded vs SMA wearing courses.

Parameter	Dense-graded	SMA
No. of samples	23	7
	2.4	
Average softening point for recovered STA binder (°C)	55.9	54.5
Standard Deviation	1.7	0.7
Coefficient of variation (%)	3.1	1.3

Similarly, to the penetration value findings, the recovered binder for the SMA asphalt concrete mixes is softer on average than that obtained for the dense-graded mixes, indicating that the SMA mixes may be undergoing less ageing. If confirmed, as in the penetration study, the higher binder film thickness may result in a slower rate of STA ageing.

The significance of the differences between the two mixes is evaluated using the Mann-Whitney test for independent samples, the results of which are summarized in Table 14. Unlike for the penetration results, the evaluation indicates that the null hypothesis cannot be rejected

Table 14. The Mann-Whitney evaluation of the recovered STA softening point values for dense-graded and SMA mixes.

SMA	Dense-graded						SMA	Dense-graded			
Softening Point Values							**Ranking**				
53.2	54.3		55.9			58.1	1	9.5		18	29
54	56		54			58.1	7	19		7	29
54.3	53.3		53.7			58	9.5	2.5		4	26.5
54.4	54		58.1			53.3	11.5	7		29	2.5
54.6	53.8		57			57.3	13	5		22.5	24
55.4	57.6		57				16.5	25		22.5	
55.4	56.4		55				16.5	21		14	
	56.3		58					20		26.5	
	54.4		55.2					11.5		15	
Count							Rank Sum				
RTFO				STA			RTFO		STA		
7				23			75		390		
U		47									
U_{crit} @α=0.02		33			98% certainty for rejection of null hypothesis not attained						
U_{crit} @α=0.05		40			95% certainty for rejection of null hypothesis not attained						
U_{crit} @α=0.20		53			80% certainty that the null hypothesis can be rejected						

for the Dense-graded and SMA results at the 95% to 98% confidence level. The null hypothesis can only be rejected at lower probabilities such as 80%. The implications of this are as follows:

- Film thickness did not have a significant effect on ageing using softening point as an AIP;
- Changes in softening point are a less sensitive indicator of ageing compared to penetration values, especially when trying to differentiate ageing with regards to factors such as film thickness, and
- If the relationship between penetration and softening point as AIP's differ from RTFOT to STA, then the behaviour of penetration index as an API is expected to differ from RTFOT to STA.

3.3. Analysis of penetration index as an AIP

Penetration index (PI) as developed by Pfeiffer and Van Doormal [22], is a measure of the temperature susceptibility of the asphalt binder used in asphalt mixes. PI can be calculated using SP and Pen as shown in Eq. 1.(1)
A temperature-susceptible asphalt binder displays a relatively high decrease in viscosity or stiffness with increasing temperature as illustrated in Fig. 11. PI has historically been a feature of specifications for asphalt binder in Europe with a PI range of − 1.5 to 0.7 being preferred. A lower PI or higher temperature susceptibility (Asphalt binder A) can lead to deformation problems at high temperatures or cracking at low temperatures [12], [14].

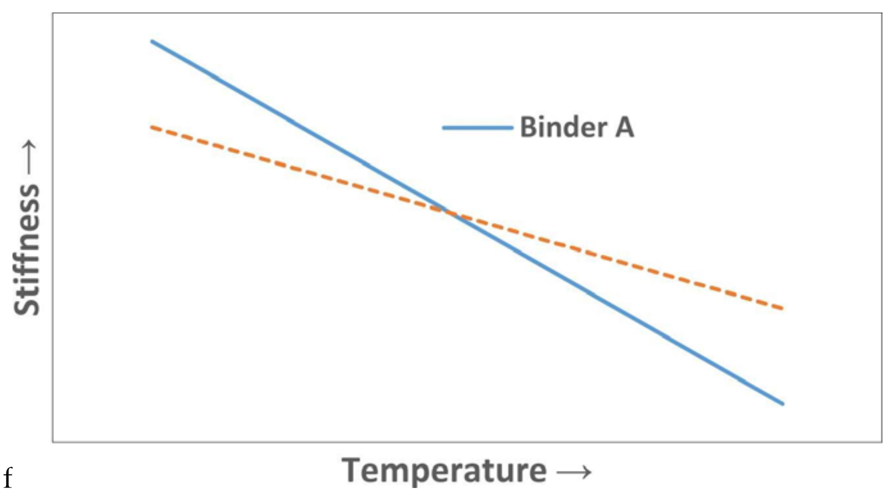

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Fig. 11. Temperature susceptibility of asphalt binder.

The average PI values for asphalt binder are given in Table 15.

Table 15. Average PI values for asphalt binder used for 2001 to 2012.

Binder	PI
Original asphalt binder	- 0.46
After RTFOT ageing	- 0.31
After STA (In-situ)	- 0.41

The PI results indicate:

- Ageing of the asphalt binder leads to a small improvement in temperature susceptibility, with the RTFOT ageing resulting in a bigger improvement in PI;
- RTFOT ageing mechanisms are not identical to the ageing mechanisms found during STA. softening point is affected to a different extent than penetration, resulting in a different PI for the RTFOT simulation compared to STA in the field, and
- Asphalt binder performance predicted by RTFOT simulation may be different to the actual performance after STA. However, the extent of this difference in prediction of performance using simulated ageing is not known at this stage.

4. Summary and conclusions

The results for penetration and softening point obtained after STA do not present a normal distribution, considering that delays during construction can only skew the result in one direction (i.e., harder), with no mechanism existing for a similar distribution of results in the other direction (i.e., softer). This precluded the use of the student's t-test as a tool for statistical analysis of the data, and the Mann-Whitney test was used instead.

Except for film thickness, the effect of other factors such as temperature and time were not known for this analysis. An analysis of the effect of film thickness indicates that film thickness affects ageing when considering changes in penetration, whereas this statement is less certain when considering changes in softening point.

The PI increases after ageing in line with expectations.

All accelerated ageing methods are based on simulations which strive to yield residues which would have properties similar to the corresponding in-situ binders after STA. However, the reaction mechanism occurring during laboratory tests to simulate STA ageing differs from that occurring during manufacture, due to various factors including:

- Varying film thickness, leading to varying concentrations of oxygen;
- Temperature differences;
- Presence of UV radiation, and
- The presence of mineral catalysts in the aggregate.

Many STA simulation methods exist internationally, including [1]:

- Thin-Film Accelerated Ageing Test (TFAAT) method [21];
- Rotating Flask Test (DIN 52016);
- Thin Film Oven Test Method (TFOT) (ASTM D1754); and
- RTFOT (ASTM D2872).

The results obtained from the RTFOT method indicate that the reaction kinetics in the laboratory differs from that during STA in the field, which is understandable, considering the different oxidative conditions maintained in the laboratory, compared to the field. The softening points of the asphalt binder after simulated ageing are more strongly associated with the results obtained from the field after STA than the penetration results are aligned with the field values.

CRediT authorship contribution statement

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

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Johan O'Connell reports financial support was provided by South African National Roads Agency (SANRAL) and the Council for Scientific and Industrial Research (CSIR). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

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