

APPENDIX K

Technical Memorandum

Updating Bituminous Stabilized Materials Guidelines: Mix Design Report, Phase II

Task 11: Durability: Ageing of bituminous binder

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EXECUTIVE SUMMARY

The short and long term ageing potential of binders in BSM-foam and BSM-emulsion have been investigated. It is apparent from the study that some short-term age hardening of foamed bitumen during mixing occurs. The time that bitumen is kept in circulation in the laboratory plant at elevated temperature before making BSM-foam, contributes to the ageing of binder, especially after (8 hours). However, the trend follows that of the age hardening of the base bitumen. The foaming process itself, however, does not appear to alter the bitumen properties. The effects of ageing are more notable for softer bitumen (80/100) than hard bitumen (60/70) with 30% drop of penetration for soft bitumen and 12-17% of the hard bitumen. For the bitumen emulsion, negligible age hardening occurs in short term because no elevated temperature is used in the mixing process.

The study has also shown that bitumen from different sources age at different rates. This is consistent with other studies, as the compositional balance and chemistry of the binders varies even if they comply with same classification requirements. The rheological properties of the BSM-foam and BSM-emulsion from extracted and recovered bitumen, show significant ageing on both compacted and cured specimens and field cores. The drop of penetration to an average of 24-45dmm of compacted mixes, 10-20dmm for the trafficked section, and 30-50dmm for untrafficked section raises concern regarding the total separation of filler with bitumen during extraction processes. The high percentage of super filler in the BSMs seemed to result in mastic being present in the recovered bitumen, hence high stiffness values. Further results show an increase in viscosity at 60°C (in-service) resulting in a mix stiffness that resists flow during in-service trafficking. However, no clear trend in age hardening for foamed bitumen mix and bitumen emulsion was observed i.e. significant variability in results is prevalent. Ageing behaviour does differ, however, for the foamed bitumen and bitumen emulsion, with the foamed bitumen having higher age hardening potential.

This ageing behaviour that occurred with both foamed bitumen and bitumen emulsion, during short-term and long-term has proven to be sufficient to warrant further research i.e. to investigate the impact of the ageing on mix performance. At the same time, the extraction and recovery processes of BSMs need further investigation.

1. INTRODUCTION

1.1. Background

The durability properties in terms of resistance to ageing of the bitumen binder, is the key factor for the binder characterization in asphaltic mixes, and hence pavement performance. While enormous advances have been made in the use of the BSMs in pavement construction and rehabilitation, the problem of binder hardening in both the plant mix process and in-service conditions remains an area where further research is warranted, (Jenkins, 2000), (Overby et al. 2004), (Gueit et al., 2006), and (Serfass et al., 2008)). Limited research that has been done in the past has indicated that BSMs can age significantly during in-service pavement life (Overby *et al.*, 2004), (Peterson *et al.*, 2000) & (Serfass *et al.*, 2008). In that respect, binder ageing has been a concern of the practitioners globally; hence the need to investigate this behaviour. Task 11 presents a general and detailed methodology of the investigation of the ageing behaviour of bitumen stabilised materials (BSMs). The methodology describes the investigation of binder ageing potential of foamed bitumen and bitumen emulsion for short term (during production, mixing and compaction) and long term (the in-service pavement) period. As such, it involves investigating the differential ageing (if any) for the foamed bitumen and bitumen emulsion to establish knowledge based during mix design of BSMs.

1.2. Methodology

In the life of asphalt pavement, the bitumen will undergo two distinct hardening phenomena. The first is short-term hardening, which occurs during mix production and construction. Second is long-term hardening, which occurs during in-service pavement life over long time. In this study the short-term ageing firstly, investigated using different types of bitumen from different refineries. The base bitumen and foamed bitumen properties were tested for its rheological properties i.e. viscosity, penetration and softening point with respect to time after circulation of bitumen in the laboratory foam plant (WBL10).

The rheological properties were also determined for the residual binder from bitumen emulsion (after evaporation of moisture). Secondly, BSM-foam and BSM-emulsion were investigated for compacted and cured specimens produced with different aggregate types mixed in the laboratory. The bitumen extracted from prepared specimens was tested in terms of its rheological properties. Thirdly, long-term ageing was investigated using cores extracted from a pavement that had been in-service for five to ten years. In this way, the differential ageing (if any) for the foamed bitumen and bitumen emulsion was investigated for the purposes of guiding the mix desing process for BSMs. The extraction and recovery of bitumen from the field cores and compacted specimen of both foamed bitumen and bitumen emulsion were done using Abson method in accordance to ASTM D1856-95a after cold centrifuge with minimum force of 3000 time gravity.

1.3. Objectives

The objectives of Task 11 include;

- Investigation of binder ageing potential of BSMs in short-term, during mixing and compaction and long-term during pavement in-service period.
- Evaluation of rheological properties of foamed bitumen and bitumen emulsion, during laboratory production to determine short-term ageing and recovered bitumen from cores extracted from in-service pavement to determine the long-term ageing.
- Investigation of differential ageing (if any) for foamed bitumen and bitumen emulsion after short-term and long-term ageing.
- If warranted from the findings, make appropriate recommendations regarding the severity of ageing of different binder types and whether this needs to be considered during the mix design phase.

1.4. Scope of the work

Task 11 focuses primarily on the age hardening behaviour of BSMs. It is known from hot-mix asphalt that age hardening occurs during mixing, construction, and long-term in-service conditions in the pavement. The same principle was used to investigate the ageing behaviour of BSMs as follows:

- The short-term ageing was investigated using different type of bitumen from different refineries. The fresh and foamed bitumens' rheological properties were tested i.e. viscosity, penetration and softening point with respect to time after circulation of bitumen in the laboratory foam plant (WBL10). The same rheological properties investigated on the residual of bitumen emulsion (after evaporation of moisture).
- Further short-term ageing was investigated from compacted and cured specimens, then bitumen was recovered and rheological properties were retested. The long-term ageing was investigated for the cores extracted from the pavement i.e. after five to ten years of trafficking.
- The bitumen was recovered (foamed bitumen and bitumen emulsion) using the Abson method according to ASTM D1856-95a, after cold centrifuge with minimum force of 3000 time gravity.
- The rate of age hardening on BSMs is discussed and recommendations provided.

1.5. Report structure

- **Section 2** provides detailed factors that influencing ageing behaviour of the BSMs.
- **Section 3** provides detailed testing methodology for the laboratory investigation on the BSMs. This includes short term age hardening and long term age hardening, as well as the bitumen extraction and recovery process for laboratory specimens and field cores. In

essence it describes the materials investigated (i.e. bitumen source and grade, prepared specimens, field cores source, location and number of cores tested). It gives details on bitumen extraction and recovery, rheological tests performed, and literature on the bitumen recovery process.

- **Section 4** provides detailed test results database on rheological properties of foamed bitumen and bitumen emulsion acquired during short term age hardening tests and long term age hardening tests.
- **Section 5** provides analysis and discussion of the test results. Details on short term ageing potential for both foam bitumen and bitumen emulsion are provided.
- **Section 6** provides conclusions of the finding obtained from the research.
- **Section 7**, provides the references used in the literature survey.

2. FACTORS INFLUENCING AGEING BEHAVIOUR OF BSMs

2.1. Background

The foamed bitumen and bitumen emulsion is produced after altering bitumen viscosity properties. The altering of bitumen provides desirable binder, which will allow a stability of mixes in a wide range of mineral aggregates to be effectively used in the pavement construction. Foamed bitumen produced through injection of small quantities of cold molecularised water as a fine mist, into hot bitumen (170°C–180°C) in an expansion chamber at high air pressure. Csanyi (1957) indicated that when the foam bitumen bubble burst during mixing, the surface tension spread the thin film of binder forcibly and rapidly over the surface of the aggregate. The modified surface tension of the binder when in the form of bubble also provides a natural force that induces a high adhesion between binder and aggregate particle. In this manner, bitumen can be mixed with aggregate at ambient temperature whilst it is foaming (in a temporally state of low-viscosity). Bitumen emulsion on the other hand produced through mechanical shearing of bitumen into small droplet (gap clearance of 0.25mm–0.5mm) mixed with emulsifying agent (anionic or cationic) and water under controlled condition of temperature (60°C–70°C) and dwelling time (1000rpm–6000rpm). The emulsifying agent induces electric charge on the dispersed bitumen droplets, which provide stability of the bitumen droplets under water continuous phase. Shell Bitumen, (2003) and Serfuass *et al.*, (2008) indicated that bitumen droplets when break during water evaporation disperse thin film of bitumen in aggregates which provide adhesion properties in the mineral aggregates.

At present, the analysis of the variables that influence foam production are presented by Brennen (1983) who identified three factors viz,

- The amount of foam produced (expansion and half-life)
- The amount of water in the foam (usually 2-3%)
- The foaming temperature of bitumen (170°C–180°C).

Although these factors are important, they do not completely explain the foam characteristics in terms of physicochemical change of bitumen. The amount of foam produced is a function of the time of discharge of the foam, air pressure in the bitumen system, and amount of water added, these factors might influences the physicochemical change of bitumen which have not been addressed. In this chapter, the effects of these factors in physicochemical change of foamed bitumen will be explored further. Brennen *et al.* (1983) also indicated that an increase in bitumen temperature generally results in an increase in expansion ratio but decrease in half-life, the same trend noted for an increase in formant water application. These factors might have significant influence in the physicochemical change of bitumen, which might results into age hardening of foamed bitumen. Jenkins in his research (2000) indicated that appropriate way of characterising the foam bitumen is to look at the entire decay curve (time lapse to total

collapse) to predict the performance of foam bitumen in the mix and coating application. However, the physicochemical changes of bitumen in this process were not considered. This chapter will include the investigation of foam bitumen characterisation outlining a new parameter of age hardening if happened during foam production.

Akzo Noble (1997), indicated that stability of bitumen emulsion is greatly influenced by the radius of bitumen droplets, viscosity of bitumen (percentage of bitumen), and the emulsifying type and percentage. Although these factors determine suitable bitumen emulsion, the influence of high shearing and chemical reactivity of emulsifier to the change of physicochemical properties of the bitumen were not reported. This Chapter will include some investigation of the bitumen emulsion properties outlining a new parameter of age hardening if occurred after evaporation of water continuous phase.

The foamed bitumen and bitumen emulsion is produced after altering bitumen viscosity properties. Csanyi (1957) indicated that the straight run bitumen 85/100 when foamed it changes penetration value to 300dmm at testing temperature of 25°C. Csanyi further commented that chemical consistency test has shown no change occurred to the bitumen even though the consistency and viscosity has changed. This observation will further be investigated in this study.

2.2. Factors influencing age hardening

The age-hardening process of the BSMs might be affected by several factors, all operating at the same time. In assessing these factors, Serfuass *et al.* (2008), Page *et al.* (1985) noted that the most critical variables to consider are the characteristics of mixes themselves. Hardening of the original bitumen for the HMA is different from bitumen stabilized mixtures. High temperatures and presence of air during plant mixing, mixing time, and construction are the variables that can cause age hardening of the HMA. These phenomena do not occur during bitumen stabilized mixing process, because mixing and lay down are done at ambient temperature, however researchers have indicated concerned at the high binder temperature required during foaming process, i.e. where bitumen is heated at 170°C–180°C and combined with hot moisture. For bitumen emulsion no elevated temperature is used for both mixing and lay down, therefore short-term hardening due to high temperature will not play a key role. The comparative manufacture and construction process for BSMs and HMA are indicated in Table K.1.

TABLE K.1: The comparative manufacturing process and construction of BSMs and HMA, (Jenkins, 2000)

Parameters	Bitumen emulsion	Foamed bitumen	Hot mix asphalt
Bitumen temperature during mixing	50°C – 70°C	170°C -180°C	140°C -180°C
Aggregates temp	Ambient 25°C	Ambient (25°C) Half warm (40°C-99°C)	Hot (140°C – 200°C)
Moisture content during mixing	60%-70% OMC	70% - 85% OMC	Dry
Type of coating of aggregates	Thin coating coarse particle and cohesion of mix with fines mortar	Partial coating of large particle with spot welding of mix with fines mortar	Coating of larger particle with controlled film thickness
Construction and compaction temp	Ambient (25°C) or Half warm (40°C-95°C)	Ambient or Half warm (40°C-95°C)	140°C–160°C

In the field, climatic effects control the variables of age hardening. The rate of the age hardening process is dictated by the severity of the environmental temperature levels, time, ultraviolet light and the access of air and moisture into the binder and the intrinsic reactivity of the binder.

2.3. The Binder dispersion and voids content

The access of oxygen into the thin film of binder in BSM-foam or BSM-emulsion is linked to the air-void content in the mixture. The high surface area of bitumen in BSM-foam and uneven distribution of the bitumen over the different granular fractions might be the factors resulting in premature ageing. Indeed, as the bitumen disperses preferably in the mortar fraction, the binder is distributed very selectively (in droplets) on a larger aggregates. The droplets of bitumen have high surface area and could have a tendency to age rapidly. The probable difference of the binder hardening between the coarse and fine fraction of BSMs should be further investigated. If a mix is not adequately compacted or sealed at the surface, or if allowed to dry out, oxidation can occur. Other factors that influencing ageing such as densification of mix under traffic need to be investigated.

Tuffour *et al.* (1993) expressed the dependence of binder aging (measured by the variation in the value of physical or rheological properties with time) on the variables mentioned above:

$$p(t) = f(T,t,l,K) \quad \text{Equation (1)}$$

Where,

- p(t) = physical or rheological properties of bitumen
- T = environmental temperature
- t = time
- l = length of diffusion path
- K = intrinsic reactivity of bitumen

Bitumen durability is a measure of the resistance to the detrimental effects of the oxidation process. Therefore, a durable bitumen is one for which p(t) changes very little with time.

The primary objective of this study was to investigate the ageing behaviour of BSMs using field and laboratory tests measurements.

It is generally accepted that the Rolling Thin Film Oven Test (RTFOT), simulates the changes that occur in binder during mixing, transportation and laying of HMA (BS, 2000). This test might not be applicable for simulating the BSMs as low temperatures are used during mixing and construction. In the same way test to simulate long-term changes (hardening) acceptable in HMA is Pressures Ageing Vessel (PVA), (AASHTO, 1993). However, the use of elevated temperature and pressure on a thin film of binder might not simulate the ageing effect occurring in BSMs. The use of these simulation tests for BSMs therefore require investigation, or a new laboratory simulation test needs be developed.

3. EXPERIMENTAL PROGRAM

3.1. Materials

3.1.1 Bitumen Sources and Grade

Four types of straight bitumen (pen-grade) from two different refineries and slow setting emulsion were procured for the laboratory investigation on this study. Two penetration-grade binders i.e. 80/100 and 60/70, were sourced from NATREF in Gauteng, and two penetration-grades i.e. 80/100 and 60/70 were sourced from CALTEX in Western Cape. These bitumen types are commonly used for the foaming process in South Africa. The selection was made to compare ageing behaviour of bitumen from different refineries. The slow setting emulsion (ANi B SS-60) commonly used for recycling was procured from COLAS-SA in Western Cape.

3.1.2 Field cores: Sources and Locations

The pavement with construction history of both foamed bitumen and bitumen emulsion were listed for the experimental investigation. To enable comparison of different environmental conditions, 40 cores were sourced from Western Cape, 36 cores from Gauteng (cored by CSIR) all from South Africa. An additional 6 cores were obtained from Saudi Arabia, transported to Stellenbosch to be included in this study. The lists of pavement sections included in this study are indicated Table K.2.

Table K.2: List of pavement section selected for field ageing studies

Bitumen emulsion	Foamed bitumen
- N7 TR 11/1 Near Cape Town	- P243/1 near Vereeniging
- MR 27 – Near Stellenbosch	- N7 TR11/1 Near Cape Town
- Grassy park in Cape Town	- Grassy Park in Cape Town
	- Shedgum road in Saudi Arabia

Table K.3 indicates the source of cores and locations, including pavement section, mix type, cores numbers, and location of extractions.

Table K.3: Summary of cores sourced for investigating on field age hardening.

Pavement Section	Mix Type	Cores number	Location of cores	Remark
Grassy Park - Near the robot - Straight section - Straight section	Foam Foam Emulsion	4 6 6	OWP, BWP OWP, BWP, YL IWP, BWP, YL	Binder was extracted and tested
MR27near Stellenbosch -Straight section -Hill section	Emulsion Emulsion	6 6	OWP, BWP, YL OWP, BWP, YL	Binder found insufficient for test. Tests discontinued
N7 TR11/1 Near Cape Town - Straight section - Straight section	Foam Emulsion	6 6	OWP, BWP, YL OWP, BWP, YL	On going
P243/1near Vereeniging - Straight section - Straight section	Foam Emulsion	18 18	OWP, BWP, YL OWP, BWP, YL	On going
Shedgum road in Saudi Arabia - Straight section	Foam	6	OWP, IWP, BWP	Binder extracted and tested

OWP = outer wheel pass, BWP = between wheel pass, IWP = inner wheel pass, YL= yellow line

3.2. Binder extraction and recovery

3.2.1 Background

The binder characteristics in the mixture cannot easily be examined, without full separation of bitumen from aggregates. Full extraction therefore, has to be performed to recover the bitumen from the mix or RAP to enable examination of its rheological properties. Full extraction implies the use of a particular solvent, and equipment to separate bitumen from aggregates.

3.2.1.1. Recovery of Bitumen from mixes.

The conventional methods for qualitative extraction and recovery of asphalt from paving mixture are done by centrifuge extraction, vacuum extraction, reflux extraction etc. (ASTM 2003). Different common solvents have been used in the binder extraction and recovery procedures, i.e. e.g. trichloroethylene (TCE), methylene chloride, benzene, 1-trichloroethane (TCA), etc. However due to the carcinogenic and environmental hazardous nature of all chlorinated solvents, the use of these solvents is phasing out (EPA, 2003), and (Collins-Garcia et al. 2000). The extraction and recovery of bitumen has an important influence on the binder characteristics. Many tests have been performed to define the most suitable extraction method and solvent, sometimes with contradictory conclusion. There is no consensus, (Okan et al. 2003). It is clear that there are several extraction-recovery methods and solvent choices for both binder content determination and binder performance characterisation. In Europe, two main extraction methods are used for extraction of bitumen i.e. centrifuge and the reflux (Soxhlet) method. Centrifuge is generally a cold process; this process is preferred because of low temperature than reflux, which

appears to age the bitumen (Burr et al. 1993). There is consensus in Europe for the removal of solvent by use of rotavapour distillation. The alternative is using the Abson method (ASTM 2003). However studies have indicated that the standard Abson recovery method may leave such an amount of solvent in the recovered binder or over-heat the bitumen if not done with care, which might result in change of viscosity properties, (Burr et al. 1990, 1993), (Peterson et al. 2000), and (NHC 2000).

Since 1970's, many USA laboratories have adopted the use of rotavapour in the recovery process. The rotavapour method for distilling solvent needs less heat, thus resulting in a lower risk of ageing of binder during recovery. The selection of solvent can also influence the final binder properties. Peterson et al. (1994) found that both the extraction and recovery process as well as chlorinated solvent could age the binder. The use of EnSolv and reclaimed EnSolv for the extraction and recovery of binder have been studied as an alternative to TCE. Studies conducted in NCAT, (2000) found that there are no significant difference between samples recovered using TCE, EnSolv n-PB, and reclaimed EnSolv, hence recommended the use of EnSolv and modified rotavapour, which have the advantage of less time in recovery process and less toxic.

3.2.1.2. Recovery of bitumen from Emulsion

Several methods exist for the recovery of bitumen from emulsion. These methods are divided into two types. 1) Thin film oven method, 2) Evaporation method "heating en mass" or a chemical reaction under defined operation conditions. The thin film method consists of storing a small amount of emulsion, 1mm thick for 24 hour at ambient temperature and for 24 hour at 50°C in the oven, (EN 14895). Heating en mass, Belgium procedure (08-34) consists of heating 50g of emulsion for 2 hours at 163°C in a 600ml beaker of specified shape to prevent foaming of the emulsion. The same principles apply for ASTM D 244-A in the evaporation method. A chemical method developed by Colas France, namely the Ethanol Precipitation method, can be used to separate the aqueous phase and partial or complete separate the emulsifier. It is believed that this is the only method, which can recover bitumen with identical properties to that of the base bitumen, with regard to not only consistency but also chemical properties, (Geit et al. 2006).

3.2.1.3. Extraction and Recovery Methods

In this study, due to the availability of equipment, the extraction and recovery of the bitumen from the compacted specimens and extracted field cores was done using standard Abson Method according to ASTM D 1856-95a. The process consists of cold centrifuge with minimum force of 3000 time gravity. Centrifuge cups were used to collect filler. Trichloroethylene solvent used to separate binder from aggregates. The centrifuge process however observed to be unable to capture all filler; therefore three to four repeat centrifuge processes were necessary. The tendency of foamed bitumen and bitumen emulsion to adhering

to the filler particles, create challenges for total separation of mix using the centrifuge. This results in super filler being recovered with bitumen. Figure K.1 and K.2 shows the Abson equipment used in the extraction and recovery process possessed by SOILAB in the Western Cape.



Figure K.1. Centrifuge extraction **Figure K.2. Abson recovery method**

The bitumen contents after core extraction calculated from the differences in mass of aggregates, moisture content, and fines in the extracts as follows:

$$\text{Bitumen content, \%} = \left[\frac{(w_1 - w_2) - (w_3 + w_4)}{(w_1 - w_2)} \right] \times 100 \quad \text{Equation (2)}$$

Where:

- W1 = mass of test portion
- W2 = mass of water in the test portion
- W3 = mass of the extracted coarse aggregates
- W4 = mass of the fine aggregates in the extracts

The recovery of bitumen from the aqueous phase in emulsion was achieved through evaporation method (ASTM 244-A). 200g of ANi B SS-60 was poured into a container placed on a burner at controlled flame using thermometer and stirred continuously until no moisture is observed, by placing clear glass on top of a container.

4. TESTS RESULTS

4.1. Rheological properties

The *Penetration Test* was performed at 25°C, with 100g of loading weight and needle at a 5 second penetration, according to ASTM D5-IP49. One set of tests was done per sample of recovered bitumen, and repeat set of tests on another sample. The average of the two replicates are recorded in the tables of results. It is important to note that penetration test protocol should be followed precisely; a slight variation can cause significant differences in the results.

The *Softening Point test* was performed according to ASTM D36. The sample and the ring and ball set-up were placed in the 800ml flask and conditioned at 5°C for 15 min. The heating mantle was used to heat the water at a constant rate of temperature change of 5°C per minute until the bitumen softens and moves with the ball bearing 25mm below the ring. The temperature of the water is recorded and the difference in temperature between two rings should not be more than 1°C.

The *Viscosity Test* was done according to ASTM D4402 using a Brookfield Model DV-I viscometer with thermocel temperature control system. The selected spindle was SC-29 for the 60°C and SC-21 for the 135°C. Temperature range was 60°C and 135°C to determine the viscosity of bitumen at field conditions and mixing temperature. The spindle was equilibrated in the clean Thermocel chamber for 15 minutes. 13g of sample for 60°C and 8g for 135°C was poured in the tube and placed in the Themorcel (with spindle temporarily removed). The spindle is hooked to the viscometer and inserted into the bitumen and left to reach equilibrium for further 15 minutes. The spindle and torque speed is selected from the digital panel and viscometer started. The torque of the viscometer is between 2 to 98% of full scale, the reading with the higher torque percentage recommended for more accurate. Three readings are recorded at an interval of 60 seconds and averaged. However, due to sensitivity of the readings, the spindle is left to rotate for 15 minutes and thereafter the readings are taken. The unit of dynamic viscosity is Pascal-Second (Pa.s) which is 1N.sec/m². The cgs unit is the gm/cm.s, which is Poise or Centipoise cP, at a given temperature,

$$1 \text{ Pa.s} = 1000 \text{ mPa.s} = 10 \text{ Poise} = 1000\text{cP}$$

Kinematics viscosity (ν) is the ratio of the dynamic viscosity (η) to the density (δ) of a liquid such that;

$$\nu = \frac{\eta}{\delta} \quad \text{Equation} \quad (3)$$

Where,

$$\nu = \text{Dynamic viscosity in Pa.s}$$

η = Kinematic viscosity in mm²/s

δ = Density in kg/l at the temperature under consideration

The unit of kinematic viscosity is mm²/s or cgs = cm²/s, which is stoke conveniently converted centistokes as follows,

$$1 \text{ mm}^2/\text{s} = 0.001 \text{ cm}^2/\text{s} = 1 \text{ centistoke}$$

The SABS 307 standard specification for the penetration, softening point and viscosity of bitumen are indicated in Table K.4.

Table K.4: Specification for road bitumen in South Africa ,SABS 307

Properties	Penetration grade			Test Method
	40/50	60/70	80/100	
Penetration at 25°C [dmm]	40-50	60-70	80-100	ASTM D5-IP49
Softening Point [°C]	49-59	46-56	42-51	ASTM D36
Viscosity at 60°C [Pa.s]	220-400	120-250	75-150	ASTM D4402
Viscosity at 135°C [Pa.s]	0.27-0.65	0.22-0.45	0.15-0.4	ASTM D4402

4.1.1 Laboratory test results

4.1.1.1. Penetration, Softening point and Viscosity.

The consistency of foamed bitumen after different periods of circulation (i.e. 1hr, 4hrs, 8hrs), was done to simulate a short term age hardening of foamed bitumen during mixing period. The age hardening of base bitumen and foamed bitumen at different circulation times is indicated in Table K.5

Table K.5: Base bitumen and foamed Bitumen rheological properties of 80/100 pen. from NATREF refinery

Properties	Original Bit	Fresh Bit				Foamed Bit		
	Bitumen circulation time							
	0hr	1hr	4hrs	8hrs	1hr	4hrs	8hrs	
Penetration 25°C [dmm] (repeat)	95(96) 95.5	82(85) 83.5	74(76) 75.0	64(64) 64.0	86(87) 86.5	77(79) 78.0	66(67) 66.5	
Softening point [°C]	47	48	49	50	47	48	50	
Viscosity at 60°C [Pa.s]	132.0	153.0	167.8	211.5	140.4	160.6	216.5	
Viscosity at 135°C [Pa.s]	0.306	0.310	0.331	0.352	0.308	0.326	0.398	
Penetration Index, PI	-0.324	-0.444	-0.458	-0.515	-0.620	-0.626	-0.358	

Supplied bitumen: Unit nr. 2900, Tank nr. F29317, Dec.2007.

Table K.6: Base bitumen and foamed bitumen rheological properties of 80/100 pen from CALTEX refinery

Properties	Base Bit	Fresh base bitumen				foamed Bitumen		
	Bitumen circulation time							
	0hr	1hr	4hrs	8hrs	1hr	4hrs	8hrs	
Penetration 25°C [dmm] (repeat)	82(85)	66(73)	62(64)	54(54)	76(76)	67(66)	58(58)	
	83.5	69.5	63.0	54.0	76	66.5	58	
Softening point [°C]	47	48	49	51	48	49	50	
Viscosity at 60°C [Pa.s]	134.0	166.0	205.0	252.8	165	200.0	235.7	
Viscosity at 135°C [Pa.s]	0.342	0.370	0.395	0.434	0.361	0.384	0.431	
Penetration Index, PI	-0.721	-0.936	-0.915	-0.780	-0.698	-0.778	-0.859	

Supplied bitumen: Unit no. APP, Tank nr., Oct.2007

Table K.7: Base bitumen and foamed bitumen rheological properties of 60/100 pen from NATREF refinery

Properties	Base Bit	Fresh base bitumen				Foamed bitumen		
	Bitumen circulation time							
	0hr	1hr	4hrs	8hrs	1hr	4hrs	8hrs	
Penetration 25°C [dmm] (repeat)	66(64)	66(67)	65(66)	53(55)	69(69)	68(66)	53(55)	
	65	66.5	65.5	54.0	69	67	54	
Softening point [°C]	50	50	51	53	50	50	54	
Viscosity at 60C [Pa.s]	220.2	237.2	255.2	387.2	227.2	235.2	396.8	
Viscosity at 135C [Pa.s]	0.370	0.369	0.376	0.458	0.356	0.366	0.460	
Penetration Index, PI	-0.574	-0.515	-0.298	-0.299	-0.417	-0.495	-0.066	

Supplied bitumen: Unit nr. 2900, Tank nr. 29306, Dec.2007

Table K.8: Base bitumen and foamed bitumen rheological properties of 60/70 pen from CALTEX refinery

Properties	Base Bit	Fresh base bitumen				Foamed bitumen		
	Bitumen circulation time							
	0hr	1hr	4hrs	8hrs	1hr	4hrs	8hrs	
Penetration 25°C [dmm] (repeat)	71(74)	68(70)	67(66)	62(65)	77(77)	69(63)	64(64)	
	72.5	69	66.5	63.5	77	66	64	
Softening point [°C]	50	50	50	53	49	51	52	
Viscosity at 60C [Pa.s]	202.0	207.0	267.2	328.8	198.0	259.6	324.0	
Viscosity at 135C [Pa.s]	0.361	0.396	0.439	0.483	0.356	0.432	0.477	
Penetration Index, PI	-0.284	-0.417	-0.515	-0.113	-0.385	-0.278	-0.109	

Table K.9: Recovered bitumen rheological properties from Emulsion, ANi B SS-60

Properties	80/100 pen CALTEX	
	Original Bit	Recovered Bit
Penetration at 25°C [dmm]	100	105
Softening Point [°C]	44	44
Viscosity at 60°C [Pa.s]	94.4	95.8
Viscosity at 135°C [Pa.s]	0.27	0.265
Penetration Index, PI	-1.125	-0.976

PENETRATION INDEX (PI)

The penetration Index (PI) of bitumen from rheological properties is determined to show the characteristics in temperature susceptibility. The PI is determined by the relationship between bitumen penetration value and the softening point as indicated in Eq 4, (Shell bitumen, 2003).

$$PI = \frac{1952 - 500 \cdot \log Pen - 20 \cdot SP}{50 \cdot \log Pen - SP - 120} \quad \text{Equation (4)}$$

Where,

SP = Softening point

Pen = Penetration at 25°C

4.1.2 Field cores test results

4.1.2.1. Penetration, Softening point and Viscosity

The consistency of recovered bitumen from foamed bitumen and emulsion mixes (cores) was investigated for long-term ageing behaviour. The descriptions of the investigated pavement sections are detailed below:

Grassy park road in Cape Town, 5th Avenue and 3rd Avenue road sections were rehabilitated in 1999 by recycling 200mm CTB with addition of 1.5% foamed bitumen and 2% emulsion respectively. 1% cement was also added on both sections during recycling. The surface was covered by a 40mm asphalt wearing course, (UWP, 1999).

MR27 road section near Stellenbosch was rehabilitated in 1988 by recycling 100mm with 1% net bitumen of ANi SS-60; the surface was paved with 40mm of asphalt concrete and a double seal (Long, 2007). P243/1 road near Vereeniging was rehabilitated in 2000 by recycling 250mm with 1.8% net bitumen on both foamed bitumen and asphalt road sections. 2% of cement was also added during recycling. 20mm of asphalt concrete and single seal was used as the surfacing,

(Long, 2007). The N7 road emulsion section was rehabilitated in 2007, 2.1% net bitumen and 1% of cement added during recycling. 30mm of asphalt concrete and UTFC covers the surface. The Shedgum Road, Saudi Arabia was rehabilitated in 2007, with 2.5% foamed bitumen and 1% cement. The surface was covered with 40mm of asphalt concrete. The test results on the recovered bitumen are provided in Table K.10 to K.13.

Table K.10: Recovered bitumen properties from Shedgum Road

Properties	ST 02 (LL3)		ST04 (LL3)		ST 08 (LR1)		ST 09 (LR1)	
	OWP		OWP		IWP		IWP	
	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM	TOP	BOTTOM
Penetration 25°C [dmm]	Outlier	Outlier	outlier	outlier	8	12	12	11
Softening point [°C]	90	90	91	88.5	77.3	84.7	79.4	83.8
Viscosity @60°C [Pa.s]		N/A		N/A				
Viscosity at 135°C Pa.s	88.4	27.35	44.6	89.1	6.7	11.85	26.25	9.225

Note: The outlier values are 1 to 5 penetrations. These extreme values are considered influenced by overheating the bitumen or inclusion of super filler in the recovered bitumen samples.

Table K.11: Recovered bitumen properties from Shedgum Road

Properties	ST 08 (RR1)				ST06 (LL3)			
	BWP				OWP			
	Layer 1 TOP	Layer 2	Layer3	Layer 4 BOTTOM	Layer 1 TOP	Layer 2	Layer 3	Layer 4 BOTTOM
Penetration 25°C [dmm]	22	24	22	21	16	18	15	17
Softening point [°C]	68.0	64.0	68.0	68.4	76.0	71.0	74.0	75

Table K.12: Recovered bitumen properties from Grassy Park Foamed BSM section

Properties	Robot		Straight section		
	BWP	OWP	YL	OWP	BWP
Penetration 25°C [dmm]	49	15	37	5	outlier
Softening point [°C]	55.8	80	51.2	70.7	44.6
Viscosity at 60°C [Pa.s]	810	N/A	411	NA	108.6
Viscosity at 135°C [Pa.s]	0.932	5.65	0.532	2.283	0.278

Note: The result of more than 80 penetrations is considered outlier as the value might have been a result of residual solvent in the recovered bitumen sample.

Table K.13: Recovered bitumen properties from Grassy Park Emulsion section

Properties	Straight section		
	YL	IWP	BWP
Penetration 25°C [dmm]	39	22	40
Softening point [°C]	56	63	54.4
Viscosity at 60°C [Pa.s]	-	-	650
Viscosity at 135°C [Pa.s]	0.61	1.108	0.76

Table K.14: Bitumen properties used in Grassy Park roads rehabilitation, UWP (1999)

Properties	60/70 CALTEX	
	Original Bit	RTFOT
Penetration 25°C [dmm]	72	69.4
Softening point [°C]	45.5	47.5
Viscosity at 60°C [Pa.s]	216	-
Viscosity at 135°C [Pa.s]	0.49	-

The extraction and recovery of bitumen from field cores extracted from N7 TR 11/1 Near Cape Town, and P243/1 near Vereeniging from Gauteng are on going. It is anticipated that after completion of tests on these cores a broader knowledge on long-term age hardening of BSMs will be provided.

As part of the ongoing tests, three temperature buttons were installed in the N7 road section on different BSM layers. The aim of installing the buttons was to record temperature and humidity variation in BSM layer for a period of one year. The effect of temperature and humidity variation in the BSMs can then be correlated with the age hardening behaviour of the recovered bitumen from BSMs on the same sections.

5. ANALYSIS AND DISCUSSION OF RESULTS

5.1. Laboratory investigation on short term ageing, for base bitumen versus foamed bitumen

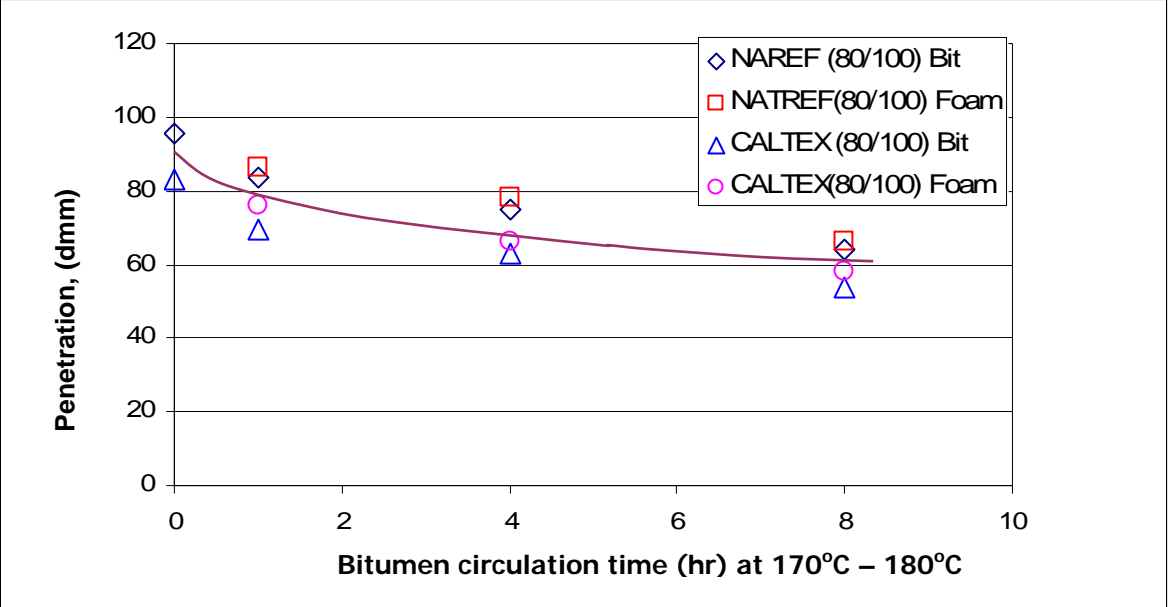


Figure K.3: Penetration versus ageing time (hr) of base bitumen versus foamed bitumen at temp. 170°C-180°C

The consistency of foamed bitumen with respect to mixing time i.e. 1 hr, 4hr, and 8hr, for 80/100 penetration binder, is presented in Figure K3. It is clear from Figure K3 that base bitumen for both NATREF and CALTEX refineries undergoes age hardening of approximately 30% in short term, for a period of 8 hours heated at 170°C – 180°C. Similar behaviour occurs for the foamed bitumen that is produced after ageing of the base bitumen i.e. the foaming process does not alter this trend. Shell bitumen (2003) has reported the same effect of age hardening on base bitumen of the HMA for the short-term ageing. The comparison between two refineries indicates that the higher the penetration of the base bitumen the less the effect of age hardening i.e. 96 penetration versus 83 penetration.

Further evaluation, Figure K3 shows that foamed bitumen age hardening follows the ageing of the base bitumen. This clearly shows that foaming process itself does not have significant effect on ageing of the base bitumen, even using different sources of bitumen.

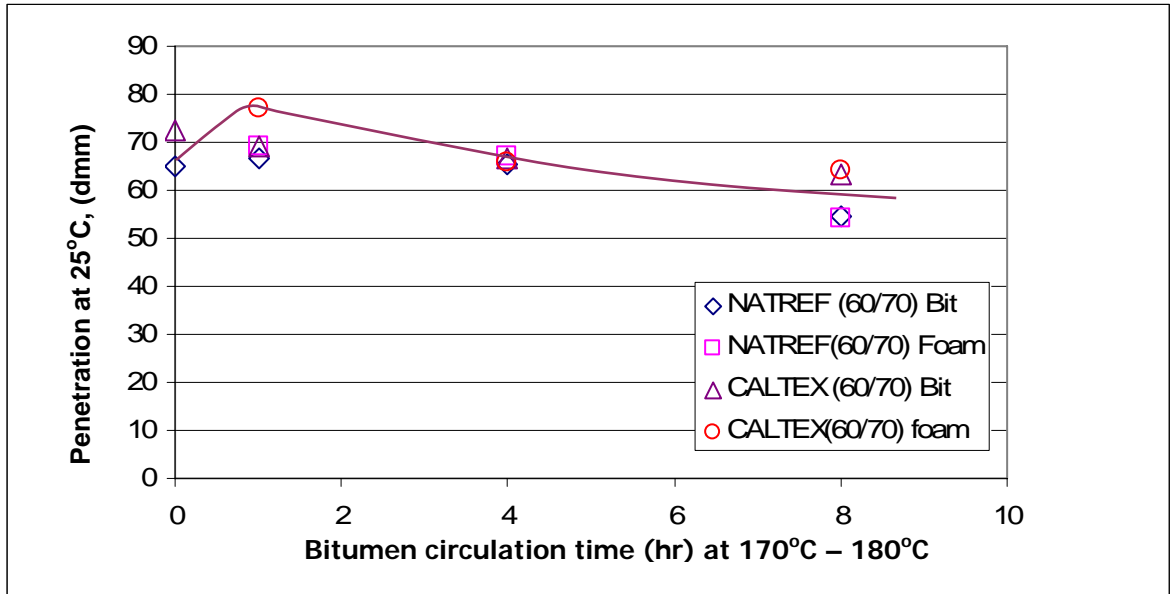


Figure K.4: Penetration versus ageing time (hr) of base bitumen versus foamed bitumen at temp. 170°C-180°C

Figure K.4 shows the ageing behaviour of base bitumen versus foamed bitumen made from 60/70 penetration bitumen circulated at a temperature of 170°C-180°C. Both base bitumen and foamed bitumen show no ageing in the first four hours. However, after eight hours age hardening resulted in a drop of penetration of 17% for the NATREF and 12% for the CALTEX binders. It can be seen from the results that the CALTEX 60/70 base bitumen used in the study does not comply with SABS 307 specification, with 73 maximum penetration tested as opposed to 70 maximum specified. The penetration of residual foamed bitumen circulated for one hour is higher than the base bitumen.

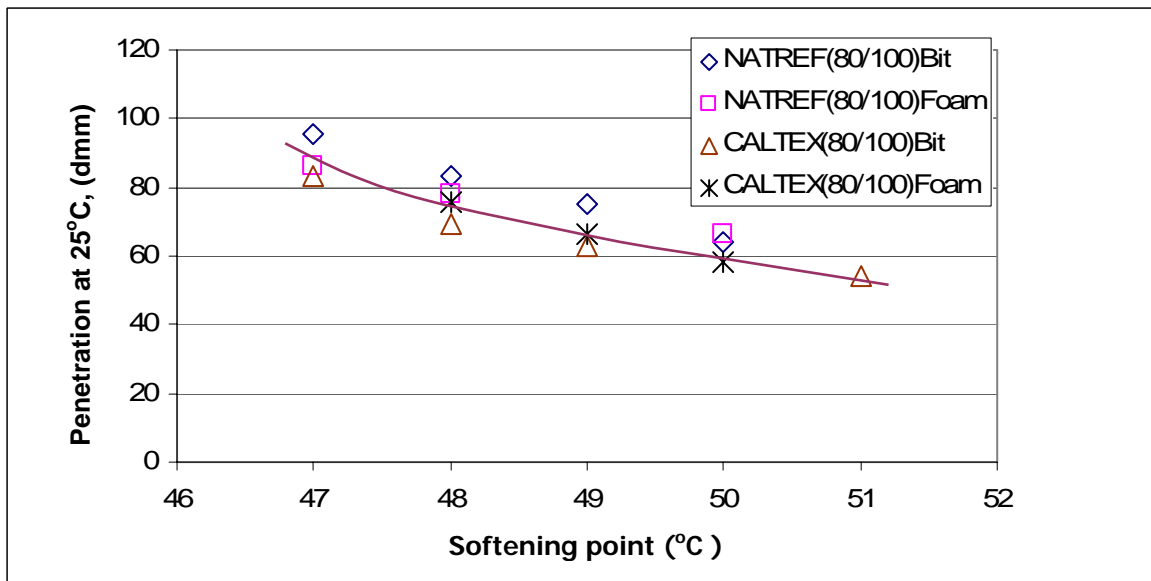


Figure K.5: Penetration versus softening point of base bitumen versus foamed bitumen at a temperature of 170°C-180°C for 80/100 pen.

The relationship between penetration and softening point is shown in Figure K5. This reveals an increase in binder hardness of 80/100 bitumen over the short term. This behaviour gives an insight into the behaviour of BSM foam. Foamed bitumen is recognised as having an affinity for the fine particles with high surface area to mass ratio. The effect of this hardening of foamed bitumen could influence cohesive behaviour of foam mastic although this has not been investigated. In addition, it should be remembered that the binder in the BSM-foam is also dispersed in a non-continuous manner. Figure K.5 shows that the softening point of base bitumen and foamed bitumen increases as the penetration decreases. The CALTEX bitumen shows a greater susceptibility to temperature effects during the ageing process than the NATREF bitumen.

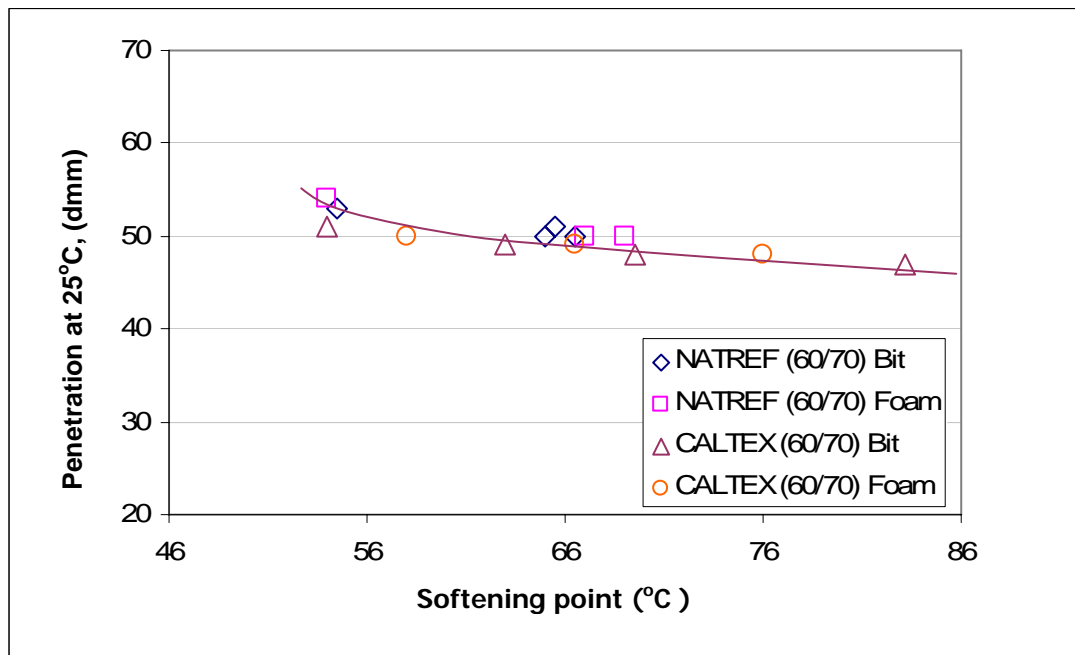


Figure K.6: Penetration versus softening point of base bitumen versus oamed bitumen at temp. 170°C-180°C for 60/70 pen.

Figure K.6 show ageing behaviour of base bitumen and foamed bitumen made from 60/70 pen binder. It can be seen that the rate of ageing of base bitumen and foamed bitumen is relative small compared to 80/100 pen bitumen. Similarly, small differences are noted for bitumen from NATREF and CALTEX. The use of 60/70 pen bitumen could have slight advantages in terms of short-term ageing. However, Wirtgen (2004) indicated that 60/70pen bitumen has problem of blocking the nozzles during recycling process.

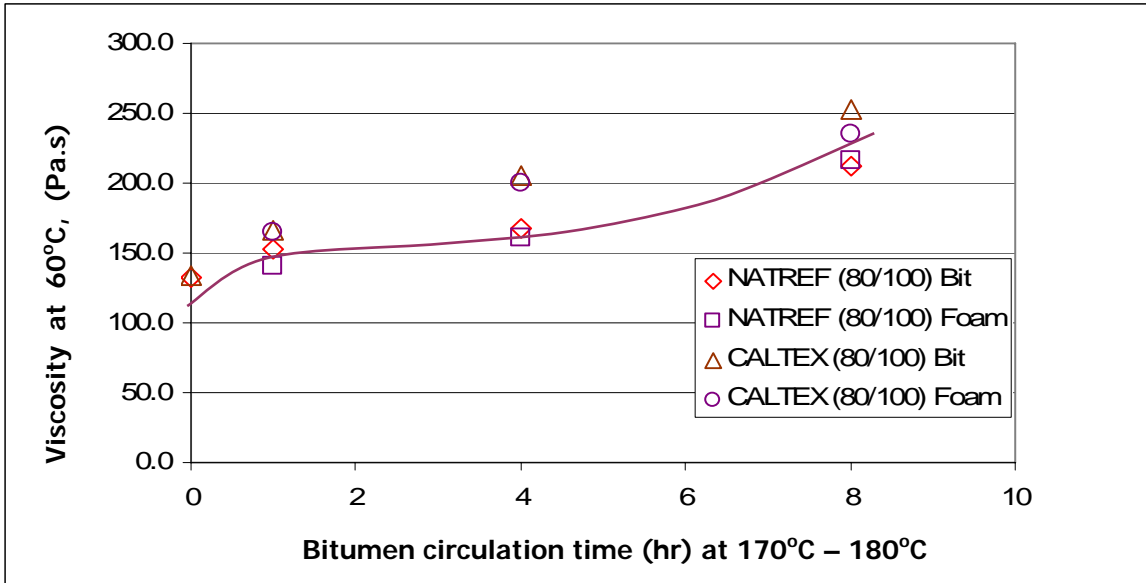


Figure K.7: Viscosity versus mixing time (hr) of base bitumen versus foamed bitumen at temp 170°C-180°C

Figure K.7 shows behaviour of the base bitumen at 60°C in terms of viscosity, versus foamed bitumen. It can be seen that the viscosity increases as the bitumen hardens. CALTEX bitumen shows higher rate of change of viscosity with time than NATREF bitumen. However, the behaviour of NATREF bitumen and foamed bitumen show less ageing susceptibility for the first 4 hours and sharply increase at 8 hours of thermal ageing. It might be concluded from this behaviour that foamed bitumen mixes produced with binder that has been circulated at high temperatures may have compromised performance. Further observations show that hardening differs for different refineries' products. This indicates that the behaviour of foamed bitumen mixes is dependent on the bitumen source. The bitumen characteristics should therefore be considered during mix design.

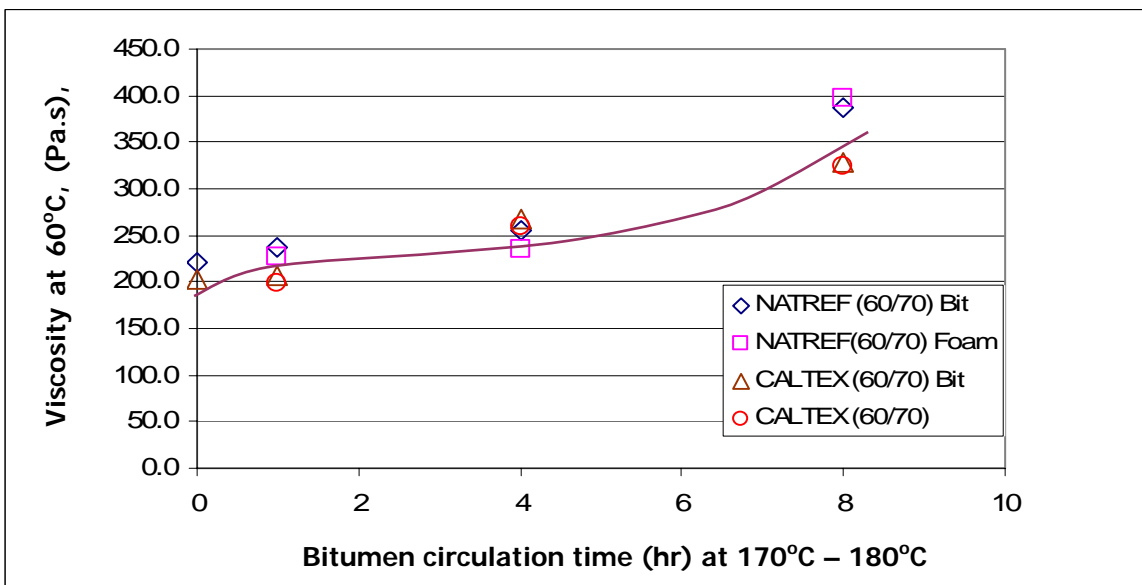


Figure K.8: Viscosity versus mixing time (hr) of base bitumen versus foamed bitumen at temp 170°C-180°C

The viscosity behaviour of base bitumen and foamed bitumen produced from 60/70 penetration bitumen exhibits a similar trend to 80/100 penetration bitumen, see Figure K.8. However, after eight hours of circulation 60/70 pen bitumen shows relative higher viscosity than 80/100 pen bitumen. The NATREF bitumen show higher susceptibility to ageing in terms of viscosity increase at longer circulation times than CALTEX bitumen. This confirms the findings of Wirtgen (2004) on the use 60/70 pen for recycling process, that higher viscosity binder than 60/70 pen bitumen might resulting into blockage of nozzles. However if less time of circulation allowed during mixing process, 60/70 pen bitumen might improve performance of BSMs.

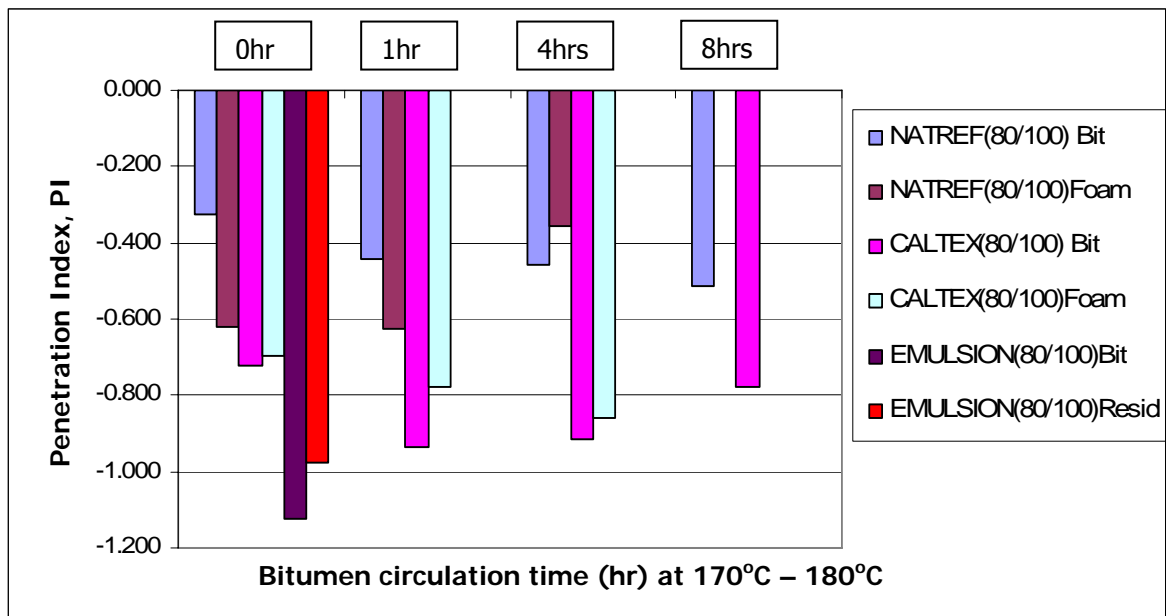


Figure K.9: Penetration Index, (PI) of the base bitumen versus foamed bitumen & bitumen emulsion for 80/100 penetration bitumen.

Figure K.9 shows the relationship between PI and bitumen circulation time, for temperatures of between 170°C and 180°C. It is clear that PI values are between -0.32 to -1.13. According to Shell bitumen (2003), most paving binder has PI values ranging between +1 to -1. The ageing behaviour of the bitumen types have thus been analysed in terms of PI. It can be seen from Figure K.8 that emulsion (base bitumen and recovered bitumen) that has been tested has higher temperature susceptibility than other base bitumen and foamed bitumen. Foamed bitumen and bitumen from NATREF lie within the limits of Shell. However, CALTEX base bitumen and foamed bitumen shown relative higher temperature susceptibility than NATREF binder.

5.2. Field investigation on long-term ageing of BSMs

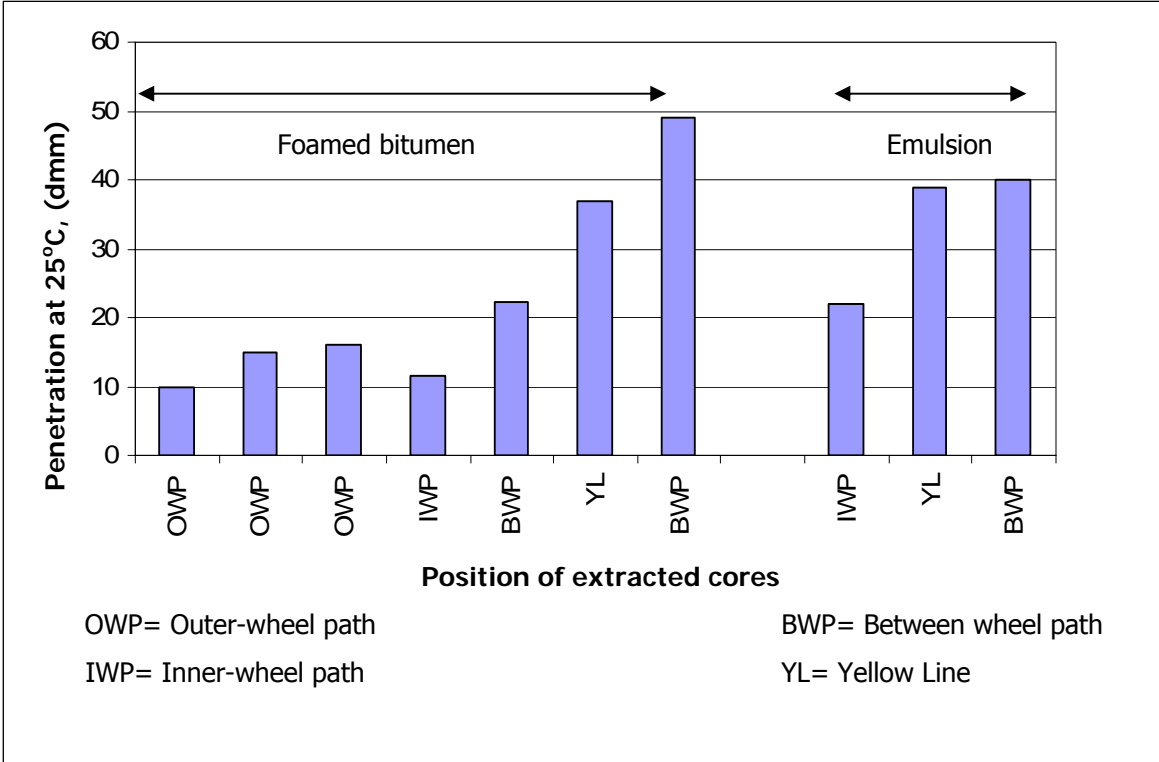


Figure K.10: Field ageing behaviour in respect to coring position of foamed bitumen versus bitumen emulsion

Figure K.10 shows ageing behaviour of foamed bitumen and bitumen emulsion with respect to position of extracted cores from the pavement. It can be seen from the graph that ageing effects of bitumen are more prevalent in the trafficked positions (OWP and IWP) compared to un-trafficked positions (YL and BWP). The ageing behaviour of foamed bitumen and bitumen emulsion mixes in the field cannot be distinguished easily from Figure K.10. However, it is noted from the figure that foamed bitumen mixes experience more ageing effect than bitumen emulsion mixes. In conclusion, the expected age hardening of the foamed bitumen and bitumen emulsion in the trafficked sections, in terms of penetration, lies between 10dmm and 20dmm and un-trafficked section lies between 30dmm and 50dmm. This behaviour contradicts previous studies, which indicate that ageing occurred mainly on un-trafficked sections, due to high void contents. Further investigation and data is needed to verify these effects.

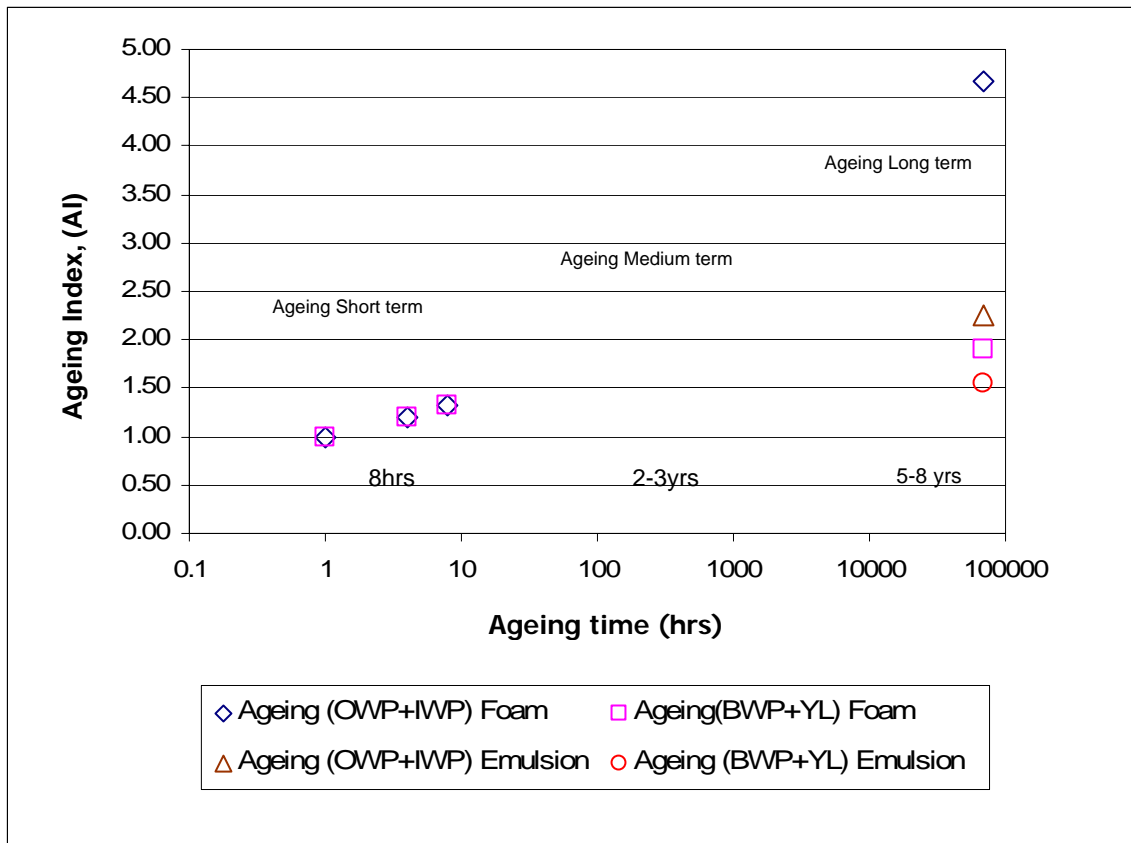


Figure K.11: Ageing behaviour short-term versus long-term of BSMs

The use of Ageing Index (AI) method, clearly distinguish the age hardening behaviour of foamed bitumen and bitumen emulsion see Figure K.11. Shell bitumen (2003) defines the Ageing Index, (AI) as a ratio of the viscosity of the aged bitumen (η_a) measured at different times, to the viscosity of the base bitumen (η_o), both measured at the same temperature. This principle used to determine the relationship of the ageing behaviour during mixing (short term) and in-service condition (long term). The viscosity at 135°C is used in calculating the Ageing Index of BSMs. The use of viscosity of aged bitumen at 60°C was inappropriate for the investigation because most of bitumen had no flow properties at 60°C. Figure K.11 shows the ageing behaviour of BSMs in short-term and long-term combined. The long-term ageing includes the different positions in the pavement i.e. trafficked and un-trafficked areas. However, from the graph, the medium-term ageing (2-3years) data is absent. The study of that period of ageing is ongoing as indicated in Table 3 Section 3.3.2.1 above.

6. CONCLUSIONS AND RECOMMENDATIONS

The age hardening of BSMs and fundamental characteristics of BSMs associated with short-term and long-term age hardening have been investigated through laboratory testing. Based on the data of the study, the following conclusions are drawn:

- The time bitumen is kept in circulation in the laboratory plant at elevated temperature before making of BSM-foam contributes to the ageing of the binder, especially after 8 hours. The effects of ageing are more notable for the softer bitumen (80/100) than hard bitumen (60/70), with 30% drop of penetration for 80/100 bitumen, compared to drop of 12-17% on the 60/70 bitumen.
- It is apparent from the study that some short-term age hardening of foamed bitumen during mixing occurs. However, the trend follows that of the age hardening of the base bitumen. Nevertheless, the foaming process in itself does not alter the bitumen properties. For the bitumen emulsion, no age hardening occurred during mixing time because elevated temperature is not used in the mixing process.
- The study has also shown that bitumen from different sources ages at different rates. This is consistent with other studies, as the compositional balance and chemistry of the binders varies even if they comply with the same classification requirements.
- Ageing behaviour of the foamed bitumen and bitumen emulsion has proven to be a point of consideration during mix design and long-term performance. In short-term, foamed bitumen has a drop in penetration by an estimated average of 30% during laboratory circulation. Whilst in the long-term, both foamed bitumen and bitumen emulsion have a reduction in penetration of on average 10 to 30dmm for trafficked section, with an increase in viscosity at 60°C that leads to reduction in flow. The impact on these changes in the binder on the mix behaviour remains to be investigated.
- The studies have also indicated that, age hardening of the foamed bitumen and bitumen emulsion mixes is dependent on the effects of traffic. Ageing occurs differently in trafficked versus un-trafficked locations in the pavement (for the limited data obtained). The trafficked location (OWP and IWP) have higher ageing influences than un-trafficked location (YL and BWP). This tendency is contrary to previous studies. Other studies have indicated that air void content of the layer is the major factor for the oxidative hardening. It is expected that un-trafficked (BWP and YL) locations will have higher void content than the trafficked (OWP and IWP) locations, hence high ageing potential. However, these factors need further investigation.

- The extreme values measured for penetration of bitumen exposed to field ageing are questionable. This raises the concern that total separation of filler with bitumen during extraction and recovery has not been successfully achieved. The centrifuge extraction might not be able to capture all filler (super filler) which is key component on the mix design of the BSMs. The Abson method of recovery can also cause variability of the results by leaving some solvent in the residual and or over-heating the bitumen, having differing impacts on the results.

6.1. Recommendation

- Age hardening, in terms of short-term and long-term exposure of the binder i.e. foamed bitumen and bitumen emulsion, has been noted for BSMs. However, due to variability and inconsistencies in the results, it is not clear how the findings could be incorporated into the classification system of BSMs in terms of ageing for the mix design. The impact on the age hardening on the performance of BSMs would require further investigation before the results can be definitively applied in the mix design process. In addition, the extraction and recovery process of BSMs needs further investigation.
- The expected age hardening of the foamed bitumen and bitumen emulsion contradicts previous studies, which indicated that ageing occurred mainly on un-trafficked sections, due to higher void contents. Further investigation and data is needed to verify (or otherwise) these effects.

7. REFERENCES

- Akzo Nobel Chemical, 1997. **Bitumen Emulsifier**, Technical paper presented in 24th AEMA meeting, Concu, Mexico.
- American Standard Test Method, 2003. **Standard Test for Recovery of Asphalt from Solution by Abson Method**. ASTM Designation D 1856-95a,
- American Association of State Highway and Transportation Official. 1993. **Standard practice for Accelerated Ageing of Asphalt Binder using a Pressure Aging Vessel (PVA)**, AASHTO Designation PPI, Edition 1A.
- Burr B. L., Davidson R. R., Glover C.J., and Bullin J.A., 1990. **Solvent removal from Asphalt**. Transport Research records TRR, 1269. Washington DC.
- Burr B. L., Glover C.J., Davidson R. R., and Bullin J.A., 1993. **New Apparatus and Procedure for the Extraction and Recovery of Asphalt Binder from pavement Mixtures**. Transport Research records TRR, 1391. Washington DC.
- Brennen M., Tia M., Altschaefl, A. and Wood L. E., 1983. **Laboratory Investigation of the Use of Foamed Bitumen for Recycled Bituminous Pavements**. Transportation Research Record 911. Pp 80-87
- British Standard Institution, 2000. **Petroleum and its products, determination of the resistance to hardening under the influence of heat and air**. British standard EN 12607-1.
- Choubane, B., Page G. C., and Musselman J. A., 1998. **Investigation of Water Permeability of Coarse Graded Superpave Pavements**. Association of Asphalt Paving Technologists, Vol. 67
- Collins-Garcia H., Mang T., Roque R., and Choubane D., 2000. **An evaluation of Alternative Solvent for Extraction of Asphalt to Reduce Health and Environmental Hazards**. TRB Annual Meeting, Washington DC.
- Csanyi L.H. 1957. **Bituminous Mixes Prepared with Foamed Asphalt**. Ames, IA: Iowa State University, Iowa Engineering Experiment Station. (Bulletin; 189)
- Environmental Protection Agency United State, 2003. **EPA's Proposed Regulation of n-Propyl Bromide**. Air and radiation regulation. EPA-430-F-039 Washington DC.
- Emery S. J. and Zacharias M. P., 1994. **Temperature Susceptibility of South African Bitumen**. 6th Conference on Asphalt Pavement for Southern Africa, CAPSA, Cape Town.
- Gueit C., Robert M., and Durand G., 2006. **Characterisation of Different Phases in the Life Cycle of the Binder in Bitumen Emulsion. Recovery Method**. Eurasphalt and Eurobitume General review no. 849.
- Heukelom W., 1973. **An Improved Method of Characterising Asphaltic Bitumen with Aid of their Mechanical Properties**. Proceeding of Association of Asphalt Paving Technologist. Vol. 42, pg 67-84
- Jenkins, K. J., 2000. **Mix Design Considerations for Cold and Half-warm Bituminous Mixes with Emphasis on Foamed Bitumen**. PhD Dissertation, University of Stellenbosch, South Africa.
- Long F and Jooste F., 2007. **Summary of LTPP Emulsion and Foamed Bitumen Treated Sections**. Technical Memorandum Modelling and Analysis Systems, Cullinan, South Africa.

- National Cooperative Highway Research Program, 2000. **Recommended Use of Reclaimed Asphalt pavement in the Superpave Mix Design Method**. NHC Final Report D9-12, USA
- Okan S. and Mang T., 2003. **Investigation of Problem in Binder Extraction from Conventional and Rubber Modified Asphalt Mixture**. 6th Rilem Symposium, Zurich, Pg 212-219
- Overby, C., Johanson, R. and Mataka, M., 2004. **Bitumen foaming: An innovative technique used on a large scale for pavement rehabilitation in Africa. Case study: Same-Himo monitored pilot project**. Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04). Sun City, South Africa
- Peterson G. D., Soleymani H. R., Anderson R. M., and McDaniel R.S., 2000. **Recovery and Testing of RAP Binder from Recycled Asphalt Pavement**, Proceedings of the Association of Asphalt Pavement Technologist.
- UWP Engineers., 1999. **In-situ Recycling of a Cement Treated Base Course using Foamed Bitumen and Bitumen Emulsion**. Grassy Park, Cape Town.
- SABS 307 (1993). Standard Specification for the Bitumen Rheological Properties for Road Construction. South Africa.
- Serfass, J. P., Carbonneau X., Delfosse F., Triquigneaux J.P., and Verhee F., 2008. **Mix Design Method and Field Performance of Emulsion Cold Mixes**. 4th Eurobitume and Eurasphalt Congress, Copenhagen.
- Shell Bitumen, 2003. **Shell Bitumen Handbook**. Shell bitumen UK.
- Stroup-Gardiner M., Nelson J. W., 2000. **Use of Normal Propyl Bromide Solvent for Extraction and Recovery of Asphalt Cements**. NCAT Report, Auburn University.
- Tuffour Y. A. and Ishai I., 1990. **The Diffusion Model and Asphalt Age-Hardening**. Proceedings of Association of Asphalt Paving Technologist. Pg 73-92.