

# FORENSIC INVESTIGATION INTO THE PERFORMANCE OF HOT-MIX ASPHALT

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## ABSTRACT

As a prologue to a larger research project to improve the durability of Hot-Mix Asphalt (HMA), the performance of five HMA wearing courses situated in South Africa's Gauteng Province was assessed in detail. Four sections reported to be performing poorly and one good performing section were investigated. The investigation included a desktop study of as-built documents, traffic records and climate data, as well as non-destructive testing to assess the structural condition of the pavements and an array of laboratory tests performed on core samples taken from the sections.

The findings of the forensic investigation underlined the high demands placed on binder stiffness by the local climate, with pavement temperatures rising to above 50°C on more than 160 days per year. Several shortcomings in the rehabilitation design processes for the studied sections were identified. Typically, reliable prediction of future traffic was lacking, and the designs failed to address distress in the existing pavement layers. The investigation provided an indication of the potential value of grading analysis methods, such as the Bailey method, for the improvement of HMA design. Analysis of the binder recovered from field cores showed that premature binder ageing had occurred at three of the five sections. The premature ageing may be related to permeability of the HMA mixes. The core samples taken from intersections showed contamination due to fuel spillage, especially at intersections, resulting in softening of the binder and an increased risk for permanent deformation at these critical locations. The findings further suggest that Stress Absorbing Membrane Interlayers should be used with caution as they may trap water in the pavement structure.

**Keywords:** forensic investigation, permanent deformation, fatigue cracking, ageing.

## 1. INTRODUCTION

The discussion in this paper is based on the outcome of a detailed forensic investigation on the performance of Hot-Mix Asphalt (HMA) on five road sections in the Gauteng province. The investigation forms part of a larger project to improve the rutting and fatigue behaviour of HMA wearing courses in South Africa. The findings of the forensic investigation were used, in conjunction with the outcomes of a state of the art survey, to define the scope of a multi-year HMA research programme currently in progress. Selection of the five sections was based on the results of a preliminary forensic investigation by Verhaeghe [1], for which the performance of a large number of HMA sections in the province was studied. The some of the main tentative conclusions of this preliminary investigation were:

- Often too little effort was invested in the design of appropriate mixes for the prevailing conditions at the sites where the mixes were to be applied. More rut-resistant mixes should be identified for demanding sites with slow moving vehicles and significant turning action such as intersections. The selection of an optimum grading curve without sudden discontinuities did not appear to have received the necessary attention.
- With respect to fine continuously graded mixes, mixes with low filler contents (i.e. less than 5.5 per cent) or high filler contents (i.e. more than 7 per cent) did not perform as well as those with filler contents of between 5 and 7 per cent.
- Continuously graded asphalt mixes with fines contents (passing 2.36 mm sieve) of approximately 50 per cent tended not to perform as well as those with lower fines contents.
- It appeared there was a need to develop a design protocol specific for Stone Mastic Asphalt (SMA) mixes. In some cases design engineers seemed to have applied Indirect Tensile Strength (ITS) and Marshall Stability requirements intended for more conventional mix types, to select the optimum binder content for SMA mixes.
- A need was identified to reassess the binder specifications to accommodate the particular conditions prevailing in Gauteng (i.e. dry winter conditions, hot summers and high ultra-violet radiation).
- Semi-gap graded mixes should be used with caution as they appear to be susceptible to fatigue cracking. It should be investigated why they appear to be susceptible to cracking and solutions need to be identified;
- The use of different binder contents between, slow and fast lanes, and possibly even the use of different mix types, should be encouraged.

The aim of the detailed forensic investigation was to expand on the findings of the preliminary investigation. The following two objectives were set for the detailed forensic investigation:

- (1) Better understand those HMA characteristics that contribute to the performance of the HMA wearing courses placed on the Gauteng provincial road network, and

- (2) Identify those aspects of HMA mix design that require further study as input for a focused HMA investigation that would involve laboratory testing as well as APT-related testing with the objective of developing and/or refining the HMA mix design method so that practitioners would be able to use it with greater confidence to achieve the desired outcomes.

The methodology used in the forensic investigation will be discussed first, followed by a description of the condition of the road sections and the observed distress. Section 4 presents the local climatic and traffic conditions. The design of the HMA mixes is discussed in Section 5, and Section 6 contains the outcome of the assessment of the pavement structures. The results of laboratory testing and likely causes of distress are discussed in Section 7, followed by a reflection on the design process and conclusions.

## 2. METHODOLOGY

The first task in the forensic investigation was to study the data available for a range of HMA sections identified during the preliminary investigation. From this data, four sections classified as poor performing and one section classified as good performing were selected for a detailed assessment. The selection was mainly based on the availability and quality of as-built data, material reports, performance data, climate data and traffic data, as well as the results of additional visual assessments performed during site visits.

The structural condition of the five selected pavements was assessed by means of Falling Weight Deflectometer (FWD) and Dynamic Cone Penetrometer (DCP) tests. The primary objective of the non-destructive testing was to establish whether the behaviour of the poor performing sections was indeed related to HMA mix specific properties and not to the condition of the substrata.

After completion of the non-destructive testing, cored samples of the asphalt surfacing were taken from the selected sections. Engineering properties were determined for the cored HMA samples, including density, stiffness, tensile strength, resistance against permanent deformation, grading and water permeability. The condition of the binder recovered from the cored samples was assessed by means of various physio-chemical tests. The paper is based on the results of the study as reported by Denneman and Van Assen [2].

## 3. CONDITION OF HMA SURFACING AT SELECTED SECTIONS

The HMA overlays on the poor performing sections formed part of rehabilitation projects conducted in 1999. The construction of the good performing section, which is the only newly constructed road section included in this study, also took place in 1999. Figure 1 shows the Visual Condition Index (VCI) of the road sections over time. The VCI parameter used by the Gauteng Department of Public Transport Roads and Works (GDPTRW) is calculated by assigning weight factors to the different distress types. In this weighted score system, the occurrence of rutting and cracking are assigned relatively high weights compared to other forms of distress. For the forensic study, it was assumed that when the VCI for a road section drops to below 70, the road has reached the end of its optimal pavement functionality and may be due for rehabilitation. As can be seen from Figure 1, the VCI for sections P1 to P4 was restored to almost a perfect score of 100 directly after rehabilitation in 1999. From this level, the VCI of the sections decreased with time. The condition of section P2 became worse than its pre-rehabilitation condition within four years. The condition of section P4 broke through the 70 level after five years. Both section P2 and P4 continued to deteriorate rapidly. The VCI scores of sections P1 and P3 reached 70 in 2005, after six years of service. For the good performing section G1, only three years of VCI data are available as the visual inspections were started three years after construction. The visual condition of the good performing section stands at 95 after six years of service.

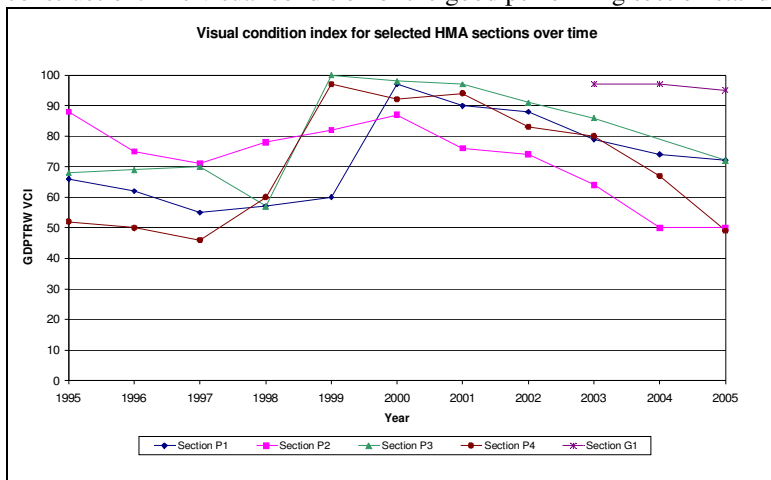


Figure 1: Visual condition of selected sections over time

The HMA at the selected sections exhibited different types of distress. The 30 mm SMA overlay on section P1 showed signs of permanent deformation and light cracking. Some surface failure, edge breaking and dryness of the binder were also observed. Due to the high weight given to rutting and cracking in the VCI calculation, these distress types are primarily responsible for the decline in VCI.

The primary problem with the 25 mm continuously graded medium asphalt (ACM) overlay placed at the intersections of section P2 is extreme permanent deformation (see Figure 2).

Sections P3 and P4 are situated on the opposite directions of a dual carriageway. The overlay placed on section P3 consists of a 4 mm Stress Absorbing Membrane Interlayer (SAMI), a 30 mm ACM middle layer and a 30 mm Bitumen Rubber Continuously-graded Asphalt (BRCA) top layer. The structure of the section P4 overlay is similar to that of P3, except that the top layer consists of an SMA instead of the BRCA layer. The primary form of distress found at both sections is cracking of the surfacing. Figure 3 shows an example of the cracking observed in the BRCA of section P3. The distress in the SMA of section P4 is of a similar nature. At the good performing section G1, no distress was reported, apart from a slight degree of binder dryness of the binder.



**Figure 2: Permanent deformation at intersection road P2**

**Figure 3: Cracked BRCA surfacing section P3**

#### **4. LOCAL CLIMATE AND TRAFFIC CONDITIONS**

Sections P1 and G1 are located north of Pretoria. Sections P2, P3 and P4 are located between Pretoria and Johannesburg. Data from weather stations close to the investigated sections were used to calculate the temperature regime to which the HMA wearing courses were subjected. The diurnal temperature distribution in HMA layers can be calculated using a model developed for South African conditions by Viljoen [3] which was further validated and published by Denneman [4]. Figure 4 shows the temperatures at different depths for the hottest recorded day since 1999 at the sections south of Pretoria. The extremes of the calculated temperature conditions at the sections since rehabilitation in 1999 are shown in Table 1. According to the local HMA design guideline by Taute et al [5] the shear resistance of HMA wearing courses decreases dramatically due to softening of the binder at pavement temperatures above 45°C. Shell [6] has shown that the stiffness of an open graded asphalt mix with a 50 pen grade bitumen falls to only 100 MPa at 50°C, a dense graded mix reaches this stiffness at 58°C. Table 1 indicates that the surface temperature reaches 50°C for more than 160 days each year and in excess of 60°C on 24 days per year for the northern sections.

The implementation of a Performance Grading (PG) system for bituminous binders, similar to the system included in the American SUPERPAVE method, is currently being debated in South Africa. The SUPERPAVE mix design methodology uses the average seven-day maximum pavement temperature at a depth of 20 mm and the average minimum surface temperature, for the selection of Performance Grade (PG) binders. The 98<sup>th</sup> percentile values for the seven-day average maximum temperatures for the roads south of Pretoria were calculated to be 56.9°C, and 59.1°C for the roads north of Pretoria. A suitable binder grade for the roads south of Pretoria would be a PG58-X, while for the sections north of Pretoria a PG64-X would be more suitable. Under conditions of slow moving traffic, such as intersections, a higher grade should be selected. Selecting a higher grade should also be considered when the design traffic load exceeds 10 million standard axles. According to a recent performance grading comparison of South African bitumen by Sabita [7] only one bitumen was found to be of the quality required (PG70-22) for application in situations with slow moving or heavy traffic at road sections north of Pretoria. In cases where high PG grades are required the use of modified binders should be considered.

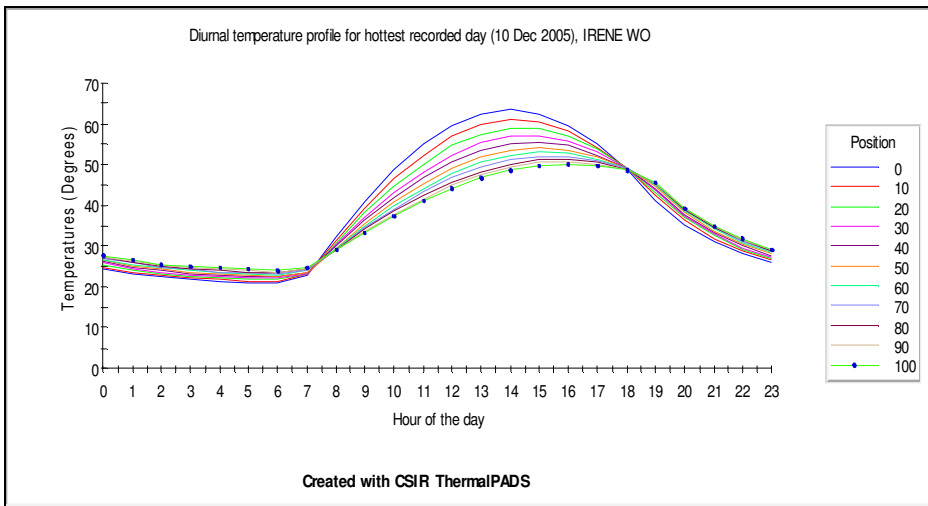


Figure 4: Prediction of diurnal temperature profile for hottest day at sections P2,P3 and P4

Road section	P1 & G1	P2,P3,P4
Maximum surface temperature	68.4° C	63.7° C
Seven day average maximum temperature (20 mm depth)	59.1° C	56.9° C
Days per year with maximum surface temperature > 50° C	162	107
Days per year with maximum surface temperature > 60° C	24	2
Minimum surface temperature	2.4 ° C	-1.4 ° C

Table 1: Summary of pavement temperature regime at selected sections

An estimate of the traffic loading carried by the sections since rehabilitation for sections P1 to P4, or in the case of section G1 since construction, was made based on traffic count data recorded in the provincial pavement management system. Based on the most recent published figures on traffic loading in South Africa by De Bruin and Jordaan [8], and Slavik and Bosman [9], a factor of 2.5 standard axles (E80s) per heavy vehicle was assumed. This factor is significantly higher than the typical values suggested in the local guideline document TRH 16: (1991) *Traffic loading for pavement and rehabilitation design*. The use of a higher factor is sensible as the loading per heavy vehicle had increased significantly, since the publication of the guideline. This is partly due to an increase in permissible axle loading and partly due to an increase in the average number of axles per heavy vehicle. Figure 5 shows the estimated accumulative traffic carried by the sections after rehabilitation or construction. The poor performing sections carried similar amounts of traffic at the time the VCI index fell to 70. Sections P1 and P3 carried 10 million E80s, sections P2 and P4, 8 million. The good performing section still had a VCI of 95 after carrying over 14 million E80s.

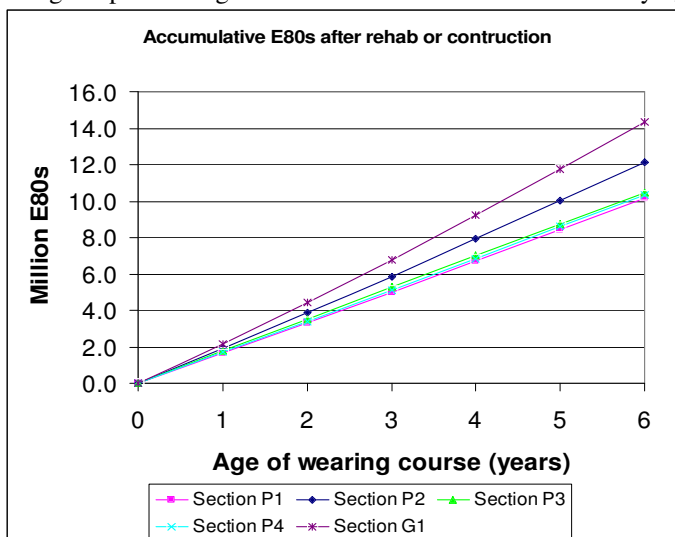


Figure 5: Estimated cumulative traffic after construction

## 5. HMA MIX DESIGNS

The aggregate gradings of the studied mixes as well as other engineering properties found in the design documents are

shown in Table 2. No design information was available for the ACM mix used as the bottom layer on sections P3 and P4. The grading of the ACM mix shown was obtained from the as-built documents. The grading curves for the mixes are shown in Figure 6. The Bailey method control sieves, as defined by Vavrik et al [10], are also shown in the figure. The maximum density line in the figure is shown for a 9.5 mm Nominal Maximum Particle Size (NMPS) mix, and is therefore not valid for the 13.2 mm NMPS BRCA mix. It needs to be noted here that the grading of the so-called SMA used at section P4 does not comply with the grading requirements of an SMA, and therefore cannot be considered a functional SMA.

Section	P1	P2	P3	P4	P3 & P4	G1
Mix type	SMA	ACM	BRCA	SMA	ACM	ACM
Sieve Size:						
19	100	100	100	100	100	100
13.2	100	100	98	100	100	100
9.5	95	96	78	92	93	99
6.7	38.5		59	29	76	79
4.75	27.7	66	48	20	63	64
2.36	21.9	51	31	19	43	42
1.18	17.8	38	21	19	32	29
0.6	15.6	28	15	18	25	23
0.3	13.3	20	11	18	17	19
0.15	9.7	12	7	14	11	13
0.075	6.7	8	5	8	7	5.8
<b>Engineering properties</b>						
Binder type	60/70	60/70	Bit-Rub	40/50	60/70	60/70
Binder content	5.8	5.5	7	6.7	5	5
Voids	6.5	3.8	4.5	6.3	N/A	4.6
VMA	18	15.4	18.6	20.4	N/A	15.3
VFB	64.2	75.2	76	69.0	N/A	70
Film thickness	10.3	6.5	14.1	9.5	N/A	7.0
Filler/Binder ratio	1.2	1.45	0.7	1.2	N/A	1.2
Marshall stability	5.4	9.9	8.3	6.4	N/A	10.9
Marshall flow	3.6	2.4	3.2	3.4	N/A	2.8
Sability/flow ratio	1.5	4.2	2.6	1.9	N/A	3.9
ITS	N/A	N/A	411	870	N/A	1086
Static Creep	N/A	N/A	N/A	N/A	N/A	284
Dynamic Creep	N/A	N/A	17	N/A	N/A	32

Table 2: Mix design information

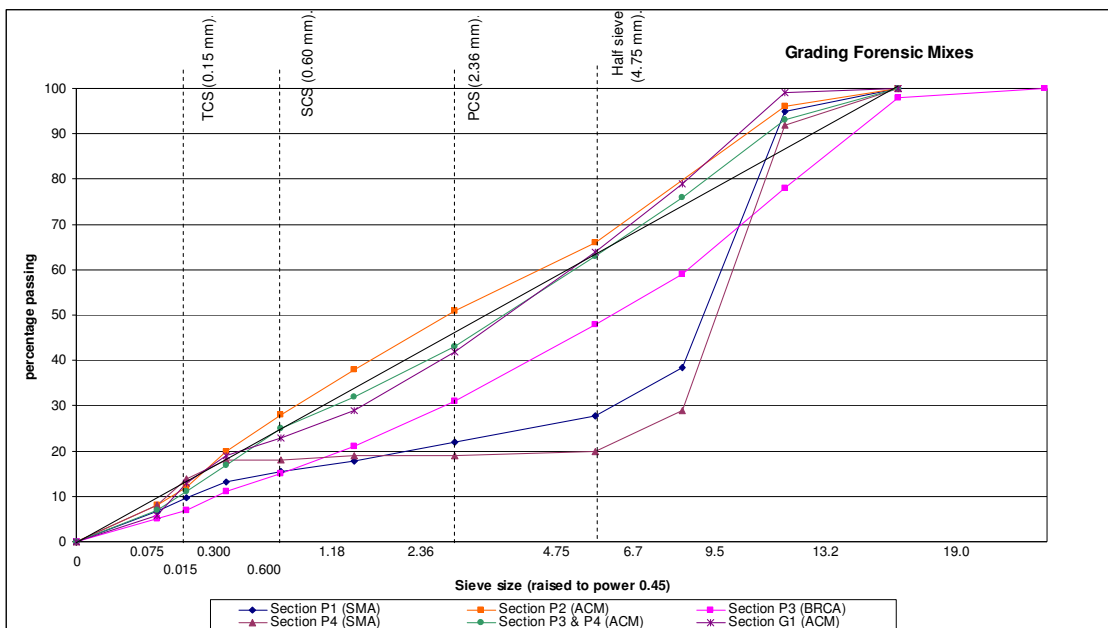


Figure 6: Power 0.45 grading curve forensic mixes

The grading of the aggregate, especially that of the coarser fractions, is a key factor determining the rutting and fatigue characteristics, as well as permeability, and workability of HMA. The gradings of the mixes were analysed using the Bailey method as described by Vavrik et al [10], a method studying the porosity of the aggregate skeleton introduced by Roque et al [11] and a guideline for rut resistant, durable mixes developed by Khosla and Sadasivam [12]. The results of the aggregate grading analyses with the above mentioned techniques provided some additional insights as to the possible reasons for the variability in field performance of the mixes.

To further explore the potential benefits of these aggregate grading selection methods for use in South Africa, they were applied to a larger data set of ACM mixes for which the field performance was known. The full results of this effort were published elsewhere [13]. A significant difference between the good and poor performing mixes was found in the grading of the coarser aggregate (>2.36 mm). The good performing mixes had a significantly higher Bailey method Coarse Aggregate (CA) ratio and a less porous aggregate fraction in the size range from 1.18 mm to 6.7 mm.

## 6. STRUCTURAL ANALYSIS

The analysis of DCP and FWD data indicated an insufficient structural strength in the lower pavement layers of section P1. This may well have resulted in the permanent deformation recorded at the surface, implying that the observed distress is not due to the SMA overlay. Lack of support is unlikely to have played a mayor role in the performance of the other sections, as the non destructive testing data indicate sufficient structural strength for these pavements.

## 7 TEST RESTULS AND DISCUSSION OF POSSIBLE CAUSES OF DISTRESS

Core samples taken from the HMA surfacings were subjected to various strength, stiffness and permeability tests. The binder recovered from the cored samples was analysed using various physio-chemical tests. The test results as well as possible links to the observed distress are discussed per road section. A summary of the laboratory test results on which the discussion in the next paragraphs is based is shown in Table 7.

Section	P1	P2	P3	P4	G1
Pen grade and mix type	60/70 SMA	60/70 ACM	80/100 BRCA	40/50 SMA	60/70 ACM
<b>Engineering properties</b>					
ITS [kPa]	975	870	990	1000	1700
ITT Emod [MPa]	1000-6000	2500-4000	3000	650-4000	1100-6000
Dynamic creep modulus [MPa]	6 – 19	4.3	18	22-37	14
Marvil permeability	impermeable	impermeable	impermeable	permeable	semi permeable
Constant head permeability [l/m <sup>2</sup> /h]	2 - 11	0.9 - 1.7	3 – 6	6 - 7	6 - 16
Contamination - Area Counts	2 - 15	2.1 - 11.9	3 - 12	2.2 - 6.9	17 - 24
Binder content [mass %]	6	5.5 - 6.5	7 – 8	6 - 7	4.5 - 5.3
Film thickness, [µm]	10	5 - 6	15 - 17	9 - 11	7 - 9
Voids (%)	3.1	1.6	3 - 4.5	5 - 8	6 - 7
<b>Binder analysis</b>					
Retained solvents	0.1 - 3,6	1.2 - 12	0.2 - 2.4	0	2 - 11
Ash content, %	6 - 4	6 - 2	2 - 1	2 - 1	2 - 1
Pen, 25 °C [µm]	31 - 113	33 - 65	21 - 60	4 - 9	14 - 18
Ring & ball °C	62 - 46	60 - 50	72 - 54	100 - 87	78 - 72
SR stiff 58 °C	16 - 1.5	10 - 3	49 - 5	6700 - 276	114 - 68
Viscosity 25 °C, MPa	3.2 - 0.3	<3	6 - 0.1	11 - 9	12 - 6
Durability index	3.2 - 3.7	3.7 - 5.4	1.8 - 2.6	1.7 - 2.1	1.9 - 2.2
Durability overall	high	high	variable	low	low

**Table 3: Summary of laboratory test results**

### 7.1 Section P1

Density results for the SMA surfacing of road section P1 did not show significant differences between the cores taken in the wheel path and those taken outside the wheel path, indicating that the observed permanent deformation was not related to densification of the SMA after construction. The rutting is also not due to horizontal movement of the asphalt layer, because the tell tale humps of asphalt material are not visible on the road's surface

Gas chromatography area count results for the recovered binder showed high levels of contamination in the cores taken

from within the wheel paths. As a result of the contamination, the penetration values and dynamic shear properties of the binder were low, indicating reduced resistance to permanent deformation of the binder. However, the level of binder softening is not considered to be critical for a stone skeleton mix like an SMA. High Performance Liquid Chromatography (HPLC) indicated normal aging characteristics similar to what can be expected for a 5 year old 60/70 penetration grade binder.

The cause of the permanent deformation must therefore be found in the underlying pavement layers. The severity of permanent deformation correlates well with the position of the weak spots in the pavement structure as indicated found by analysis of FWD data.

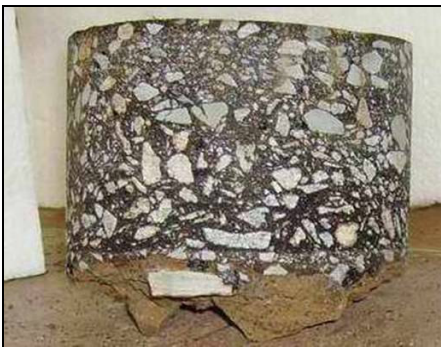
## 7.2 Section P2

Figures 5 and 6 show pictures of the cores taken from the severely deformed P2 section. The core shown in Figure 5 was taken from the wheel path, where the HMA material is approximately 60 mm thick. The core in Figure 6 taken from the area between the wheel paths is approximately 100 mm thick, giving an indication of the extent by which migration of material has taken place. On both cores, the 25 mm new ACM overlay placed during the 1999 rehabilitation can still be discerned. It seems that most of the displaced material is part of the underlying old ACM layer of unknown composition that deformed after it had been overlaid.

The void content of the material taken from HMA overlay in the wheel track is 0.9 per cent on average. At void content of less than 2.0 per cent the aggregate may start floating in the binder when the binder expands at high temperatures. The lack of resistance against permanent deformation of the mix is also apparent from the low dynamic creep modulus obtained. The average dynamic creep modulus for the tested samples was 4.3 MPa, with results below 10 MPa considered to be indicative of limited resistance against permanent deformation.

Analysis of the recovered binder indicates that at one of the intersections binder softening may have taken place due to contamination with oil products, which may have contributed to the low dynamic creep results. The ageing characteristics of the binder were found to be within acceptable limits.

Despite the poor resistance to permanent deformation of the new mix, most of the permanent deformation seems to have taken place in the older asphalt layer that was not removed before the new overlay was placed.



**Figure 5: Core from outside wheel path of section P2**



**Figure 6: Core taken from the wheel path of section P2**

## 7.3 Section P3

Figure 7 shows a typical core sample taken from road section P3. The top 30 mm consists of a BRCA layer. The ACM bottom overlay had in most cases completely disintegrated. Visual inspection of the cored samples revealed uncoated aggregate where the binder had stripped off. The 4 mm SAMI layer directly underneath the ACM layer was still intact. The SAMI formed the boundary between the old asphalt layer, which is also visible in the picture, and the 1999 overlay. Analysis of the recovered bitumen-rubber binder revealed a difference in the level of ageing of cores taken from relatively good performing areas compared to cores taken from poor performing areas. Penetration test on binder recovered from the good performing area yielded values around 60 while the penetration value for the binder recovered from the poor performing area were found to be about 21. The ductility test results and the dynamic shear properties of the recovered binder confirmed the difference in fatigue resistance between the good and poor performing areas. HPLC testing showed that the binder in the poor performing areas had aged prematurely, with an Asphaltenes fraction of over 25 per cent.

Stripping can have many causes. In this case a probable scenario is that the SAMI acted as an impermeable layer and

water that entered the ACM layer through cracks in the surface got trapped between the BRCA layer and the SAMI. Pore pressure build-up under traffic loading in the ACM layer would have initiated or accelerated the stripping process. The cracks that allowed water to enter may have been caused by:

- The use of a binder compromised by overheating, resulting in early fatigue cracking,
- Reflective cracking it is possible that the SAMI was not successful in combating existing cracks reflecting to the surface,
- Construction joints opening up.



**Figure 7: Typical 100mm diameter core from section P3**

#### **7.4 Section P4**

Marvil permeability test results showed the SMA top overlay at section P4 to be highly permeable. The water dispersed rapidly in horizontal direction through the layer. From a visual inspection of the cored samples, it became clear that permeability of the SMA layer was due to a network of large interconnected voids. From the cores, it was also observed that the old existing asphalt material underneath the SAMI had stripped completely.

The porous nature of the SMA may be linked to unusual shape of the grading curve. The complete lack of aggregate particles in the mid-size range seems to have resulted in the very fine particles moving to the bottom of the layer through the large voids, leaving a permeable top section. The porous nature of the SMA is likely to have contributed to the ageing of the binder. Penetration, softening point, ductility and dynamic shear tests all indicate that the binder had become so hard and brittle that it had little or no remaining resistance against fatigue cracking. The Asphaltenes fraction was approximately 30 per cent and the percentage of aromatics 20, which is an indication that the binder reached the end of its functional life.

The following facts need to be considered when attempting to establish the main reason for failure of the overlays.

- The SMA top overlay is highly permeable,
- Construction joints have opened up along the entire section,
- An unusually hard 40/50 pen grade binder was used in the SMA,
- Some reflective cracking was observed, indicating that the SAMI was not completely successful in combating propagation of existing cracks, and
- The old stripped and cracked asphalt layer was only partially milled off and the remaining material continued to strip after rehabilitation.

With the available data it is not possible to determine the dominant factor in the poor performance of the section. However, the sequence of failure is likely to be the same for both the carriage ways (P3 & P4), as both the SMA and the BRCA surfacings exhibited similar distress types after having carried a similar amount of traffic. In both cases, the introduction of water into the pavement structure seemed to have lead to stripping of the weakest layer. In case of P3 this was the new ACM layer, and in the case of section P4 it was the existing asphalt layer. Questions arise about the role of the SAMI in the mechanism that lead to stripping in the surfacing structure. A SAMI can be seen as a highly impermeable barrier in the pavement which may cause pore pressure build-up in the case of poor drainage or in the presence of more permeable HMA layers.



## 7.5 Section G1

Marvil permeability and constant head permeability test results show that the ACM on the good performing section G1 has above average permeability. Analysis of the recovered binder revealed that the bitumen is considerably harder than what would be expected of a 6 year old 60/70 penetration grade. At the time of analysis, the condition of the binder indicated a potential for fatigue failure. It has been reported that since the completion of the investigation, the ACM layer has started to crack, be it at locations outside the specific section investigated in this study.

## 8. DISCUSSION OF DESIGN PROCESS

### 8.1 Traffic data gathering

In order to assess whether the HMA sections underperformed, the traffic estimate used for the design needs to be known. It appears that for all investigated roads, gathering of traffic load was insufficient. The value of any civil engineering design is limited when one of the main boundary conditions, namely the design loading, is unknown. None of the design documents on the roads available for this research included traffic load survey information. The rehabilitation design for section P3 and P4 is the only document that included traffic count information. However, the visual traffic count used in the document is converted to traffic load by means of an unrealistically low factor of 1.0 standard axle (E80) per heavy vehicle. For section P1 a single one day traffic estimate was found in the correspondence, although it is not known whether this number was used in the actual design.

As a result, sections P3 and P4 are the only sections for which a conclusion can be drawn on premature failure of the surfacing. The rehabilitation was designed to carry 9 million standard axles and last for 10 years. If a factor of one E80 per heavy vehicle is applied, the BRCA surfacing in the southbound direction lasted for 4.2 million E80s (and 6 years) and the SMA overlay in the northbound direction lasted for 3.4 million E80s (and 5 years). Using the factor of a single E80 per heavy vehicle as a boundary condition, the conclusion must therefore be that the surfacing underperformed. If a higher load factor is used, such as the factor of 2.5 standard axles per heavy vehicle used in this investigation, the sections have reached their design load, however the HMA still failed prematurely, because it did not last for the 10 year design life.

On the other sections no such conclusions can be drawn, as neither the design traffic load, nor the assumptions of the predicted traffic loading are known. It is doubtful whether any such calculations were made for these sections. An important note here is that the design of a new HMA surfacing should be based on two input variables; the first is the expected traffic load, and the second is the required service life. Assuming that none of the sections were designed to last for less than ten years, which would be a typical design period for an overlay, it is fair to say they all underperformed regardless of whether they carried the total design traffic or not.

### 8.2 Rehabilitation design

Apart from shortcomings in the investigation of traffic load for the rehabilitation design, several other comments on the rehabilitation design process can be made. All four rehabilitations studied in this forensic investigation included an overlay as the primary form of upgrading of the existing road. For three of the four rehabilitated road sections it was established that at least part of the observed problems were caused by existing pavement layers:

- The permanent deformation at section P1 is taking place in one of the deeper layers of the pavement structure,
- The permanent deformation at road section P2 is mainly due to the unstable old surfacing layer that was not removed during the rehabilitation,
- The old asphalt layer under the new overlays of the Section P4 was stripping, and
- Indications were found that at least some of the cracking observed on sections P3 and P4 is reflecting from deeper pavement layers.

### 8.3 HMA mix design

With respect to the design of the two SMA mixes included in this investigation, it was noted that the design sheets on neither of the mixes mention voids in coarse aggregate (VCA) established in the rodded unit weight test, or drain down test values, which are required parameters to be determined in SMA design. The failure to include the parameters on the design sheet may be due to inexperience with SMA design at the time.

The selection of binder content for the SMA section P4 seems to be predominantly based on the minimum requirements for ITS, which is not relevant to SMA. The aggregate grading curve of that same mix placed at section P4, which does not satisfy the criteria for an SMA, is another indication that design experience was lacking.

The preliminary forensic investigation by Verhaeghe [1] found that in some cases mix types were selected that were not the most suitable for the specific conditions at the site. Of the sections studied in this forensic investigation questions

can be raised about the selection of a fine graded mix for section P2. A coarse graded mix, such as an SMA, might have been better equipped to resist the high stresses caused by the large percentage of slow moving truck traffic using the intersections on this road.

## 9. CONCLUSIONS

The results contained in this paper should to a large extent be viewed as five separate case studies. Care should be taken not to extent generalization of the results of individual road investigations beyond what is scientifically justifiable. The cases were by no means picked at random and can therefore not be expected to provide a typical view of the performance of HMA surfacing or the quality of mix design. The complex combination of factors influencing the performance of an HMA mix makes it a challenging task to identify the one dominant component that caused the surfacing to perform good or poorly a challenging task. Nonetheless, a number of trends have emerged from this investigation. These are summarized below.

- HMA pavements in parts of South Africa are subjected to high temperatures over extended periods. To combat permanent deformation of HMA, the use of coarse graded mixes, and preferably mixes with a stone skeleton, that rely less on the binder for shear resistance should be encouraged, where necessary in combination with modified binders. Special attention should be given to cases with slow moving loads and increased risk of concentrated fuel spillage, such as intersections and inclines. Too often, “off the shelf” standard HMA mixes are used in high demand situations that call for individually designed solutions.
- When designing coarser mixes, care should taken that this does not result in permeable mixes that are prone to premature binder ageing.
- The grading of the aggregate used for the mixes included in the forensic investigation were analysed using the Bailey method and related methods. The analysis indicated correlation between the the grading analysis and field performance. These findings were validated on a larger set of ACM mixes [13]. Aggregate grading analyses methods remain part of the multi-year HMA research project
- The results of this study suggest that Stress Absorbing Membrane Interlayers (SAMIs) may result in water getting trapped in the pavement structure, which can lead to pore pressure build-up and stripping. SAMIs should therefore be used with caution.
- Based on the evidence available from this investigation, the general impression is that little effort has gone into providing an accurate prediction of traffic loading on the sections. The lack of accurate traffic load data is regrettable, as the costs of the prescribed seven day load survey is limited when compared to the overall costs of a rehabilitation project. Also, the rehabilitation design process for the studied sections in all cases resulted in an overlay solution. This seems to not have adequately addressed problems with sources deeper in the pavement structure. It is proposed that overlay “blanket” solutions are being used too widely and without proper investigation of possibly more appropriate alternatives. The need for proper rehabilitation investigation, aimed at creating an holistic understanding of the condition of the pavement, and the need for design aimed at addressing the source of the distress, is evident from the results of the study.

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