10th CONFERENCE ON ASPHALT PAVEMENTS FOR SOUTHERN AFRICA

THE INFLUENCE OF TEMPERATURE DISTRIBUTION AND VOIDS CHARACTERISTICS ON DURABILITY BEHAVIOUR OF BITUMEN STABILIZED MATERIALS

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Abstract: Temperature distribution and voids characteristic in a pavement layer play a significant role in both the ultimate gain in mix engineering properties and the exhibition of premature distress in the field conditions. In this study, the influences of temperature distribution and voids characteristics on durability bahaviour of Bitumen Stabilized Materials (BSMs) were investigated. Different methods were applied both in the field and in the laboratory conditions. In addition, quantification of effect of temperature distribution and voids characteristics on mechanical properties on BSMs samples was performed.
The results indicate that temperature distribution across the pavement section is not uniformly distributed over the layer. That is, maximum temperature is relatively higher on BSMs depth closer to the top surface than deeper in layer. A higher temperature gradient observed on field condition was found to influence negatively the mechanical properties (permanent deformation) of the BSMs mixes. On the other hand, the voids content characteristics were found to occur not only in the courser particles but also in the mix mastic of BSMs.

KEY WORDS: Bitumen stabilized material, temperature distribution model, voids characteristics, permanent deformation, durability

1. INTRODUCTION

Temperature distribution and voids characteristics in pavement structure play a significant role in both ultimate gains in mix engineering properties and by exhibiting premature distress. The influences of temperature and voids in Hot Mix Asphalt, HMA have been studies (Solaimanian et al., 1993; Jia et al., 2007; Highter et al., 1984 and Burger, 2005). But less is known for BSMs. Therefore, in order to evaluate the influence of temperature and voids on mix properties for BSMs it is ideal to have full understanding of their distribution and its influence that occur under field conditions. Temperature and voids distribution coupled with environmental conditions have found to influence gain in mix engineering properties, whilst adverse environmental conditions coupled with dynamic loading, have found to initiate the premature distress of the BSMs. Lazios et al., (2007) reported that the stiffness modulus gain of foam mix in the field tends to occur within weeks or months of construction. Loudon International (2008) found that premature distress of permanent deformation occurred in full-depth in-situ recycled (FDR) of BSM-foam was a result of higher temperature distribution in BSMs-foam layer coupled with excessive loading. Fu et al., (2007) reported failure on FDR of BSM-foam due to infiltration/suction of subgrade moisture through capillary action resulted from higher percentage of voids distribution in the mix. These findings emphasize the importance of predicting field temperature and voids distribution and its influence on the durability and performance when adjudicating mix selection. The effect of strength development for BSMs should be considered during mix design linked with environmental information applicable to a specific location.

2. RATIONALE FOR DEVELOPING TEMPERATURE DISTRIBUTION AND/OR EVAPORATION MODEL FOR PREDICTING LONG-TERM PERFORMANCE OF BSMs

BSMs mixes are produced with lower bitumen content and higher conservation of energy. Therefore, the mixes are characterized by partial coating of thin film of binder (bitumen) in mineral aggregates after the water evaporation. This results in formation of high voids content and makes the mixes less susceptible to temperature variations. However, depending on mix composition, the higher binder content and/or RAP (reclaimed asphalt pavement) content, in a mix, temperature distribution in the layer may adversely influence the performance of BSMs. Kröger and Burger (2006) reported that heat transfer in the pavement layers takes place from a region of high to low concentration. That means surface layer (AC or Seal) which is exposed to a high atmospheric temperature, depending on the voids and binder content in the mix, heat transfer from surface layer might reach underlying BSM-layer. However, it is a common practice that prior to application of surface layer, BSM-layer is exposed to atmospheric condition to ensure curing and strength development. The current curing period in practice is empirical, largely based on 7-14days of cure, which might not result to optimal performance of BSM-layer as foamed bitumen cures slightly different from bitumen emulsions. Weinert (1980) indicates that several distinct climatic regions exist. These regions are characterized by different environmental conditions like, temperature, relative humidity, wind and rainfall. Temperature and voids distribution in BSMs is known to influence the following:

- Evaporation of moisture in the mixes, i.e. enhancing breaking of emulsion and adhesion of the binder to the mineral aggregates
- Development of bonding between the binder and mineral aggregate surfaces; Stiffening of the mastic, which in turn affects stiffness, shear properties, and ultimate strength of the mixes;
- Equilibrium moisture content in the mixes and
- Ultimate durability behaviour of the mixes for long-term performance

Therefore, the rationally for application of a temperature distribution and/or evaporation models to be able to account for local environmental condition on pavement structure has an advantage of understanding the curing period (moisture evaporation) before opening of BSM-layer to traffic or application of surface layer (AC or Seals). The testing and evaluation framework presented in this paper is based on the relevant on the determination of temperature distribution and voids characteristics in BSMs. Selected field conditions and materials type were investigated using field extracted cores and laboratory prepared samples. The findings on the influence of temperature distribution and voids characteristics in pavement structure comprising BSM-layer are presented and discussed.

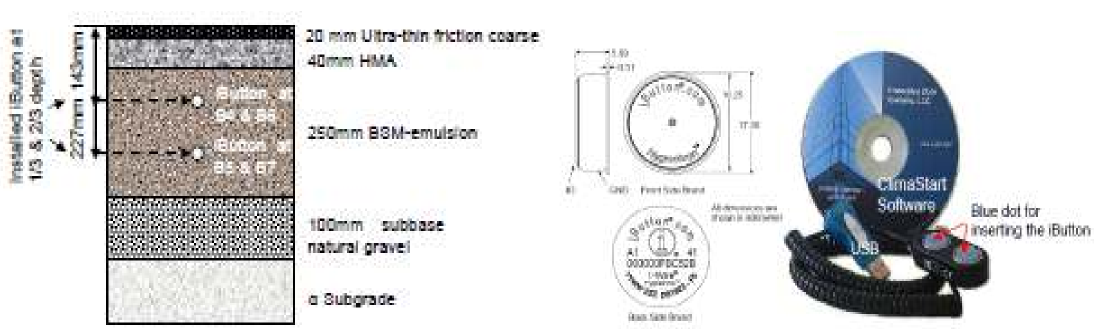
3. EXPERIMENTAL PROGRAM

3.1 Temperature monitoring and evaluation

Limited studies have been carried out in the past that includes experimentation with the curing temperature and moisture to investigate the influence of these factors on the behavior of BSMs mixes (Moloto, 2010; Serfass *et al*., 2003), but without the consideration of the temperature distribution in the BSM-layer under field conditions. Although simulating all field conditions under laboratory conditions might not be feasible and developing different procedure will not be realistic, understanding of the heat transfer of BSM-layer gives insight for simulation of the laboratory curing procedure more accurately. Monitoring of temperature distribution in this study was done at different depths on BSM-layer under field conditions. The aim was to understanding the link between temperature gradient, voids characteristics with climatic seasons and durability behavior of BSM layer.

3.1.1 Field investigation on temperature distribution

Field investigation on temperature distribution was done on BSM-emulsion in-situ recycled pavement structure at the N7 expressway near Cape Town. This pavement section was selected because the materials used in the recycling on this project formed the main research component done in the revised TG2 mix design guideline. The monitoring of the temperature distribution in the BSM-emulsion layer was done by using specialized device (iButton, DS1921G from Fairbridge Technology Ltd). The iButtons were installed at two different depths in the BSM layer of 250mm thick, i.e. at 1/3 depth and 2/3 depth. That is from the top surface of the pavement it is 143mm and 227mm respectively. The constructed pavement structure after recycling with bitumen emulsion is presented in Figure 1(a). The installed iButtons aimed at storing the temperature data and thereafter recovered into excel spreadsheet by the software called ClimaStart. The iButton and the required accessories are presented in Figure 1(b).



a**]** N7 pavement structure with BSM-emulsion layer   b] iButton with required accessories

Figure 1: Pavement structure with BSM-layer, location of iButtons and accessories required for monitoring of temperature distribution

The layout of the installed iButtons along BSM-emulsion layer section is presented as follows: Two points approximately 1.5Km apart in the longitudinal direction were selected in flat terrain. At these points two iButtons (B5 and B7) in transverse direction were installed near the centerline (inner lane,IL) and two iButtons (B4 and B6) were installed near the shoulder (yellow line,YL) as indicated in Figure 2.

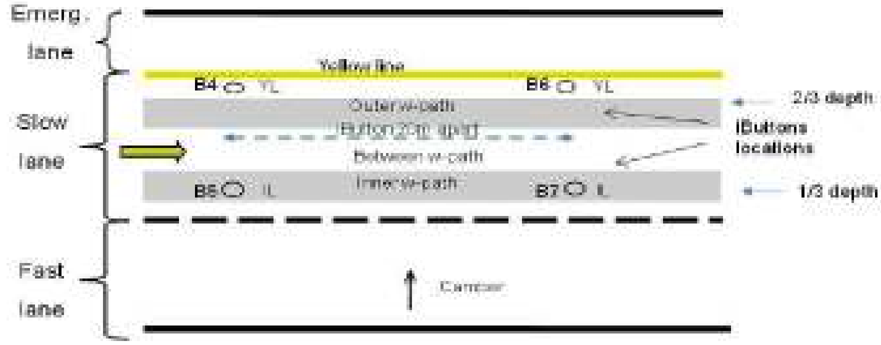


Figure 2: Layout and locations of installed iButtons in a BSM-emulsion layer at N7 expressway

The installations of iButtons were done after the completion of the rehabilitation project. A hole of 50mm diameter was drilled and iButton inserted. Similar material was backfilled and compacted in a hole to maintain the homogeneity. The selection of depths was based on the following reasons; Temperature and relative humidity (RH) varies across the pavement due to cross-fall (camber), i.e. higher RH being at the YL due to higher concentration of water and possible infiltration from the shoulder and/or side drain. The temperature intensity is always higher at the surface and decreases deeper in a layer.

3.2 Voids characteristic in mix matrix

The fundamental influence on moisture damage and age hardening in the BSMs is linked with air voids content. The voids content characteristics is a result of level of compaction as well as the nature of dispersion of binder into selective fractions in the mineral aggregates, binder thickness, mastic filler, addition of active filler and binder-mineral aggregates interaction. It is apparent that understanding of the voids content distribution in BSMs is vital in both laboratories compacted specimen as well as cores extracted from the pavement in the field. In this study, the quantification of the voids content in the material composition for the BSM mixes was determined after carrying out test on the relative bulk density (RBD) and maximum theoretical relative density (RICE) on the specimens. Further, analysis of voids content distribution was performed at microscopic levels using Scanning Electron Microscopy (SEM). The results of the analysis of different mix composition are presented and discussed.

3.3 Laboratory testing methods

3.3.1 Cores extracted from field pavement structure

The cores from two different roads were analyzed: P243/1 near Vereeniging in Gauteng and Shedgum Road in Saudi Arabia. The cores from P243/1 were extracted from two different pavement sections, i.e. foamed bitumen and bitumen emulsion. The material composition during foamed bitumen recycling includes 40mm HMA and 200mm of cement-treated Quartzite sandstone base, whereas with bitumen emulsion similar pavement structure was recycled but the base material was cement-treated ferricrete. The binder content during stabilization was 1.8% with 2% active filler (cement). 36 briquettes were extracted from YL, OWP[1] and BWP[2] from different stations along the road. The cores extracted from Shedgum

[1] OWP = On wheel path

Road came from full-depth in-place foamed bitumen recycling. Full-depth recycling involves 100% RAP in the mix composition, i.e. pulverization of 300-400mm distressed HMA and stabilization of top 150mm with 2.5% foamed bitumen. The quantification of the voids contents and the effect of temperature distribution on the resistance to permanent distribution were evaluated on the prepared cores specimens. Further investigations on the extracted cores were binder ageing and moisture susceptibility, the detailed testing methods and parameters for binder ageing and moisture susceptibility are not presented here but reader are referred to the PhD thesis by Twagira, (2010).

3.3.2 Laboratory prepared specimens

In the laboratory, the specimens were prepared using vibratory BOSCH® compactor see Figure 3. The vibratory compactors normally pack aggregate particles in a specimen closely, similar to field conditions. The materials from N7 expressway, i.e. Hornfels-RAP as well as Quartzite crushed stone from Prima quarry were used for laboratory prepared specimens. These aggregates were graded to a maximum size of 19mm and percentage passing 0.075mm of 10% and 6% respectively. The selected aggregates were stabilized with foamed bitumen or bitumen emulsion, 2% net bitumen content was applied, whereas 0% and1% active filler (cement or lime) was added to the stabilized materials. The total number of prepared and tested mixes were 12.

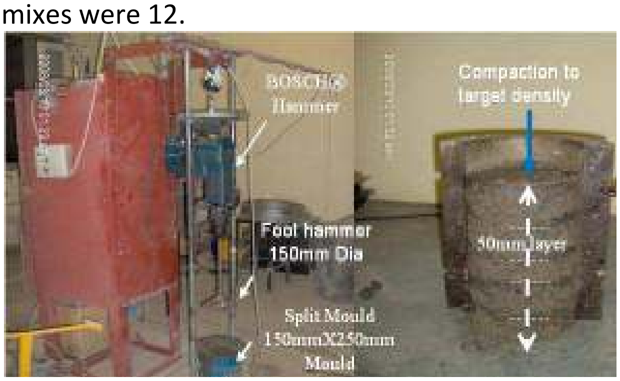


Figure 3: Modified vibratory BOSCH® hammer and compacted specimen layers

The curing technique on compacted specimens was done as follows: compacted specimens were placed in a draft oven at 30°C for 20hours unsealed, followed by sealing and raising the temperature to 40°C for 48hours. The same curing method was followed for bitumen emulsion and foamed bitumen. After curing, the specimens were sealed in a different bag and left to cool at ambient temperature before testing. The quantification of voids contents and the effect of temperature distribution on the resistance to permanent deformation were performed on prepared specimens.

4. ANALYSIS AND DISCUSSION OF RESULTS

The studies on HMA by Jia *et al.*, (2007); Highter *et al.*, (1884) and Burger (2005) indicated that the temperature distribution in the pavement layer is influenced by the time of solar radiation and the heat transfer coefficient. That means, pavement layer conductivity varies in the depth during the day and the night. Jia *et al*., (2007) indicated that temperature distribution in the pavement layer can be assumed adiabatic at a certain depth. That is to say, deeper in the pavement layer the temperature is constant and the effect of

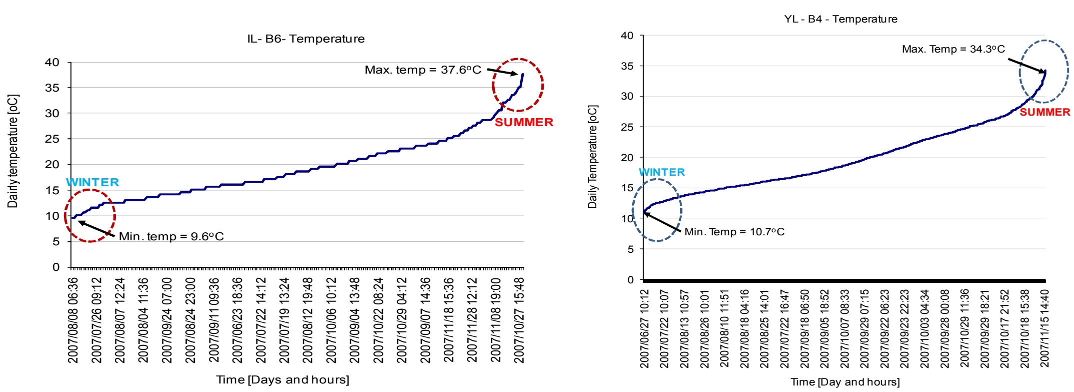
[2] BWP=Between wheel path

conductivities is negligible. A BSM-layer in South Africa pavement structure is constructed shallower at depth of 50mm or less. Therefore, the variation in the temperature distribution under field conditions needs to be clearly understood.

4.1 Temperature distribution in the BSM-emulsion layer

4.1.1 iBottons at position B5 and B4

The data from iButtons installed at position B5 (near Inner lane, IL) and B4 (near Yellow Line, YL) records temperature values at 1/3 and 2/3 depth of BSM-layer respectively. The data were captured for the period of six (6) months; that is from June 2007 (winter) to December 2007 (beginning of summer). The analysis of temperature data is presented in Figure 4 (a). It can be seen from the results in Figure 4(a) that during *winter* the temperature reading at 1/3 depth (position B5) was 9.6°C. Whereas during the beginning of summer the temperature reading in the same position (B5) was 37.6°C. For position B4, the recorded temperature values at 2/3 depth of the BSM-layer are presented in Figure 4(b). It can be seen from the results in Figure 4(b) that during *winter* the temperature reading was 10.7°C, whereas during the beginning of summer, the temperature reading at the same position (B4) was 34.3°C. The comparison of the temperature data on BSM-emulsion layer at different depth of 1/3 and 2/3 during winter period and beginning of summer shows that BSM-emulsion layer experiences temperature gradient. The fact that the top layer 1/3 of BSM-emulsion experience overall higher temperature than bottom layer 2/3, this indicates that temperature distribution in a BSM-emulsion layer is not uniform.



a] Position B5 (IL) temperature data at 1/3 depth of BSM-layer

b] Position B4 (YL) temperature data at 2/3 depth of BSM-layer

Figure 4: Daily temperature data near the inner lane (IL) and Yellow line at 1/3 and 2/3 depths on the BSM-emulsion layer respectively, at N7 expressway near Cape Town

4.1.2 iBottons at position B7 and B6

The data from iButtons installed at position B7 (near Inner lane, IL) and B6 (near Yellow Line, YL) records temperature values at 1/3 and 2/3 depth of BSM-layer respectively. The data were captured for the period of 2 years; that is from winter to summer to winter full climatic cycles i.e. June 2007 (winter) to June 2009 (winter). Unfortunately, during recovery the iButton from position B7 was damaged, so it was unable to retrieve the recorded data. Therefore, the data presented in Figure 5 is based on the analysis of temperate recorded from position B6 alone. The results in Figure 5 show that during *winter* the temperature reading at 2/3 depth (position B6) was 9.6°C whereas, during the peak summer the temperature reading in the same position (B6) was 49.6°C.

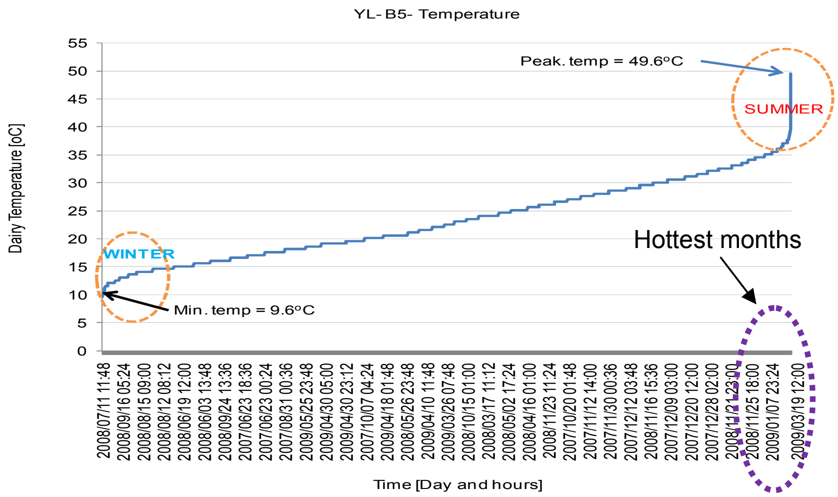


Figure 5: Daily temperature data near the yellow line at 2/3 depth on the BSM-emulsion layer at N7 expressway near Cape Town

The hottest months of summer in the study period was found to be consistence in all years i.e. 2007, 2008 and 2009 which is December until March. The extract of the conservative hot days in Figure 5, gives an indication of the summer maximum, minimum and average temperature in BSM-emulsion layer as presented in Table 1.

Table 1: The extract of the maximum's daily hottest temperature in the BSM-emulsion layer at 2/3 depth during summer period

Year	Month	Date	Time [hrs]	Temp. [°C]	Max. temp [°C]	Min. temp [°C]
2009	March	19th	18:00	49.6		
2007	Dec	22nd	18:36	39.6		
2009	Jan	11th	18:24	38.6		
2009	Feb	08th	19.48	38.6		
2008	Jan	10th	17:36	37.7		
		Average temperature		40.8	49.6	37.7

The maximum temperature data presented in Table 1 and Figure 5, for the BSM-emulsion layer measured at 2/3 depth is 49.6°C. The trend observed in Figure 4 and 5, shows that maximum temperature is relatively higher on the BSM-emulsion depth closer to the top surface than deeper in a layer. From the general trend, it is evident that the temperature at 1/3 depth in position B7 (iButton damage) was expected to be higher than 49.6°C during peak summer. The temperature of this magnitude in a BSM-layer coupled with field loading will influences significantly the mechanism of the material durability behaviour and long-term performance. This was evident when similar magnitude of temperature was used to determine the resistance to permanent deformation on cores and laboratory prepared specimens. The corresponding results are presented and discussed.

4.2 Determination of temperature gradient using solar time

Having described the temperature variation at different depths in the BSM-emulsion layer, it is important that temperature gradient in a layer is analysed. The daily temperature values recorded during beginning of summer time at position B4 and B5 (or 1/3 and 2/3 depths of BSM-layer respectively) are used for temperature gradient analysis. The temperature values for B6 and B7 are not comparable due to damage of iButton at B7. The extracts of temperature values in summer at different solar time are presented in Table 2. It can be seen from the results that at the top of BSM-emulsion layer (1/3 depth) in the morning hours, temperature is lower and increases during the afternoon hours and later decrease during the night hours. Whereas, at the bottom layer, (2/3 depth) temperature is relatively lower during morning hours and increase during the day but at lower rate compared to the top, and during night stay higher than top layer. The top layer however seems to cooling down at higher rate in the night due no solar radiation. The reason for the hourly temperature variation in the BSM-emulsion layer is linked to the changes in air temperature, wind speed and relative humidity at different time in a day (i.e. from morning to night).

Table 2: Temperature gradient in the BSMs-emulsion at different solar time

Depth [mm]	2007- Oct-22nd		2007-Oct-21st		2007-Oct-20th	
	Morning		Afternoon		Night	
	Time [hours]	Temp. [°C]	Time [hours]	Temp. [°C]	Time [hours]	Temp. [°C]
1/3 (143)	8:00-9:00	22.6	12:00-14:00	33.6	20:00-22:00	32.1
2/3 (227)		*25.6*		*29.7*		*33.7*
	2007- Nov-16th		2007- Nov-15th		2007- Nov-14th	
1/3 (143)	8:00-9:00	22.1	12:00-14:00	34.1	20:00-22:00	28.6
2/3 (227)		*24.9*		*31.0*		*33.2*

A typical hourly temperature variation in a BSM-layer at different depths in a day (i.e. from morning to night) is defined as temperature gradient as presented in Figure 6. It can be seen from the gradient that BSM-layer at the top experience lower temperatures in the morning and increases during the day and cools faster during the night.

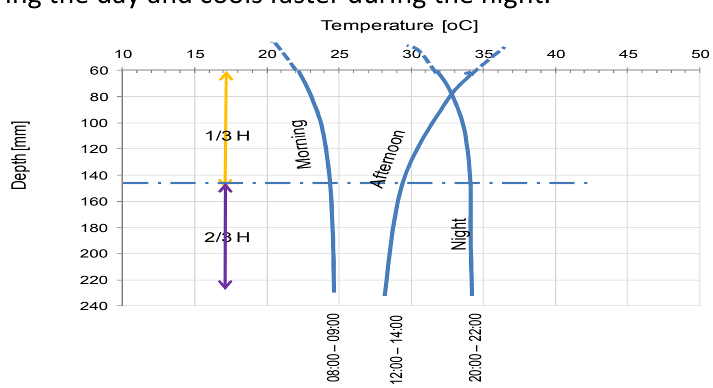
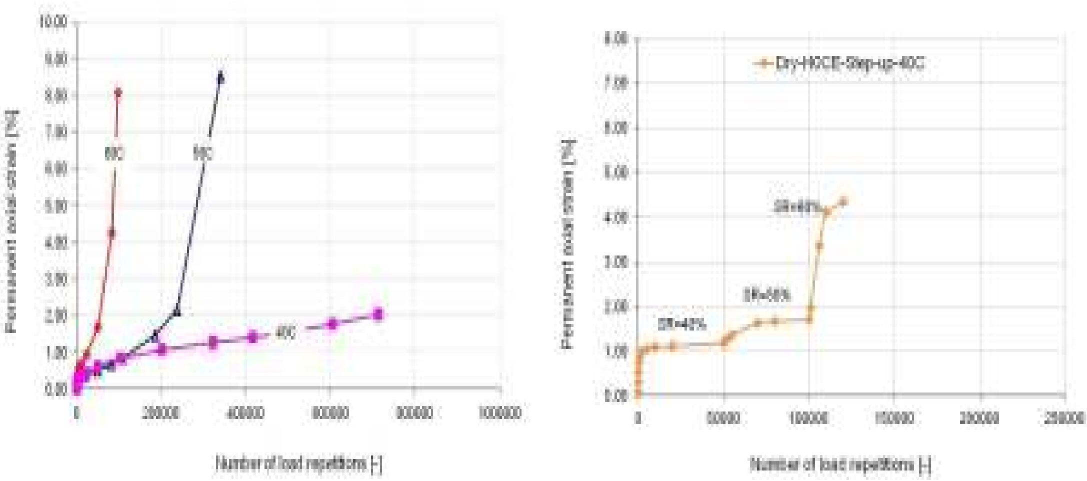


Figure 6: Temperature gradient through BSM-emulsion layer, with surface layer extrapolated

The temperature gradient analysis gives an indication of heat transfer through the BSM-layer. That means, understand of environmental factors such; solar radiation, air temperature and wind speed, together with heat transfer coefficient (thermal conductivity) and material properties of BSM-layer modelling of critical parameter such a moisture loss in the BSM-layer can be established. To this end, future research is recommended to provide accurate prediction of moisture loss in BSMs for optimum application of surface layer and/or appropriate time for opening BSM-layer to traffic. Burger (2005), developed a model for heat transfer in HMA under field condition using South African conditions. This model has potential to be developed further for its applicability in BSMs.

4.4 Influence of temperature distribution on permanent deformation.

The limited laboratory results are presented in this paper to demonstrate the influence of measured field temperature i.e. 49.6°C in the performance of BSMs. Three cores extracted from Shedgum Road in Saudi Arabia as discussed in section 2.3.1 were conditioned and tested for permanent deformation. The conditioning and testing procedure were done according to Stellenbosch protocol (ITT, 2005). Sensitivity analysis on three different temperatures were investigated, i.e. 40°C, 50°C and 60°C. The results are presented in Figure 7(a). It can be seen from the result that the critical temperature lies between 40°C and 50°C. Laboratory specimen prepared from BSM-emulsion without the addition of active filler was conditioned and tested for permanent deformation. The multistage permanent deformation was applied at 40°C. The result is presented at Figure 7(b). It can be seen from the result that at Stress Ratio (SR) of 60% critical flow was achieved i.e. higher than 4% axial strain. It is evident from the results that recorded temperature gradient in BSM-layer couple with materials properties can significantly influence the durability behaviour and long-term performance of BSMs.



a] Permanent axial strain of field cores (BSM-foam) tested at SR of 40%, confinement 100kPa and active variable temperature.

b] Multistage permanent axial strain on lab. spec (BSM-emulsion) with no filler and H0CE) tested at 40°C, confinement 100kPa and variable SR

Figure 7: Influence of temperature distribution on durability and long-term performance of BSMs

4.5 Voids characteristics in laboratory compacted specimen

The results of the inter-particle voids content in the BSM-foam and BSM-emulsion for laboratory prepared specimens are presented in Table 3 and Figure 8. These results show that BSM-emulsion voids content fall in a range of 10% to 13%, while BSM-foam shows inter-particle voids content of 13% to 16%. This shows that the ranges of voids content in BSMs are higher than that of typical HMA.

Table 3: Bulk relative density, Rice density and voids content in BSMs

Binder type	BSM-mix type	Bulk relative density, BRD [Kg/m^3]	RICE density [Kg/m^3]	Voids content [%]
BSM-foam	H0CF	2 177	2590	16.0
	H1CF	2 232	2593	13.9
	H1LF	2 241	2592	13.5
	Q0CF	2163	2553	15.3
	Q1CF	2196	2573	14.6
	Q1LF	2198	2561	14.2
BSM-emulsion	H0CE	2245	2566	12.5
	H1CE	2287	2564	10.8
	H1LE	2237	2694	13.0
	Q0CE	2289	2580	11.3
	Q1CE	2201	2516	12.5
	Q1LE	2273	2584	12.0

Note: Aggregates type, H=Hornfels-RAP, Q=Quartzite stone, C=cement, 0=No cement added

The analysis on the trends of the voids properties in terms of binder and aggregate types are presented in Figure 8. The result shows that aggregates type, that is, either Hornfels-RAP or Quartzites, has no particular influence (or trend) on different voids content measured on BSMs mixes. However, there is general trend of increase in voids content on BSMs without addition of active filler compared with the one with addition of active filler (i.e. lime or cement).

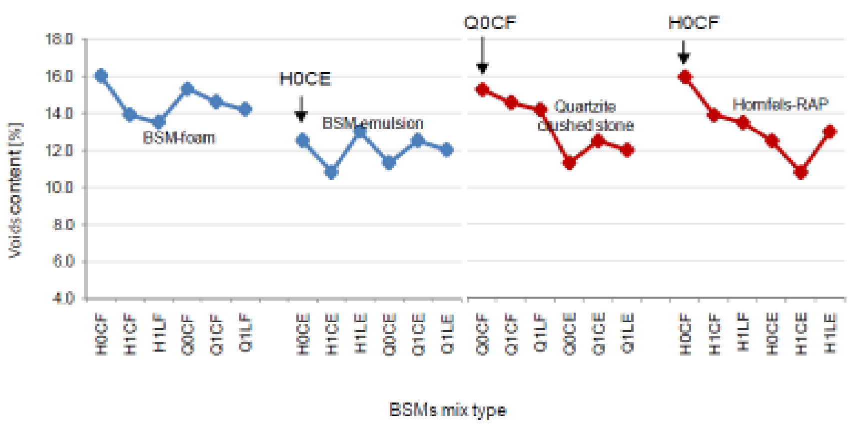


Figure 91: Voids properties of BSMs and influence of mineral aggregates types.

From the voids properties results, it is evident that BSMs has total higher voids content in the mix matrix. However, the voids properties in different mix composition have found not to correspond to the moisture damage behaviour (Twagira *et al.*, 2009). This shows that voids content structure in the mix matrix might be largely isolated and less interconnected. The behaviour of voids structure distribution in the BSMs mixes is illustrated in Figure 9.

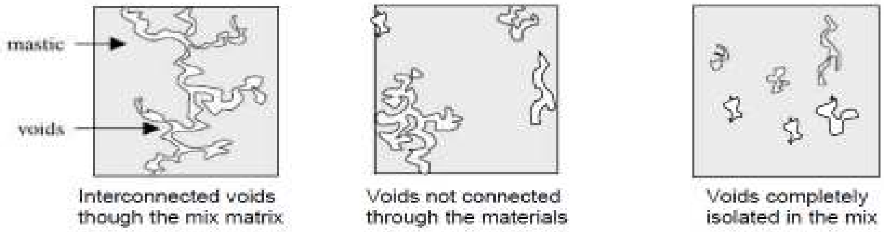


Figure 9: The different mode of voids structure present in the BSMs

4.2.1 Voids characteristics in field extracted cores

The voids characteristics of BSM mixes exposed to field conditions were analyzed from cores extracted from an in-service pavement section. The volumetric properties of the field extracted cores from P243/1, near Vereeniging in Gauteng, are presented in Table 4.

Table 4: Volumetric properties of the field extracted cores from P243/1

Volumetric properties	Mixture type					
	Foamed bitumen			Bitumen emulsion		
	YL	OWP	BWP	YL	OWP	BWP
MC [%]	11.3	11	19.7	9.6	9.6	-
Voids [%]	16.4	16.0	15.2	24.9	25.9	23.7

Note: Aggregates type, Foam=Ferricrete, Emulsion= Sandstone

From the voids content results in Table 4, it can be seen that bitumen emulsion mixes have higher voids contents compared to the laboratory compacted specimen (Table3). This is because of a larger aggregate size of RAP content recycled with crushed cement treated material in the mix. The condition of cores extracted from the field shows that compactability of RAP aggregates with sandstone leave large amount of voids in the mix. The cores extracted from Shedgum Road came from full-depth in-place foam bitumen recycling. The calculated voids content is related to binder content and rutting behaviour in different locations (i.e. OWP, IWP[3] and BWP) of pavement structures, as presented in Table 6.

Table 6: The average percentage voids, bitumen content and rutting, of the cores extracted from different stations and locations of Shedgum Road.

Volumetric properties, Top and bottom of core		Core extraction location and position on pavement					
		ST04 right OWP	ST04 left OWP	ST08 right IWP	ST08 Right BWP	ST09 left OWP	ST09 left BWP
Top	Rut [mm]	10	20	0	0	20	0
	BC [%]	8.4	7.7	6.8	6.8	9	7.4
	Voids [%]	5.5	5.0	8.4	8.4	2.5	9.4
Bottom	BC [%]	8.4	7.1	6.8	6.8	9.5	7.5
	Voids [%]	10.2	10.9	11.6	12.8	5.4	13.3

Note: Aggregate type: recycled 100% Limestone-RAP

The extracted cores from different stations (ST04, ST08 and ST09) were sliced into two sections. The binder content (BC) recovered from the top and bottom slices were recorded. The result shows that recycled layer has relatively higher BC than typical HMA; this is because 100% RAP was used in the mix with the addition of 2.5% foamed bitumen.

[3] IWP=Inner wheel path

However, the binder content seemed consistently equal for the different locations (Table 5). The general trend shows that voids content is related to binder content and field rutting. The location with higher voids content and lower binder content has lower rutting. Likewise, the location with lower voids content and higher binder content has higher rutting. This behaviour is graphically presented in Figure 9.

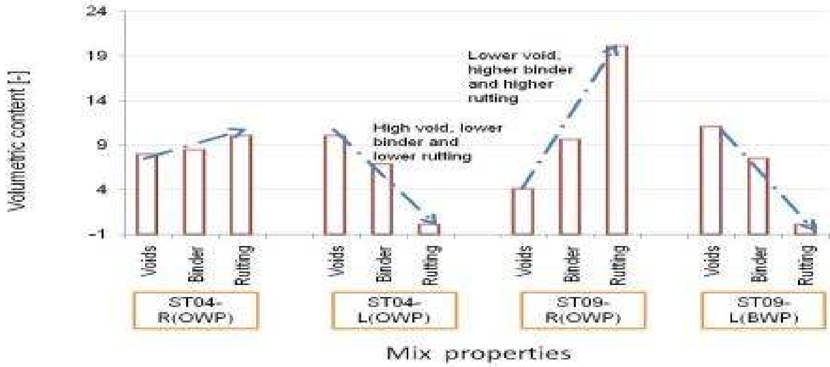


Figure 9: The relationship between voids content, binder content and rutting behaviour in BSM mixes from Shedgum Road

Addition investigation was done by relating the voids content in cores and laboratory specimens, with the age hardening of the binder. The results are presented in Figure 10. It can be seen from the results that air voids content in some BSM mixes has no direct correlation with age hardening behaviour. For instance, mix at ST8-BWP has lower voids content of 10%, but higher ageing effect, i.e. reduction of original pen of 60-70dmm to 20dmm. On the other hand, mix from ST8-IWP has voids content of 10% but same ageing effect of pen reduction to 10dmm. The inconclusive outcome prompted further analysis on voids characteristics at microscopic level.

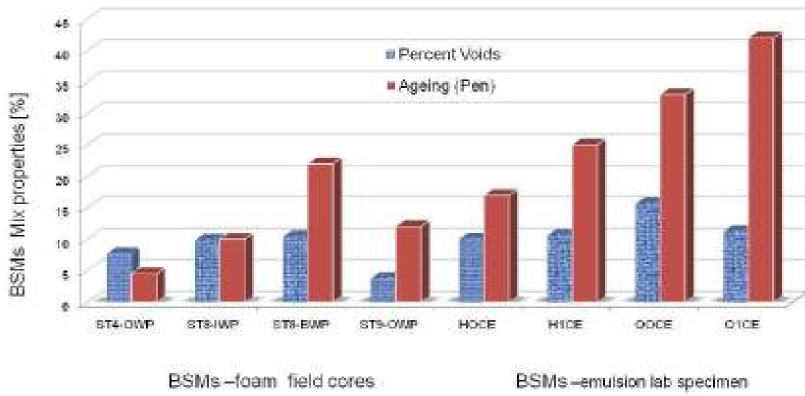
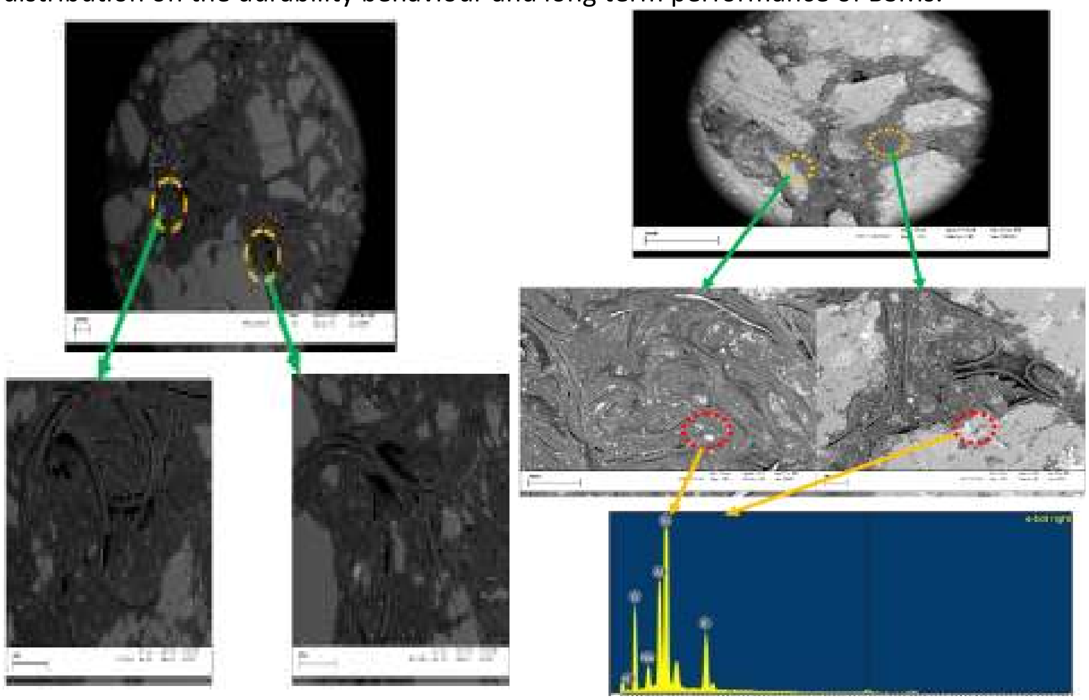


Figure 10: Comparison between air voids content and age hardening behavior in BSMs

4.2.2 Voids distribution in the mix matrix using SEM analysis

Analysis of voids distribution in limited samples was done using Scanning Electron Microscopy (SEM). The SEM measuring technique is commonly applicable in the field of mineralogy; therefore, analysis of the BSMs samples in this study was done at the Department of Geology, Stellenbosch University. Sample preparation and testing method using SEM technique will not be presented here, however for more details readers are referred to PhD thesis by Twagira, (2010). The result of SEM analysis on BSM-foam samples (Q1CF, or Quartzite aggregates stabilised with foamed bitumen and addition of cement and

H0CF, or Hornfel-RAP stabilised with foamed bitumen, without addition of cement) are presented in Figure 11(a) and (b) respectively. The images show that thread-like structures of bitumen mastic are present between coarse particles. However, the mastic in Q1CF shows a continuum of bitumen embedded with filler particles (rich in bitumen) and interconnected by threads of bitumen. Similar behaviour occurred in H0CF, but bitumen seems to be lightly dispersed in the mineral aggregates, this is due to lack of cement as dispersion agent. Voids in the mastic are observed in the H0CF with cracking behaviour compared to the voids in Q1CF. It is evident that the pattern of voids content distribution in the BSMs seems to be complex, because the voids are not only distributed in the course particle, but also through the mastic. Therefore, further investigation on wide range of mixes is required in the laboratory and in the field to understanding the influence voids distribution on the durability behaviour and long term performance of BSMs.



a] BSM-foam, Q1CF specimen　　　　b] BSM-foam, H0CF specimen

Figure 11: SEM analysis at magnification (200µm) on BSM-foam samples, Q1CF and H0CF

The bright spot noted on the mastic and on the large aggregate fraction of the Hornfels-RAP were further analysed using Energy Dispersive X-ray spectrometer, EDS. The discussion on the EDS results will not be presented here. However, the readers are referred to PhD thesis by Twagira, (2010) for more details.

5. CONCLUSIONS AND RECOMMENDATIONS

The influence of temperature distribution and voids characteristics on durability behaviour of BSMs were analysed in this paper. From the results presented, the following conclusions and recommendations can be made:

- The maximum temperature recorded in BSM-emulsion layer during peak summer at the depth 2/3 below the layer is 49.6°C and minimum is 37.7°C. The magnitude of this field temperature coupled with materials properties can significantly influence the durability behaviour and long-term performance of BSM layer. The determined voids content varied from 10%-13% for BSM-emulsion and 13%-16% for BSMs-foam. These values are higher than typical voids for HMA. Therefore, understanding of temperature distribution and voids characteristics is vital in BSMs mixes.

- Field investigation on BSM-emulsion layer shows that the temperature across the pavement section is not uniformly distributed over the layer. The trend observed shows that maximum temperature is relatively higher on BSM depth closer to the top surface than deeper in layer. Therefore, temperature gradient in a layer may be used to determine influence on moisture evaporation. That means, understanding of the temperature distribution in BSM-layer is important for judging the appropriate time (in hours or days) the constructed layer can be surfaced or opened to traffic.
- The key factors that have been indicated to influence temperature distribution and voids characteristics in BSMs are: heat transfer and voids structure. The heat transfer in the BSM-layer depends on the local environmental factors such as solar radiation, wind speed and relative humidity as well as materials properties. Therefore, modelling of these factors is required for proper prediction of evaporation and strength gain in the layer.
- The results from SEM presented in this study shows that the pattern of voids content distribution is complex because the voids are not only among the coarse particles but also through the mastic. Therefore, the linkage of voids content distribution with mechanism of failure in BSMs required further investigation both in the lab and under field conditions.

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