EVALUATION OF PERFORMANCE OF ASPHALT PAVING MIXES UNDER HARSH CONDITIONS USING THE MMLS3

Frederick Hugo[1]
Ian Bowker[2]
Jaco Liebenberg[3]
Dennis Rossmann[4]

[1]Institute for Transport Technology (ITT), Department of Civil Engineering, Stellenbosch University.
Private Bag x1, Stellenbosch, 7600, South Africa
fhugo@sun.ac.za

[2]Gibb Engineering and Science
14 Kloof Street, Cape Town, 8001, South Africa
ibowker@gibb.co.za

[3]GHD (Pty)Ltd.
201 Charlotte Street, Brisbane, 4500, Queensland, Australia
Jaco.liebenberg@ghd.com

[4]South African National Roads Agency (SANRAL)
58 Van Eck Place, Pietermaritzburg, 3201, KwaZulu-Natal, South Africa
rossmand@nra.co.za

Abstract

The Draft Test Protocol: *DPG1: Method for evaluation of permanent deformation and susceptibility to moisture damage of bituminous road paving mixtures using the Model Mobile Load Simulator (MMLS)* (DPG1, 2008) has load frequency as a test variable. This was added to the original test protocol adopted by the MMLS users group in Baton Rouge in 2004 to simulate harsh trafficking conditions. Indications are that the adaptation was necessary and successful in curbing premature failures. The paper reports on analysis and synthesis of national and international case studies of applications of this mode. Three are in South Africa: One in Western Cape (N1 - Hex River Pass), the other in KwaZulu Natal (N3 – Marianhill) and the third is from an APT HMA field study for Gauteng Government Department of Public Works and Transportation (a test section on the R80). The fourth case study pertains to airport pavements in Dubai and Australia. A synthesis of the case studies provided evidence of the relationship between slow speed MMLS tests and field performance of HMA under harsh full-scale trafficking. Thus ratifying the guidelines in DPG1.

[1] Emeritus Professor, Stellenbosch University, Western Cape, SA
[2] Engineer: Airports, Roads & Highways, Arcus Gibb, Western Cape, SA
[3] Principal Pavement Engineer, GHD, Brisbane, Australia
[4] Engineering Specialist SANRAL, Durban, KZN, SA

INTRODUCTION

The MMLS has been used for testing pavements and pavement materials since 1997. Currently there are nineteen units in use globally. They have been used for accelerated pavement testing (APT) of a variety of pavement performance characteristics including among other:

1. Rutting
2. Moisture damage
3. Fatigue
4. Failure mechanisms
5. Evaluation of Pavement Structural systems including geo-synthetic reinforcement
6. Skid resistance
7. Pavement surface characterisation

Many of these applications are unique and conducted according to specific user guidelines. An international user group shares findings during an annual meeting in January. The equipment is compatible with and serves as a useful tool to supplement the application of full-scale APT. It has been used in conjunction with full-scale test systems such as the MLS10, the HVS and full-scale test tracks. It has also been used to evaluate full-scale pavements including airports and highways insitu.

In 2004 a test protocol was developed for application to test rutting performance and moisture damage by the MMLS users group meeting at Baton Rouge. This followed the evaluation of the performance of the full-scale test track at Reno in Nevada. Epps et al (2002) reported on the analytical evaluation of performance of full-scale truck trafficking. Subsequently similar testing was done to evaluate the full-scale testing of asphalt pavements at NCAT and testing of overlays on a highway in Texas with the TxMLS. In Southern Africa it was used in conjunction with the MLS10 in Mozambique.

In 2008 the Road Pavement Forum in South Africa (RPF) adopted a Draft Test Protocol: *DPG1: Method for evaluation of permanent deformation and susceptibility to moisture damage of bituminous road paving mixtures using the Model Mobile Load Simulator (MMLS3)* (DPG1, 2008) after recommendations by a committee that had been established in 2007. This Protocol can be accessed on the Southern African Bitumen Association (SABITA) website http://sabita.co.za/documents/MMLS%20draft%20protocol%20Fin%20Dec08.pdf It was drafted on the basis of the Baton Rouge protocol and the other reported successful applications as an APT tool.

The use of the MMLS for evaluating performance of HMA under moderate climatic conditions and high-speed traffic had proved to be very successful. However, it was found that the 2004 protocol needed to be expanded to cater for physical characterizations of asphalt materials influenced by more extreme conditions such as steep gradients, prolonged high temperatures, very heavy slow traffic and high tyre pressures. This was addressed by adapting the trafficking speed and the allowable rut depth. A unique feature of the DPG1 (2008) was therefore the recommendation to differentiate between different trafficking conditions in terms of topography, climate, wheel load and trafficking mode.

This paper reports on analysis and synthesis of national and international case studies of applications of the revised protocol. Three are in South Africa. One is in the Western Cape (N1 - Hex River Pass), the second is in KwaZulu Natal (N3 – Marianhill) and the third is from a research study for the Gauteng Government Department of Public Works and Transportation (test section on the R80). The other case study pertains to airport pavements in Dubai and Australia.

Each of the case studies relate to specific aspects of the factors that affect performance. This provided a unique opportunity to link the DPG1 to full-scale field performance supplementing earlier similar studies. The synthesis of the case studies was done to validate the slower MMLS trafficking guidelines in the Draft Protocol. This will enhance the ability of pavement engineers to improve durability and performance of asphalt pavement layers under harsh conditions.

CASE STUDY 1: HEX RIVER N1 – SOUTH AFRICA

The N1 in the Hex River valley passes through a steep gradient subject to high summer temperatures. Initial testing of the HMA followed the guidelines of the Baton Rouge Protocol. Some early rutting failures manifested and an in depth study was done to investigate the cause of the failures.

The prematurely failed section manifested early fattening and deformation under severe heavy duty traffic conditions, i.e. steep uphill gradient in excess of 6%, high temperatures (>60C in layer) and very slow moving traffic (<5 km/h).

The project comprised a 40mm bitumen rubber asphalt overlay on the National Route 1, South Africa, between Kanetvlei and the Hex River Pass over a distance of 20.3 km. The design traffic volume was taken to be 23 million equivalent 80 kN axle loads (E80's) in fifteen years. The summer daytime maximum average temperature is 30.4C in January with the average highest for the month record as 38C. The region has a mean annual (MAP) rainfall of 320 mm with the rainfall peaking between April and August. In order to economize, changes were made to the originally prescribed asphalt layer. The contractors proposed use of BRA (Bitumen Rubber Asphalt continuous graded). However, BRA was considered unsuitable for the steep gradients ranging from 6.5% to 7.2%. It was also considered sensitive to fuel and oil spillages that frequently occur on these slow trafficked areas. A continuously graded asphalt with 60/70 binder, was finally selected as the production mix. Details of the production mix finally selected for the critical section are shown in Table 2.

About one year after construction, the 4.0 km of the slow uphill lane exhibited fattening and deformation failures over +50% of the total length of the section. This was after the first summer following construction. The premature failures ranged in severity from mild fattening to excessive deformation (more than 10mm) under the severe heavy duty traffic conditions, i.e. steep uphill gradient in excess of 6%, high temperatures (>60C in layer) and very slow moving traffic (<5 km/h). An extensive and detailed diagnostic study was done to determine the possible causes. The findings were reported at the ISAP conference 2010 in Nagoya Japan (Pretorius et al 2010). They reported that the cause could be attributed to a number of factors including high temperature, steep gradients and heavy traffic. Other factors included contamination by migrating material fines, grading specification tolerances and rich binder applications.

Some of their reported findings were very useful and interesting:

1. A meaningful difference was found in the Voids-in-mix (VIMs) results. The re-tested samples after trafficking indicated lower VIM's results of approximately 1%. Results from good control sections indicated VIM's mostly higher than 5%, while VIM's results attributed to the failed section indicated significantly less than 5% (caused by binder/0.075 mm aggregate higher values).
2. The bitumen fully complied with the relevant SANS307 specification, but indications are that the bitumen tended towards the "softer" side of the limits of the specification.
3. Based on the results of both the cores and retesting of retained asphalt samples, it was found that the grading somewhat fluctuated, but in general agreed with the target specification (except for the material passing the 0,075 mm sieve which may have been from external packing onto fattening/bleeding).
4. Post construction deformation appeared to have caused these marginal mix properties enhancing traffic compaction during the hot summer period.
5. It seems that a combination of marginally high initial binder contents and possible high and/or fluctuating tack application may have resulted in the higher binder content found in distressed site recovered areas.
6. It is apparent that the poor rutting performance that some mixes exhibit under slower MMLS3 testing speed than 7200 appl/h. could be due to variations in percentage material passing the 0.075mm causing the VIM's to close up under trafficking. This would reduce the stability and resistance to deformation of the mix under the harsh uphill conditions.

Closing Remarks relating to Case Study 1

A specification of 1.8 to 2.0 mm maximum rutting, at lower trafficking speeds (i.e. 1800 – 2 400/h) would probably have been more applicable than the original 7200/h. This would generally require the use of high EVA modification, or other proven plastomer (or special binder grade) in the mix in order to obtain the high performance criteria. This was confirmed in later field assessments (one year later) when it was found that even some of the control areas considered to be in good condition in terms of binder and fines relative to design targets, started to show fattening and signs of rutting. In order to comply with the revised MMLS specification, an EVA modified binder (5.5% EVA with 60/70 Pen. Binder) was used for the replacement mixes. The performance of the replacement mix to date (18 months, two summers later) has confirmed satisfactory mix performance. The one factor that is under surveillance is the manifestation of some minor cracking that may be due to fatigue occurring as a result of a too dry mix. It is apparent that the fatigue life of the asphalt material has to be considered in conjunction with the rut resistance.

CASE STUDY 2: N3 MARIANHILL - SOUTH AFRICA

The N3 freeway is the primary economic arterial between Durban and Gauteng. At the turn of the century it was due for rehabilitation after circa 20 years of service. The unique type of loading on the road required a rut resistant asphalt mix with appropriate fatigue resistance properties. A comprehensive asphalt mix design process was used with performance prediction of the mix to be of key importance. It is clearly an excellent case study of harsh operational conditions for HMA.

The design challenge of requiring both rut and fatigue resistance to withstand the very heavy traffic necessitated the use of asphalt mixes with modified binders. The MMLS was used to select an appropriate asphalt mix with A-P1 or A-E2 as binder. Thus far it is performing as expected. It was of particular interest to find that the final binder selection was done on the basis of the proposed performance limits set in the Draft Protocol (2008).

Liebenberg et al (2011) present extensive details of the mixes and the design process. The following is noteworthy from their paper:

1. The section of the N3 between Marianhill and Key Ridge was initially constructed in 1985/1986. Some maintenance was done between 1994 and 1999 by mill and replacement of rutted asphalt in the slow lane, crack sealing and a 40 mm continuously graded asphalt overlay.

2. To select the most appropriate of two possible asphalt mixes, three trial sections of varying binder contents were constructed for each of the binder types.

3. Extensive performance tests including MMLS APT, Hamburg wheel tracking and flexural beam fatigue testings were performed. Cores and beams were extracted from the trial sections.

4. The predicted cumulative E80’straffic loadings over a period of 15, 20 and 30 years were estimated from detailed consideration of the traffic volumes at the time of the design (2006). Due to the steep gradients the majority of the heavy traffic travels in the slow lanes. In terms of Equivalent Standard Axle Loads (E80’s) the traffic equated to between 2.8 E80 per heavy vehicle southbound and 3.1 E80's per heavy vehicle northbound.

The alternative designs for a structural design period of 15 years or 57 million E80s comprised:

a. An asphalt inlay of 160 mm asphalt base with a stiff asphalt base for the slow lane and

b. A partial inlay of the middle lane was found to be the most economical by removal of the upper 80 mm of the asphalt and replacement of it with an asphalt mix similar to that for the slow lane.

c. An ultra thin friction course (UTFC) on all the lanes in order to meet functional requirements (texture depth and skid resistance).

5. In order to satisfy the pavement design requirements, two mixes comprising two alternative binder types, namely elastomer (A-E2 mix with 3.5% SBS) and plastomer (A-P1 mix with 4% EVA) for the asphalt base, were evaluated. Modified binders were preferred at the section rather than conventional unmodified binders that were considered unsuitable for the harsh conditions. Details of the design are fully discussed by Liebenberg et al (2011). Aggregates comprised quartzite and tillite. Between 10 and 15% Reclaimed Asphalt (RA) was included in the mix.
6. The asphalt base grading was selected continuous by using the Bailey method. The final mix lies within the specified COLTO grading envelope guides.
7. Performance testing was used to select the most appropriate asphalt mix. Six trial sections were constructed in the northbound slow lane, approximately one km north of the Marianhill Toll plaza. A total of 228 cores were extracted for testing of rut resistance, moisture susceptibility and permeability. In addition, 16 beams were extracted and subjected to flexural beam fatigue testing. [Refer Liebenberg et al (2011) for details].

Dry MMLS tests at 60 C and 7 200 repetitions per hour (standard speed) were performed on the 4,2 % and 4,5 % A-P1 mix as well as the 4,3 % and 4,5 % A-E2 mix. However to determine the performance of the mixes under slow loading conditions, MMLS tests were done on the 4,2% A-P1 and 4,3% A-E2 mixes at 2 400 repetitions per hour in accordance with the DPG1 (2008) guidelines. Wet MMLS tests were performed on the 4,2% A-P1 and 4,3% A-E2 mixes using the slow speed to determine moisture susceptibility and potential for stripping of the mixes. The results provided an excellent basis for evaluation of DPG1 as a tool for evaluating performance under harsh conditions. Table 1 presents the results of the MMLS tests at standard fast - dry speed (7 200/h) and slow – dry and wet speed (2 400/h). The significant difference in MMLS rutting performance of the EVA and SBS mixes at 50C and 60C is noteworthy.

Table 1: MMLS Rut Depth after 100k Trafficking (mm) (after Liebenberg et al, 2011)

	Fast - dry	**Temp C**	**Slow - dry**	**Slow - wet**	**Temp C**
A-P1 (4% EVA) surfacing	1,23	50			
A-E2 (3.5% SBS) surfacing	1,85	50			
A-P1 (4% EVA) base	1,14	60	1,66	1,81	60
A-E2 (3.5% SBS) base	1,94	60	2,49	3,21	60

On completion of the dry MMLS test at 2 400 repetitions per hour, the A-P1 binder mix had a terminal rut of 1.66 mm after 100 000 repetitions, while the A-E2 binder mix had a rut depth of 2.49 mm after 100 000 repetitions (fifty percent more).

The rut depth after 100 000 repetitions of the wet MMLS test at 2 400 repetitions per hour for the A-P1 mix was 1.81 mm and no signs of stripping was observed when the sample was visually inspected. The rut depth after 100 000 repetitions of the A-E2 mix was 3,21 mm and some early signs of stripping was observed at the end of the test. Overall, the A-P1 binder exhibited better performance than the A-E2 mix. The A-P1 binder rutting was also well below the maximum threshold of 2,5 mm after 100 000 load applications recommended by DPG1 (2008).

Fatigue resistance

Liebenberg et al (2011) also evaluated the fatigue properties of the two mixes by four point bending tests on specimens cut from two slabs that were removed from the pavement. This is an important parameter that is easily overlooked on the assumption that good rut resistance is equivalent to a good fatigue resistance. The fact is that the blending of the mix requires careful consideration to satisfy both requirements. This is particularly important when the asphalt layer is less than 100mm thick. With such a thickness the higher stiffness of the mix could be detrimental to fatigue. By following this mix design and selection process, the final mix selected for this project was an A-P1 mix with a target binder content of 4.3% and target Marshall void content of 4.8 %. The fatigue resistance of both the mixes was found to be fit-for-purpose.

Closing Remarks Relating to Case Study 2

Since the completion of the construction work the performance of the mix has been carefully monitored. Some interesting data has been collected enabling the performance to be evaluated.

Construction for the proposed rehabilitation took place from September 2007 to August 2008 and the road open to traffic by 2009. Liebenberg et al (2011) determined and recommended traffic volumes for the service life of the rehabilitated pavement. Their data was reviewed to benchmark the situation for future reference. It was noted that for 2006, the traffic volume was in the order of

16 000 vehicles per direction with a heavy vehicle count of up to 17 percent thereof. The total vehicle loading was measured in equivalent standard axles (E80's) at 2.8 E80's per heavy vehicle on the southbound route and 3.2 E80's per heavy vehicle on the northbound route.

Using the above information and forecasting, traffic growth was back-calculated at 3.2%. This assumed that construction would take two years before exposing the rehabilitated pavement to traffic. The forecasted cumulative traffic over one year during 2009 was then compared with the recorded traffic counts for 2009 received from SANRAL. Good correlation was found and the cumulated trafficking of the new asphalt was ca. 3 million E80's or 5 percent of the design traffic volume.

The rutting performance since completion of construction also provided interesting findings. The results of the left rut measurements and road gradients after one year exposure to traffic were received from SANRAL and compared graphically. No correlation was found between the maximum gradient and maximum rut. It is however interesting to note that maximum rut values manifest in road sections prior to reaching maximum gradient. This is the case for both positive and negative gradients. This condition is most emphasized on the northbound carriageway of Section 2, Figure 1. The measurements were taken on the road surface and may include some rutting from the UTFC. This was not explored prior to the application.

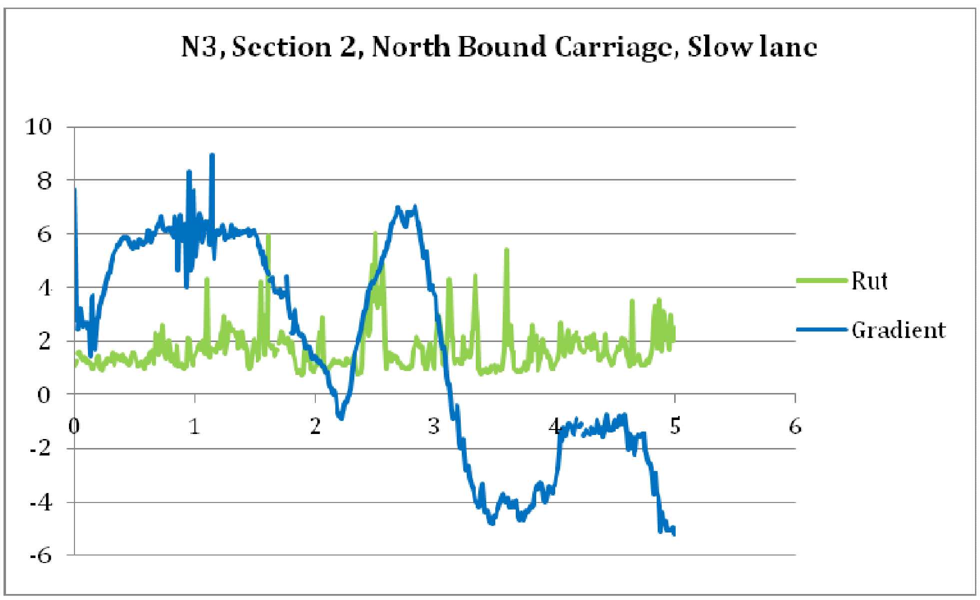

Figure 1 Correlation between Rutting and Gradient on Section 2

It is also apparent that the cross-fall did not have an influence on which wheel track had a greater rut. Generally it appears that the left wheel track on the slow lane had the greater rut on average. This could be as a result of lesser confinement pressure as the left wheel track is closest to the road edge. Figure 2 below is an illustration of the cross-fall variation versus wheel rut for the southbound carriage on Section 2 of the N3.

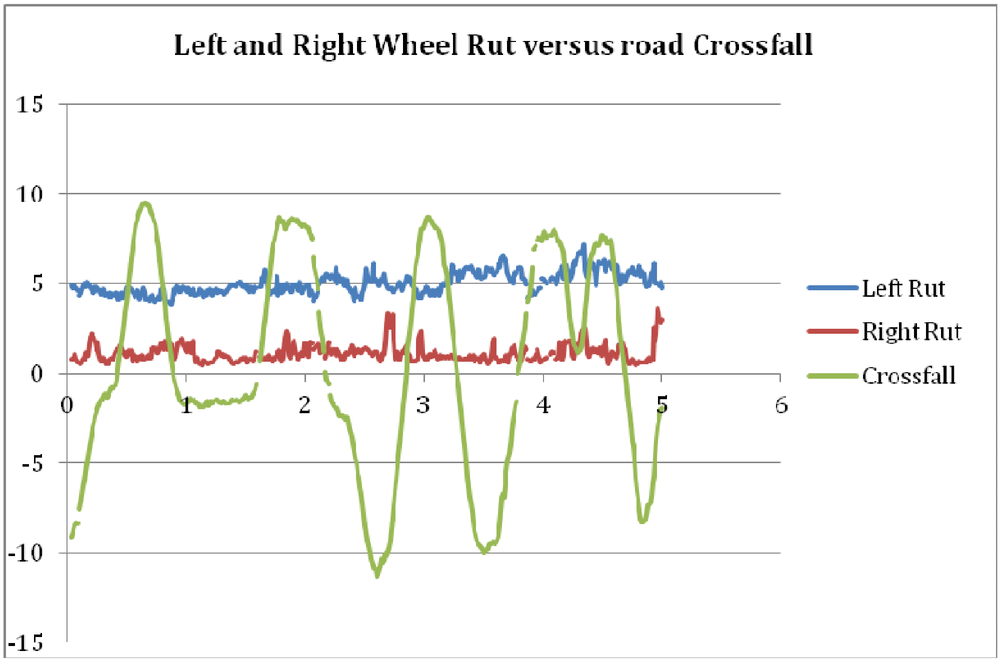

Figure 2 Correlation between Rutting and Crossfall on Section 2

CASE STUDY 3: RESEARCH STUDY TO INVESTIGATE IMPACT OF HARSH CONDITIONS ON RUTTING PERFORMANCE USING HVS-MMLS APT

In 2007 the Gauteng Government Department of Public Works and Transportation (GGDPWT) initiated a study by the CSIR to develop more reliable design procedures to overcome premature rutting and fatigue distress of HMA surfacing under harsh conditions.

The intent was to include the findings in an update of HMA design methods. Several reports were completed and some invaluable findings had already been made when the study was put on hold in 2009.

A primary component of the study comprised evaluation of performance of HMA under APT with an HVS of the CSIR and a MMLS of the Institute for Transport Technology in Stellenbosch. The object was to compare the extent of rutting and the rate of deformation (rutting) of the two APT systems in terms of mm/load application under similar environmental and stress conditions. These characteristics are basic to the ability of HMA to function sustainable under harsh conditions.

Some findings were presented in sessions of the Road Pavement Forum meetings in South Africa as research progressed. Verhaege et al (2007) and Denneman et al (2008) also presented aspects of the study at international conferences.

In the paper by Denneman et al (2008) they provided the background to the study. The details fall outside the scope of this paper and only information relative to evaluation of improved performance of HMA under harsh conditions will be discussed. A test section was constructed on Road P159/1 on the western side of Pretoria adjacent to the R80. It was surfaced with a standard continuously graded medium HMA material defined as the Standard Reference (SR) mix. (see details in Table 2). Subsequently minor changes were made to the mix to improve rut resistance (mix RR1) The underlying structure is stiff to ensure that rutting was confined to the HMA.

HVS testing with a standard legal axle load (40 kN on a dual set of 11R22 tires at 620 kPa inflation pressure) and trafficking in a uni-directional channelized mode was classified as "standard." Surface temperature of the HMA was kept at four specific temperatures during the various phases of the tests using an environmental control box and an array of heaters. The selected temperatures were 40C, 50C, 55C and 60C. The test mode was also adapted to evaluate the effect of layer thickness, trafficking direction and contact footprint.

The MMLS test system was used for testing both in the laboratory and in the field adjacent to the HVS. Details of the system can be found in DPG1 (2008) as well as Smit et al (2003). Speed and temperature conditions were varied according to the test protocols for the study. The majority of tests were performed at a 2.9 kN load level with a 750 kPa tyre inflation pressure that was validated using the Stress-In-Motion (SIM) device to resemble contact stresses used for the HVS trafficking most closely (refer de Beer and Sadzik 2007). The testing speed was varied between 2400 load applications per hour load (2400/h) and 7200/h. Temperature was varied between 40C and 60C with the MMLS covered by an environmental chamber to maintain a constant temperature. Trafficking was only done dry. Findings were presented in two reports by Hugo and De Vos (2008a and b).

A third series of MMLS3 tests was conducted in the ITT Stellenbosch laboratory during September through December 2008 on the HMA RR1 mix that had been designed to be more rut resistant than the SR mix. The full MMLS dataset was subsequently critically reviewed, analysed and synthesised in order to compare the results of the HVS with results of the MMLS (Hugo and Gerber 2008). The synthesis provided some findings validating the procedures included in DPG1 (2008). These are discussed below.

Discussion of Findings and Overall Synthesis by Hugo and Gerber (2008).

In the report by Hugo and Gerber (2008) the authors used the deformation rate during the secondary phase of rutting to compare performance of the mixes under the respective APTs. This presents the data on log-log axes, where the gradient of the trend line serves as an indicator of the rutting performance of the mix. The secondary phase is generally considered to start from between 2 500 and 25 000 load applications.

For their analyses, a power trend line was fitted to the rutting data obtained from 10 000 load repetitions onwards up to 200 000 load repetitions except when the test was terminated prior to this. This was done so that comparisons could be made between the MMLS field and laboratory data and the HVS field data. The original analyses reported by Denneman (2008a) also used this methodology.

The relationship between the respective deformation rates (mm/pass) for the different mix types and related structures at the different test temperatures (C) were then analysed. The equations of the power trend lines were used to calculate gradients of each trend line, for each test. An exponential trend line was determined to define each specific series of tests. The results are shown in Tables 3 and 4.

Although the post-construction structure of the mix affects the primary phase of deformation, the effect of this on the secondary rate of deformation was not considered within the scope of this discussion.

The initial MMLS tests were conducted at 7200/h and the results were reported earlier by Hugo and de Vos (2008 a,b). They stressed the need to test at a slower speed than the conventional 7200/h in order to be compatible with the performance evaluation of the HVS operating at 10kph. The test programme was changed accordingly. The tests by Hugo and Gerber (2008) were all done at 2400/h.

Overview of Findings

The cluster of HVS and MMLS test results were reviewed in two categories, namely Series 1 and 2. Variables that were included are temperature, load frequency, layer thickness, mix type, trafficking direction and HVS contact stress during trafficking. Series 1 and 2 were considered by comparing the appropriate relative MMLS and HVS test results.

Series 1 was reviewed and synthesised in terms of performance relating to:

1. Mix SR (define)and initial performance of a rut resistant mix RR1
2. MMLS laboratory testing vs. field testing
3. layer thickness under HVS testing vs. MMLS performance

The following aspects were considered:

- HVS Benchmark layer thickness: 40 mm (std)
- Variable Layer thicknesses: (25 mm & 60 mm)
- Performance of mix types: SR and RR1
- Traffic direction: Uni-directional (uni)
- Load composition: Standard case 40kN, 620 kPa

The following HVS tests were considered: 441A4 (59.1C), 442A4 (42.1C) & 443A4 (49.55C), 444A4 (50.6C) and 445A4 (49.25C). These test results were compared with MMLS tests:

- 50 mm SR ITT lab test (SR 50 mm Lab EDV) 7200/h
- 50 mm SR ITT lab test (SR 50 mm Lab EDV) 2400/h
- 40 mm SR field test Roadlab (J) 2400/h
- 40 mm RR1 field tests EDV (Q) & (R) 2400/h
- 50 mm RR1 lab tests (RR1 50 mm JG 2,3,4,5) 2400/h

The thickness of the asphalt field cores extracted by the CSIR for lab testing was generally greater than 40mm and in some cases 50mm. This could have impacted the performance results of the field tests but was not considered or investigated further.

From a comparison of the HVS and MMLS trend lines presented graphically in Figures 3 and 4 the following noteworthy observations were made:

1. Decrease in MMLS trafficking speed to 2400/h resulted in an increase in the rate of rutting especially at 60C. [The extent of rutting also increased but this was not explored specifically for the various tests since the primary phases of rutting of the respective tests differed significantly. This would influence applications. However this is not likely to have a significant effect of the total rut towards the end of the initial life cycle.]
2. Rate of rutting increased for both the MMLS and the HVS with an increase in test temperature
3. Increase in the rate of rutting reduced with an increase in test temperature as the speed was increased from 2 400 to 7 200/h
4. Performance of the SR mix under trafficking by the two APT machines yielded very comparable results. This applies to both lab and field MMLS testing.
5. Field performance of Mix SR was very similar to Mix RR1 (i.e. no significant improvement in rutting performance evident). It is important to take into account that 60C testing is well above the softening point of the binder that was used for the asphalt mix (Denneman 2008a).
6. Performance of RR1 and SR was similar at 50C but at 60C the RR1 mix performed better than the SR mix. The reason for this is not readily apparent since no further lab testing of SR mixes we done.
7. Rate of rutting of mix RR1 appeared to be greater than field rutting of the RR1 mix at 60C.
8. Rate of rutting of the 60mm layer was smaller than 25 and 40 mm asphalt under HVS trafficking. The reason for this is not readily apparent.

The results of Series 2 were reviewed and synthesised in terms of MMLS performance in a similar manner relating to:

1. HVS trafficking direction: Uni-directional (uni) vs. Bi-directional (Bi)
2. Load composition: Varying between Standard HVS case as before, n-shape: 60kN 800kPa, m-shape: 60kN 420kPa. The notated shapes (a term coined by Morris De Beer of CSIR) relate to the transverse contact stress pattern under the tyre due to the respective loads and tyre pressures.
3. HVS Contact stress (m-vs. n-footprint) Refer Denneman (2008a)

The following HVS tests were considered:

441A4 (Uni 40kN/620 kPa, 59.1C); 446A4 (Bi n-60kN/800kPa, 59.7C) & 447A4 (Uni n-60kN/800kPa, 63.3C), and 448A4 (Bi m-60kN/420kPa, 62.1C).

These test results were compared with MMLS tests:

- 50 mm SR ITT lab test (SR 50 mm Lab EDV) 2400/h
- 40 mm SR field test Roadlab (J) 2400/h
- 40 mm RR1 field tests EDV (Q) & (R) 2400/h

- 50 mm RR1 lab tests (RR1 50 mm JG 2,3,4,5) 2400/h

From a comparison of the HVS and MMLS trend lines presented graphically in Figure 4 the following noteworthy observations were made:

1. HVS Test 446A4 had a slightly higher rutting rate than Test 448A4 at a lower test temperature due to higher applied contact stresses of Test 446A4
2. HVS Test 447A4 can be compared with Test 446A4. Contact stresses are the same but *trafficking direction and test temperatures differ.*
3. Comparing Tests 448A4 and 447A4 rutting rates of HVS Tests 448A4 (lower temp and stress) vs. Test 447A4 (higher temp and stress) exhibit similar trends. Hence conclusive deductions are not readily apparent *except for the fact that the m-shape yielded smaller rutting rates.*
4. Test 446A4 and Test 441 A4 were both at approximately similar temperatures. Accordingly, it can be concluded that *the uni-directional trafficking results in a higher damage in terms of rutting rate than the bi-directional trafficking.* Furthermore, the contact stress of the uni-directional test was less than contact stress of the bi-directional test. This lends further support to the above conclusion about the impact of the trafficking direction.

In general, the rutting rates related to the different test temperatures of the individual HVS and MMLS tests yield similar gradients when trend lines are added. Furthermore, the rates pertaining to the HVS and MMLS tests at the respective temperatures and similar load compositions in terms of contact stresses, are located in tight clusters.

Conclusions from Case Study 3

1. The findings lend support to the guidelines proposed for harsh conditions. The results also correlate well with other reported case studies in the paper.
2. The MMLS3 laboratory and field test results compare favourably with the HVS test results.
3. There is no real difference in the rutting rates of the two mixes (SR and RR1) at the respective test temperatures. Further validation is therefore necessary to confirm the findings pertaining to the performance of the mix.
4. Uni-directional trafficking results in a higher damage in terms of rutting rate than the bi-directional trafficking.
5. From the findings of the study in terms of the recently published MMLS Protocol DPG1 (2008), the mixes would not meet the criteria for a critical temperature of 60C. However the criteria for a critical temperature of 50C are met and good performance of the mix could be expected under those conditions. This highlights the importance of selecting an appropriate test temperature for operating conditions that the mix will be subjected to.
6. The findings from the study show that the application of the MMLS as a comparative testing tool for rutting performance is justified. Furthermore it lends support to the differentiation of the test modes that as outlined in the Protocol.

7. One aspect that became evident during the study was that changes to the gradings of the aggregate alone, were not successful in improving the rutting performance of the HMA mixes where the target grading has been selected carefully to achieve rut resistance.

8. In the same vein, the tests at 60C were above the softening point of the binder. Hence rutting resistance was primarily dependant on the stone skeleton.

9. It appears that the overlap of the rutting performance under MMLS and HVS trafficking is considerable. So much so that similar rutting limits could be established for the HVS to indicate acceptable threshold limits.

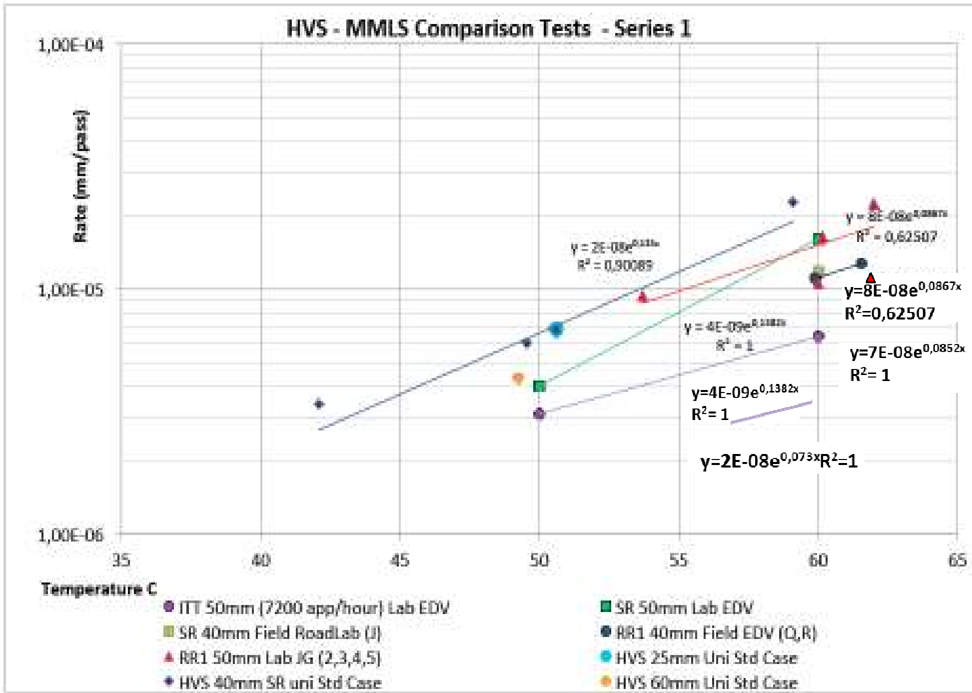

Figure 3 Comparison Tests of HVS and MMLS Series 1

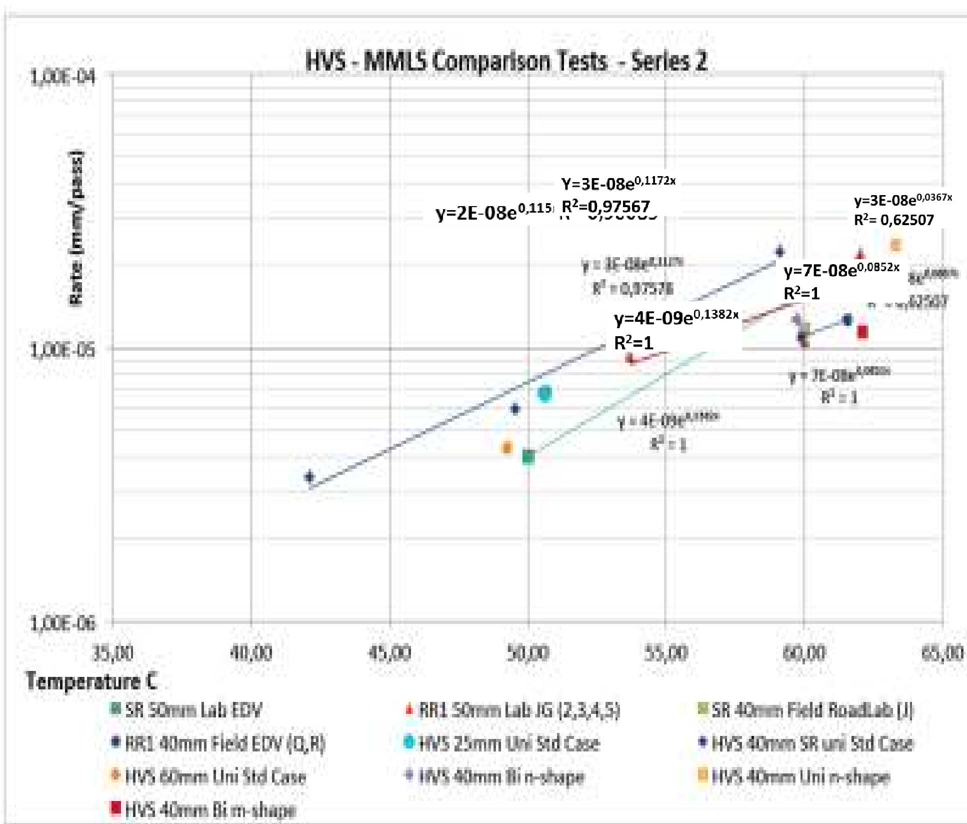

Figure 4 Comparison Tests of HVS and MMLS Series 2

Table 2: Details pertaining to HMA characteristics of the respective Case Studies [After Denneman et al (2008)[1]; Liebenberg et al (2011)[2]; Pretorius et al (2010)[3]]

R80[1]	R80	R80	N3[2] Mariann-hill	N3 Mariann - hill	N3 Mariann hill	N3 Mariann - hill	N1[3] Kanet-vlei remedial	N1 Kanet-vlei original
Mix Type	**Std Ref**	**Std Ref**	Colto Base rev	Colto Base rev	Colto Base rev	Colto Base rev	Colto surf	
Sieve size [mm]	**Mix design**	**Recov**	Mix design – Bailey	Mix design – Bailey	Mix design – Bailey	Mix design – Bailey	**Mix design**	**Mix design**
26.5			100	100	100	100		
19			96	94	96	94		
13.2	100	99.9	82	83	82	83	99	98
9.5	99	98.8	69	69	69	69	87	89
6.7	86	89.6					70	70
4.75	71	74.8	49	52	49	52	57	55
2.36	43	46.5	33	35	33	35	36	37
1.16	26	30.1	23	25	23	25	25	26
0.600	18	21.2	17	18	17	18	17	
0.300	13	15.7	12	13	12	13	14	13
0.150	8	9.6	8	9	8	9	9	9
0.075	5.4	5.2	5.3	6.3	5.3	6.3	7,0	6.8
Hyd lime %			1.0	1.0	1.0	1.0	1.0	1.0
Binder [%]	5.0	5.1	4.2	4.4	4.2	4.4	4.3	4.8 (Ave 4.9)
Binder Type	60/70	60/70	A-P1 (4% EVA) PG 70-28	A-E2 (3.5% SBS) PG 64-22	A-P1 (4% EVA) PG 70-28	A-E2 (3.5% SBS) PG 64-22	5.5% EVA with 60/70	60/70
VIM [%]	4.3*	5.7**	4.2	4.4	5.0	4.9	6.5	5.5 (Ave 5.3)
(VMA) [%]	15	15	14.3	13.5	14.3	13.5	16.2	15.4
Gyr voids @N = 300	2.4	2.4	3.0	2.7	3.0	2.7	3.3	3.8
ITS at 25 C [kPa]	1180	1180	1135	1110	1135	1110	1240	1144
Max TRD			2491	2500	2491	2500	2.578	
BRD			2336	2380	2336	2380	2.410	2.743
Thickness of Film - µm			7.7	7.0	7.7	7.0	6.8	7.8
MMLS Data								
Test Temp C		60 ± 2	60 ± 2	60 ± 2	60 ± 2	60 ± 2	55 ± 2	50 ±2
Dry/Wet	Dry	Dry	Wet	Wet	Dry	Dry	Dry	Dry
Test Speed appl/h	2400	2400	2400	2400	2400	2400	2400	7200
Core Voids%			4.0	3.9	3.8	4.1	5	
Ave Rut@100k	1 -2	1 -5	1.81	3.21	1.66	2.49	1.43	1.67
Std Dev σ			0.386	0.882	0.307	0.533		
Cov %			21.4	27.5	18.5	21.4		
$\mu+2\sigma$			2.6	5.0	2.3	3.6		

Table 3: Summary of the HVS Rutting Gradients and Temperatures

(after Table 4.1 Hugo &Gerber 2008)

Test	Temp	Equation	R	Constant	Power	X1	X2	Y1	Y2	Gradient
441A4	59.10	$y = 0.0022x^{0.6338}$	0.934	0.0022	0.6338	10^4	$2.\ 10^5$	0.75	5.04	2.25E-05
442A4	42.10	$y = 0.0762x^{0.2316}$	0.897	0.0762	0.2316	10^4	$2.\ 10^5$	0.64	1.29	3.39E-06
443A4	49.55	$y = 0.0017x^{0.5504}$	0.973	0.0017	0.5504	10^4	$2.\ 10^5$	0.27	1.41	5.98E-06
444A4	50.60	$y = 0.0234x^{0.3623}$	0.967	0.0234	0.3623	10^4	$2.\ 10^5$	0.66	1.95	6.79E-06
445A4	49.25	$y = 0.0228x^{0.3312}$	0.906	0.0228	0.3312	10^4	$2.\ 10^5$	0.48	1.30	4.3E-06
446A4	59.70	$y = 0.0173x^{0.431}$	0.926	0.0173	0.431	10^4	$2.\ 10^5$	0.92	3.33	1.27E-05
447A4	63.30	$y = 0.0142x^{0.4935}$	0.911	0.0142	0.4935	10^4	$2.\ 10^5$	1.34	5.87	2.38E-05
448A4	62.10	$y = 0.0658x^{0.3257}$	0.979	0.0658	0.3257	10^4	$2.\ 10^5$	1.32	3.51	1.15E-05

Table 4: Summary of the MMLS3 Rutting Gradients and Temperatures
(after Table 4.2 Hugo & Gerber 2008)

Test	Temp	Equation	R^2	Constant	Power	X1	X2	Y1	Y2	Gradient
RR1 Lab JG2	60.00	$y = 0.1555x^{0.2602}$	0.975	0.1555	0.2602	10^4	$2.\ 10^5$	1.71	3.72	1.06E-05
RR1 Lab JG3	62.00	$y = 0.0232x^{0.4507}$	0.993	0.0232	0.4507	10^4	$2.\ 10^5$	1.47	5.68	2.22E-05
RR1 Lab JG4	53.70	$y = 0.1657x^{0.2474}$	0.978	0.1657	0.2474	10^4	$2.\ 10^5$	1.62	3.39	9.35E-06
RR1 Lab JG5	60.15	$y = 0.1854x^{0.2777}$	0.982	0.1854	0.2777	10^4	$2.\ 10^5$	2.39	5.50	1.63E-05
RR1 Field Q	59.90	$y = 0.0623x^{0.3265}$	0.987	0.0623	0.3265	10^4	$2.\ 10^5$	1.26	3.35	1.1E-05
RR1 Field R	61.55	$y = 0.0317x^{0.3857}$	0.988	0.0317	0.3857	10^4	$2.\ 10^5$	1.11	3.51	1.27E-05
SR Field J	60.00	$y = 0.0601x^{0.3334}$	0.995	0.0601	0.3334	10^4	$2.\ 10^5$	1.30	3.52	1.17E-05
SR Lab EDV T1	60.00	$y = 0.1174x^{0.308}$	0.987	0.1174	0.308	10^4	$2.\ 10^5$	2.00	5.04	1.6E-05
SR Lab EDEV T3	50.00	$y = 0.2621x^{0.1647}$	0.989	0.2621	0.1647	10^4	$2.\ 10^5$	1.19	1.96	4.01E-06

CASE STUDY 4: APPLICATION TO AIRPORT PAVEMENTS

Emery (2008) has used the MMLS on a number of applications to successfully evaluate performance of airport pavements. These are of particular interest because they pertain to layered asphalt pavements carrying extremely heavy axle loads under high tyre pressures and high temperatures. This is particularly relevant on taxiways used in prolonged high temperatures even though the gradients are very flat.

In their studies Emery and Mihaljevic (2008) considered and compared the use of the MMLS and the Cooper wheel tester that is used in Australia. They concluded that the MMLS has the advantage of being more closely linked to field performance and that the results can be assessed in absolute terms. Accordingly, tests with the Cooper wheel tester were considered outside the scope of the paper and will not be discussed in any detail.

As Emery and Mihaljevic (2008) reported, they used the MMLS Accelerated load testing (APT) to evaluate heavy-duty asphalt mixes placed on Dubai International Airport (DIA) for expansion and rehabilitation works. The DIA pavement structure consisted of six asphalt layers totalling 400mm thickness, and a cement treated subbase layer. Details are shown in Table 5.

The wearing course comprised a BC20* material with 20mm nominal stone size with a PG76 Cariphalte Fuelsafe binder. A coarse grading was used for runway surfaces while a fine grading was used for all other pavements. Two BC20 intermediate layers contained PG76 grade polymer modified binder while three BC32 base course layers 32mm nominal stone contained straight run unmodified 60/70 grade bitumen. The Cariphalte Fuelsafe binder (a mix of plastomeric and elastomeric polymers) provided a stiff binder that is also resistant to hydrocarbons.

Shortly after opening sections of the new pavements to aircraft traffic at DIA, rutting failures appeared with rut depths measured from 6 mm up to 34 mm. The rutting was in areas of very slow trafficking, such as on aprons and around taxiway holding points. It had occurred in the hot Dubai summer. Cores showed a reduction in air void content from the time of construction to the time of the investigation of up to 4.0 percent. A considerable difference was measured between trafficked and non-trafficked sites. This was ascribed to secondary compaction.

Table 5: Dubai Pavement Thickness Design

(after Table 1 Emery and Mihaljevic 2008)

Description	**Layer Thickness (mm)**	**Material (nominal stone size, binder)**
Wearing	55	BC20 PG76 Cariphalte Fuelsafe – two gradings (coarse and fine)
Intermediate	65	BC20 PG76 SBS Modified Binder
Intermediate	65	BC20 PG76 SBS Modified Binder
Basecourse	70	BC32 60/70 Bitumen
Basecourse	70	BC32 60/70 Bitumen
Basecourse	70	BC32 60/70 Bitumen
Subbase	200	Cement Treated Fine Crushed Rock
Subgrade		Natural Sandy Subgrade CBR=15%

APT was done in the laboratory with the MMLS. Previous testing with the MMLS system had been used to evaluate asphalt sections at airports pavements (Molenaar et al., 2004 and Jenkins et al., 2003). However those studies had all used the conventional 7200 load applications per hour. Since the rutting was linked to slow aircraft speeds, the MMLS testing on pavement cores was run at the slower speed of 1800 /h. At the slow speed on the BC32 base course, rutting of 3.94 mm found at only 50,000 cycles. This yielded an extrapolated rut of 4.10 mm at 100,000 cycles. The effect of test speed on rut depth is shown in Table 6.

Table 6: MMLS Test Results on Dubai Asphalts at Different Test Speeds

(after Table 4 Emery and Mihaljevic 2008).

Asphalt layer, grading and binder	**Final Rut Depth at 100,000 load applications (mm)**	
	Normal (7200 load appl/h)	**Slow (1800 load appl/h)**
Wearing course, BC20* fine grading, Cariphalte Fuelsafe PG-76 binder	1.40	1.70
Wearing course, BC20 coarse grading, Cariphalte Fuelsafe PG-76	1.27	2.14
Intermediate layer, BC20 fine grading, PG-76	1.45	1.82
Basecourse, BC32, 60/70 binder	1.48	4.10

* Max nominal aggregate size (mm)

They decided to use MMLS slow speed testing to investigate performance of the existing 12L/30R northern runway at DIA by coring and testing. This pavement had been in operation for ca. 7 years. Only minor rutting had been observed and it was deemed to be an acceptable rutting rate with respect to the operational conditions. A test temperature was selected to simulate the insitu pavement and the test speed was 1800 load applications/hour. The measured MMLS rut depths (Table 7) and known good field performance correlated to give confidence that the existing Baton Rouge protocols are appropriate at slow speed (1800 loads applications/hour).

Emery and Mihaljevic (2008) also eloquently applied the analytical approach for estimating full-scale rutting of a layered asphalt airport pavement system under trafficking. The laboratory MMLS rut testing was linked to field rutting performance analytically.

Table 7: MMLS testing of Cores from Dubai Runway 12L/30R.

(after Table 5 Emery and Mihaljevic 2008).

Parameter	Wearing course		Basecourse	
Binder	Plastomeric (PE blend)		PG76	
Sample	1	2	4	5
Air voids	4.6%	4.1%	7.0%	6.1%
Rut depth at 100,000 applications in MMLS slow speed (mm)	1.22	1.32	1.35	1.11

Linking MMLS Results and Field Rutting

They used this data to compare with performance of the respective asphalt layers of a real pavement. Their results showed a good correlation with actual field performance with the analytical calculations within 20 percent of the measured ruts. The analysis followed the procedure described fully by Epps et al (2002). It was also reported in other studies (Smit et al, 2003 and Walubita et al, 2002). It is referenced in the DPG1 (2008). A synthesis of their approach is briefly summarized below.

Testing was done with the MMLS. The procedure they followed only differed in one significant way namely the speed of MMLS trafficking. Their fundamental analysis of the rutting performance of some mixes was done with due regard to actual effective traffic volume, vertical stress due to load, load frequency and temperature (aircraft type, tyre pressure, wheel loading, lateral wander), climatic conditions and layer thicknesses. This process brings together the effect of temperature gradients in the asphalt (with the surface layers being tested at higher temperatures than the basecourse layers) and stress (with the greater stresses in the surfacing layers being reflected in the stress potential factor).

The MMLS test results of the Dubai asphalt were used to calculate an estimate of field rutting for comparison with actual measured rutting.
The Boeing 777-300ER is extensively used at DIA and it was adopted as the design aircraft. For the comparative analyses the aircraft was modelled at 1533kPa tyre pressure and 269kN tyre load. The MMLS was modelled at 700kPa en kN tyre load (equivalent to maximum takeoff weight). The MMLS was modeled at 700kPa and 2.9kN.

The results were remarkably close to the actual measured values. As an example, on Taxiway M north of Runway 12R30L ruts measured 32 -34 mm compared to the calculated scaled calculated rut depth of 28.3mm. In each case the traffic volume was estimated to have been 20 000 aircraft movements.

The authors concluded that 60% of the rutting in the 400mm deep asphalt could be attributed to the three 60/70 BC32 basecourse layers. This was despite the fact that these layers are in cooler conditions than the surfacing layers and are subject to less loading stress. The MMLS test results showed that the 60/70 bitumen is effectively too low in viscosity and a harder bitumen or a modified bitumen is required to improve the performance.

The method has proved to be particularly valuable for the design of new heavy-duty asphalt mixes intended for high loads in hot climates. It was concluded that the measured rutting at the reduced speed of testing with the MMLS was a reasonable approach to evaluate the performance under the harsh conditions at Dubai airport with due consideration of the multi-layered structure. It was evident that the results passed the "*test of reasonableness*" of Carl Monismith so frequently quoted.

CONCLUSIONS FROM THE SYNTHESIS OF THE CASE STUDIES

The synthesis of the case studies validated the relationship found between the slower MMLS tests protocol and field performance of the HMA under harsh full-scale trafficking. This provided useful information to adjudicate the guidelines included in the Draft Protocol DPG1 (2008) for this test mode. It will enhance the ability of pavement engineers to improve durability and performance of asphalt pavement layers under harsh conditions. This provided support for the application of the MMLS as an APT tool to adjudicate evaluation of permanent deformation and susceptibility to moisture damage of bituminous road paving mixtures.

Trends in permanent rate of deformation of HMA subject to temperature and speed changes under the MMLS trafficking compare well to results obtained under full scale HVS testing under similar conditions.

The ability to scale MMLS HMA field and laboratory performance test results analytically to actual field rut performance as outlined in DPG1 was confirmed. The reported case study by Emery and Mihaljevic, (2008) successfully expanded the application from highway pavement layers to airport pavement layers with harsh environmental and load conditions.

The findings from the study show that the application of the MMLS as a comparative testing tool for rutting performance is justified. Furthermore it lends support to the differentiation of the test mode as outlined in DPG1.

The successful application of full-scale and scaled APT for exploring performance of HMA under harsh trafficking conditions was validated in terms of temperature, and speed of trafficking. Aspects that became clear during the study were that:

- changes to the gradings of the aggregate alone, were not successful in increasing the rutting performance of the HMA mixes.
- limitations of rutting performance of unmodified binders and benefits of modified binders could be explored and managed by MMLS APT.
- cost-effective selection of appropriate binders for specific applications and conditions could be achieved through MMLS APT.
- the change of the original Baton Rouge protocol limit of < 1.8mm rutting under 7200 appl/h trafficking for airports to the same limit under 1800

appl/h was validated by the evaluation of the performance of an existing runway with known good rutting performance under the latest heavy aircraft trafficking.

Some interesting aspects of asphalt mix design for harsh conditions were captured during the synthesis in reporting the background to the case studies. These were however not integrated in the analysis of the APT that was focused on rutting performance and therefore outside of the scope of the study.

The case studies presented in this paper cover an extensive and diverse geographic area. Therefore the overall positive validation of the guidelines in the draft Protocol DPG1 (2008) provides strong support for the application of the MMLS as an APT tool to adjudicate evaluation of permanent deformation and susceptibility to moisture damage of bituminous road paving mixtures using the MMLS.

ACKNOWLEDGEMENTS

The sponsoring clients and/or professional pavement engineers involved in the designs of the projects have been requested for permission to publish the paper on the basis of their respective reports. The work presented in Case Study 3 in the paper was made possible by the sponsorship of the Gauteng Department of Public Transport Roads and Works (GDPTRW). Riyaaz Nieftagodien, a graduate student intern of ITT did the analysis of the field rutting performance data presented in Case study 2. The authors express thanks to all, for permission to present and/or publish the findings in the paper. A special word of thanks to Dr. Steve Emery for sharing his experience on airports presented in Case Study 4.

Some interesting aspects of asphalt mix design for harsh conditions were captured during the synthesis in reporting the background to the case studies. These were however not integrated in the analysis of the APT that was focused on rutting performance and therefore outside of the scope of the study.

REFERENCES

1. **DPG1 – Method for evaluation of permanent deformation and susceptibility to moisture damage of bituminous road paving mixtures using the Model Mobile Load Simulator (MMLS3)**, 2008. Best Practice Protocol developed under the auspices of the Road Pavement Forum (RPF) and approved for use and distribution at the bi-annual meeting held in Pretoria,
2. Epps, M, Ahmed, T, Little, DC, Hugo, F, Poolman, P and Mikhail M, 2002. **Performance prediction with the MMLS3 at WesTrack, International Conference on Asphalt Pavments**, 9th, 2002 Copenhagen, Denmark
3. Pretorius, F.J., Bowker, I., Grobler, J. & McGregor, G, 2010. **Premature Deformation Failure of an Asphalt Surfacing: Case Study on N1 at Hex River Pass**, South Africa, ISAP 2010
4. Liebenberg Jaco, Dennis Rossmann, Philip Joubert, 2011. **Asphalt mix design for the rehabilitation of National Route 3 between Marianhill and Key Ridge**, Paper submitted for presentation at the CAPSA 2011 meeting.

5. Verhaege, BMJA, Myburgh, PA and Denneman, E, 2007. **Asphalt Rutting and its Prevention**, CD Rom Proc 9th Conference on Asphalt Pavement for Southern Africa (CAPSA'07), Gaborone, Botswana September
6. Denneman, E, Steyn, WJvdM, Maina, J, Sadzik, E, 2008. **Evaluation of Deformation Response of HMA under APT and Wheel Tracking Tests**, Third International Conference on Accelerated Pavement Testing, Madrid, Spain.
7. Smit, AdF, Hugo, F, Rand, D and Powell, B, 2003. **Model Mobile Load Simulator Testing at the National Center for Asphalt Technology Test Track**, Transportation Research Record 1832, Transportation Research Board, National Research Council, Washington DC.
8. De Beer and Sadzik, 2007. **Comparison of Contact Stresses of the Test Tyres used by the 1/3rd Scale Model Mobile Load Simulator (MMLS3) and the Full-Scale Test Tyres of the Heavy Vehicle Simulator (HVS) – A Summary**, Proceedings of the 26th Southern African Transport Conference (SATC 2007), Pretoria, July.
9. Hugo, F, De Vos, ER, 2008a. **Evaluation of HMA Rutting Performance Under MMLS3 Trafficking in the Laboratory and in the Field on a trial section on the R80**, First Paper prepared for Gauteng Government Department of Public Works and Transportation, May.
10. Hugo, F, De Vos, ER, 2008b. **Evaluation of HMA Rutting Performance Under MMLS3 Trafficking in the Laboratory and in the Field on a trial section on the R80**, Second Report prepared for Gauteng Government Department of Public Works and Transportation, September.
11. Hugo, F, Gerber, JAK, 2008. **Additional MMLS3 Laboratory Testing and a Synthesis of Selected Tests for Evaluation of Rutting Performance of the HMA on a Trial Section of R80 under HVS & MMLS3 APT Trafficking**, Report for Gauteng Government Department of Public Works and Transportation, December 2008
12. Denneman, E, 2008a. **Technical memorandum Assessment of the permanent deformation characteristics of a standard Hot-Mix Asphalt; Level one analysis of laboratory study results**, Technical memorandum CSIR/BE/IE/ER/2007/0014/B, prepared for Gauteng Provincial Government Department of Public Transport, Roads and Works Directorate by CSIR Built Environment, Pretoria, March.
13. Emery, S, 2010. **Australia Personal communication**, Kubu Australia Pty Ltd
14. Emery, Stephen, Mihaljevic, Ivan, 2008. **Accelerated Load Testing of Asphalt Mix Designs for Heavy Duty Pavements in Hot Climates**, 23rd ARRB Conference, 2008, Adelaide Australia
15. Molenaar, P, Hugo, F, Beukes, J, Catin, G, 2004. **Rehabilitation of runway 03L-21R at Johannesburg International Airport, the quest for a suitable surfacing mix**, Conference on Asphalt Pavements for South Africa 8th, 2004, Sun City, South Africa
16. Jenkins, KJ, Pretorius, FJ, Hugo, F and Carr, R, 2003. **Asphalt Mix Design of Cape Town International Airport using Scaled APT and other Selected Tests**, 6th International Rilem Symposium on Performance Testing and Evaluation of Bituminous Material, Zurich Switzerland
17. Walubita, LF, Hugo, F, Epps, M, 2002. **Indirect Tensile Fatigue Performance of Asphalt after MMLS Trafficking under Different Environmental**

Conditions, Journal of the SA Institute of Civil Engineering, Johannesburg, SA Volume 44, No. 3

KEYWORDS: RUTTING PERFORMANCE; ENVIRONMENTAL IMPACT; TRAFFICKING SPEED; APT; MMLS; AIRPORT PAVEMENTS