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Indirect tensile fatigue performance of asphalt after MMLS3 trafficking under different environmental conditions

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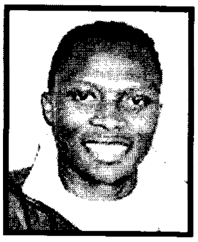
Cores were extracted from test sections of an in-service asphalt pavement that were trafficked with the Model Mobile Load Simulator (MMLS3) under different environmental conditions (dry, hot and wet) to assess pavement performance/damage through indirect tensile fatigue testing. Particular emphasis was placed on the effect of water during wet trafficking. Analysis was based on a comparison of the residual fatigue life of trafficked core-specimens compared to untrafficked core-specimens, and the difference (represented as a ratio) was construed as indicative of the performance/damage of the asphalt under the corresponding environmental conditions (dry, hot and wet) during MMLS3 trafficking. Under dry and hot MMLS3 trafficking conditions, the asphalt exhibited improved fatigue performance due to material densification. The asphalt from the wet trafficked sections manifested a decrease in fatigue life relative to the untrafficked asphalt due to water damage. Moisture damage in the asphalt was evident through degradation, loss in strength and stiffness, micro cracking and stripping. From the findings, it was apparent that for asphalt materials susceptible to moisture damage, the fatigue life expectancy is significantly reduced by wet trafficking, such that even light axle loads (2,1 kN) with high tyre pressures (690 kPa) cause substantial damage. Overall, the study demonstrated that the MMLS3 used in conjunction with laboratory fatigue testing is a valuable APT tool that can be used to evaluate the response and performance of the surface layers of full-scale, in-service asphalt pavements under different environmental conditions.

Key words: Accelerated pavement testing (APT), MMLS3, fatigue performance, environmental conditions



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INTRODUCTION

In asphalt pavements, fatigue damage manifests as crocodile cracks, often starting longitudinally along the wheel tracks, caused by primarily repetitive traffic loading often in conjunction with environmental effects. The cracks can originate from the surface and/or bottom of the asphalt layer depending on the pavement structure and loading conditions. This weakens the structural capacity of the pavement, making it even more susceptible to environmental damage, particularly water. Structural damage can in fact also be precipitated by the presence of water in the asphalt or on the pavement surface during trafficking.

In this study, the reduction in residual fatigue life of a core-specimen was taken to be representative of the loss in structural capacity. The indirect tensile fatigue life ($N_{f(trafficked)}$), or the number of load cycles to fatigue failure, of core-specimens from test sections trafficked by the one-third scale Model Mobile Load Simulator (MMLS3) was determined. These were then compared to the number of load cycles to failure ($N_{f(untrafficked)}$) of core-specimens from test sections not trafficked by the MMLS3. The ratio of residual fatigue life of trafficked relative to untrafficked sections ($N_{f(trafficked)}/N_{f(untrafficked)}$) was considered as indicative of the material performance/damage under the corresponding environmental conditions during MMLS3 trafficking. A high value, ie close to or greater than 1,0, was indicative of little damage or, in the latter case, an increase in fatigue life.

Cores were obtained from sections trafficked by the MMLS3 and from adjacent untrafficked sections on an in-service asphalt (AC)* pavement (highway US 281) in Jacksboro, Texas (USA). The objective of the study was to evaluate the indirect tensile fatigue performance of the asphalt after trafficking with the MMLS3 under dry (38°C), hot (pavement heated to 50°C) and wet (with water on the pavement surface at 24 °C and 30°C) conditions, as well as to gauge the extent and degree of MMLS3 damage on the asphalt materials under these conditions.

All characteristic temperatures were measured at 25 mm depth within the pavement structure. Particular emphasis was placed on the impact of water damage under wet MMLS3 trafficking in terms of asphalt degradation, micro cracking, stripping, stiffness loss, strength loss and residual fatigue life. These MMLS3 tests were part of the Texas Department of Transportation (TxDOT)'s full-scale accelerated pavement testing (APT) programme commissioned in 1995 to model material performance of in-service pavements, evaluate new rehabilitation materials, and investigate load damage equivalency and ment testing (APT) and has worked in a number of African states, Europe, Israel, the United States and Canada. He is still very active as a consultant internationally.

Prof Hugo has published more than one hundred papers and is the recipient of a variety of awards in the field of pavement engineering, including the SAICE/CAPSA Award for Outstanding Achievements in of Asphalt Technology (1990) and the SAICE Award for Meritorious Research (1995). He has served on various committees of SAICE and other professional societies and technical committees. He is currently a member of the Education and Training and APT Committees of the TRB, aa life member of the Association of Asphalt Paving Technologists (AAPT) and a member of the Society for Asphalt Technologists in Southern Africa. He is an honorary fellow and past president of SAICE (1993).

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truck-tyre pavement interaction (Hugo *et al* 1999 [a],[b]; Smit *et al* 1999; Walubita *et al* 2000).

Although a wide array of tests and measurements such as surface rut profiles, layer deformations and in-situ asphalt stiffness measurements were conducted during and after MMLS3 trafficking (as part of the TxDOT APT programme), the focus of this paper is on the fatigue performance of the asphalt materials. Therefore the study described concentrates on the indirect tensile fatigue tests and the related material damage. Full details of the APT test protocols and results from one field site and a historical background of the TxDOT APT programme have been documented and published elsewhere (Hugo *et al* 1999 [a], [b]; Smit *et al* 1999; Walubita *et al* 2000). Also see www.mls.sun.ac.za.

TEST OBJECTIVES

The MMLS3 tests in Jacksboro (Texas) were first commissioned in 1998 to investigate the stripping phenomenon evident on the southbound outside lane of highway US 281 (Hugo *et al* 1999[a]; Smit *et al* 1999; Walubita *et al* 2000). Preliminary diagnostic studies indicated that water ingress into the pavement layers had substantially reduced the indirect tensile fatigue performance of the lightweight aggregate asphalt concrete (LWAC) located in an underlying layer (Smit *et al* 1999). LWAC is an asphalt mix with manufactured aggregate, which is relatively porous with a low density (approximately 2 350 kg/m^3 compared to 2 600 kg/m^3 for Texas limestone). In-situ asphalt stiffness measurements as well as micro cracking under wet MMLS3 trafficking also indicated that the asphalt surfacing (overlay) on the northbound carriageway was potentially susceptible to moisture damage (Hugo *et al* 1999a; Smit *et al* 1999). For this reason, additional MMLS3 testing was recommended in 1999 on both the north- and southbound carriageways of US 281 to ascertain whether the overlays were moisture susceptible given that they had performed well under dry trafficking conditions. Apart from testing the surfaces of the two carriageways, tests were also suggested for the second layer of each carriageway by milling off the top layers. The intent was to conduct both hot and wet tests on the original and milled surfaces. This enabled the performance of the individual layers/ materials of the upper pavement structures to be distinctively evaluated. The test objectives were summarised as follows:

- to investigate the impact of water on pavement degradation and stripping under wet MMLS3 trafficking through an evaluation of indirect tensile fatigue performance of the asphalt materials after trafficking
- to conduct a similar evaluation of the effects of high temperature on the fatigue performance of the asphalt materials after trafficking
- to perform density and strength tests to gauge the moisture sensitivity of the pavement materials and to supplement the field measurements of in-situ asphalt stiffness and laboratory fatigue tests

The main purpose was to compare the performance trends of the different asphalt materials or processes used to rehabilitate the upper layers of the highway sections, taking into account the MMLS3 test results of Hugo *et al* (1999) [a],[b], Smit *et al* (1999) and Walubita *et al* (2000). Indirect tensile fatigue life was defined as the number of repetitive load cycles to full crack propagation across the specimens in a haversine stress-controlled test that is fully discussed below. Density, strength and moisture susceptibility tests were also conducted to supplement the field measurements and laboratory fatigue tests and validate the findings. These tests are discussed briefly and relevant findings related to fatigue are presented.

TEST SITE

MML3 testing was done on highway US 281 on a section approximately 8 km south of Jacksboro in Texas (USA). Highway US 281 is an in-service four-lane highway with two lanes in either direction (north and south). It is a high traffic volume highway with average daily traffic (ADT), according to 1994 traffic data, totalling 3 100 (approximately 1 550 per direction), with 10% travelling the inner lanes (Hugo *et al* 1999 [a], [b]).

MMLS3 trafficking was conducted on the inner lanes while the outside slow lanes remained open to conventional traffic.

PAVEMENT STRUCTURES AND MATERIALS

The pavement structure for highway US 281 is shown in figure 1. Interest was in the top 70 mm consisting of three asphalt layers, with the top two being different rehabilitation materials for each of the two carriageways – northbound (US 281N) and southbound (US 281S).

Essentially, the base material/structure at 70 mm depth is the same under both structures; approximately 100-125 mm asphalt, 380 mm unbound base and the subgrade (figure 1). The original pavement was constructed in 1957 with the latest rehabilitation overlays placed in 1995 and 1996 for the southbound and northbound lanes respectively.

The southbound lanes (US 281S)

The southbound lanes were rehabilitated in 1995, using a process which entailed a 50 mm (nominal) overlay of recycled and repaved LWAC with some fresh limestone asphalt added along with a dosage of rejuvenating oil. This process will be referred to as *Rehab A* (figure 1). The average air void content measured by the saturated surface dry (*SSD*) method (ASTM D2726) was 12,5%. This method was used consistently throughout this study, but it should be noted that the method is not well

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* For the benefit of international readers who are more familiar with this terminology, the term 'asphalt' is used synonymously to mean asphalt concrete (AC). Also AC is used interchangeably to mean asphalt and/or asphalt concrete.

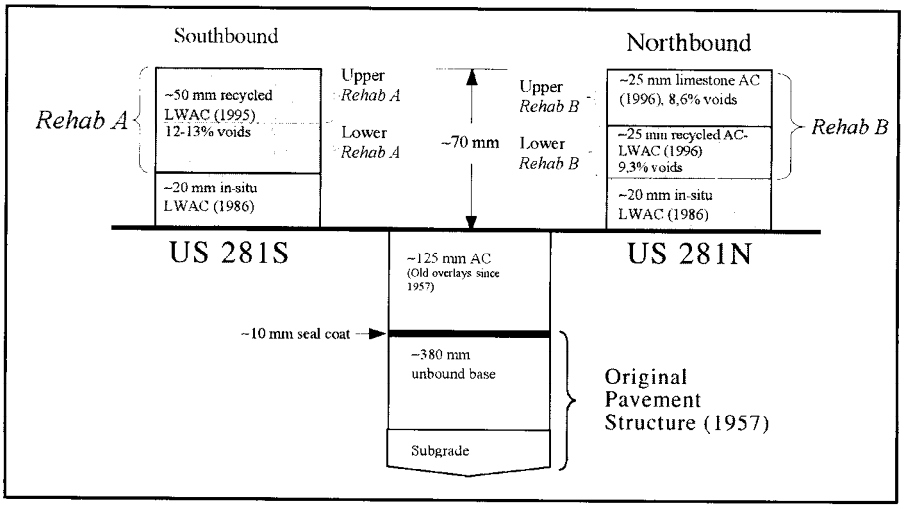

Figure 1 US 281 Pavement structures

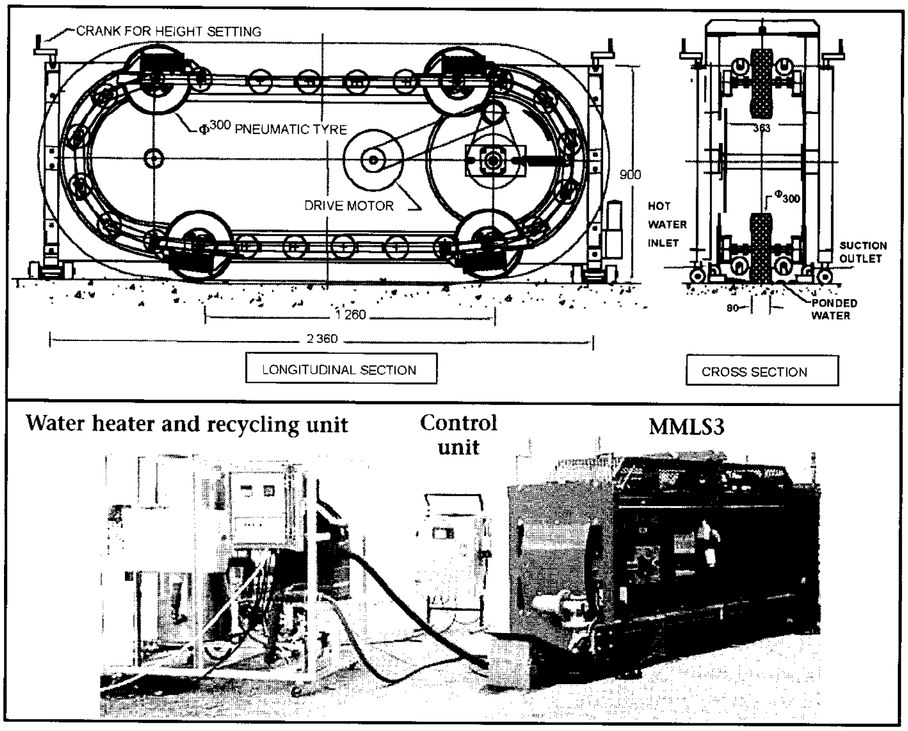

Figure 2 Diagrammatic views of the MMLS3 and a pictorial view of the setup during a typical wet trafficking test

suited for accurately measuring high air void contents where there is a higher probability of interconnected voids. Immediately below *Rehab A* is an approximately 20 mm thick in-situ LWAC layer paved in 1986.

The northbound lanes (US 281N)

The northbound lanes were reconstructed in 1996, using a process which entailed scarifying the heated LWAC in situ to a depth of 25 mm and treating it with rejuvenating oil before compaction, thus leaving the composite approximately 45 mm thick (figure 1). Thereafter the composite LWAC layer was overlaid with 25 mm conventional limestone asphalt concrete (limestone AC) with an air void content of approximately 8,6% by the SSD method (ASTM D2726). The recycled LWAC and conventional limestone AC considered together will be referred to as *Rehab B* (figure 1). The upper 25 mm reprocessed LWAC had an air void content of approximately 9,3% by the SSD method (ASTM D2726) (Walubita *et al* 2000).

TEST METHODOLOGY

The APT test plan involved field-testing with the MMLS3 and intermittent measurement of temperature, surface rut profiles, pavement layer deformations and in-situ asphalt stiffness. Thereafter cores were extracted for fatigue and supplementary testing including density, strength and moisture sensitivity. The MMLS3 and fatigue testing are discussed subsequently.

The MMLS3 machine

The one-third (1/3) scale Model Mobile Load Simulator (MMLS3) is a low-cost APT device consisting of four recirculating axles, each with a single 300 mm diameter wheel. Figure 2 shows a pictorial view of the setup during a typical wet MMLS3 trafficking test together with two diagrammatic views. The wheels can be laterally displaced across 150 mm in a normal distribution about the centre line to simulate traffic wandering, if desired. The tyres may be inflated up to a pressure of 800 kPa. Axle loads can be varied between 2,1 kN and 2,7 kN. The axle loads are automatically kept constant at a predetermined value by the special suspension system (Muller 1999).

Nominal wheel speed is 2,5 m/s (9 km/hr, 4 Hz), applying about 7 200 axle loads per hour. Frequency was calculated on the basis of time of contact using a measured tread length of 110 mm. A single 1,5 kW variable speed motor drives a drum that draws the four wheels which are linked through a closed loop chain on both sides of the loading wheels. The chain links are supported by sets of guide wheels running on rails. The MMLS3 can be used both in the field on in-service pavements and on laboratory constructed pavement structures. Some environmental conditions (such as temperature and trafficking under wet conditions) can also be controlled during testing to simulate field and/or desired conditions.

Axle load repetitions and environmental control

A total of eight tests were conducted in 1998 and 1999 on eight test sections with a total application of about 3,67 million MMLS3 axle loads (Smit *et al* 1999; Walubita *et al* 2000). Details of the tests are shown in table 1. The difference in the number of MMLS3 axle loads applied on each test section was due to logistical constraints and the fact that on some of the hot test sections trafficking was terminated, based on the rutting failure criteria (Walubita *et al* 2000). Rutting was one of the distresses monitored during MMLS3 trafficking, but these results are outside the scope of this paper. For analysis and comparison purposes, however, equivalent MMLS3 axle loads were considered, ie rutting performance was evaluated on the basis of number of trafficked axle loads. Where trafficking had been terminated early, the rutting performance was determined by extrapolating the performance curve.

Four hot tests were conducted with the pavement heated to 50°C at 25 mm depth before and during trafficking, using an environmental-temperature control chamber to cover the MMLS3 and the test section. Two hot tests were carried out directly on the surfaces of *Rehab A* and *Rehab B*. The other two were done on the surfaces of milled sections (lower Rehab B and lower Rehab A) of the north- and southbound inner lanes, respectively. A dry test, at ambient temperature, without pavement heating or environmental con-

Table 1 MMLS3 test details

Test no	Test section	Surface type	Test condition	Trafficking temperature °C (@ 25 mm depth)	MMLS3 axle loads
1	*n1*	Top surface	Hot (pavement heated)	50	320 000
2	*n2*	Top layer (upper *Rehab B* [limestone AC]) milled off			160 000
3	*n3*		Wet (1 mm hot water)	30	320 000
4	*s1*	Top surface	Hot (pavement heated)	50	180 000
5	*s2*	Top layer (upper *Rehab A*) milled off			80 000
6	*s3*		Wet (1 mm hot water)	30	160 000
7	*n4* (*n-dry*)	Top surface	Dry (no environmental control)	38	1 000 000
8	*n5* (*n-wet*)	Top surface	Wet (1 mm water)	24	1 450 000

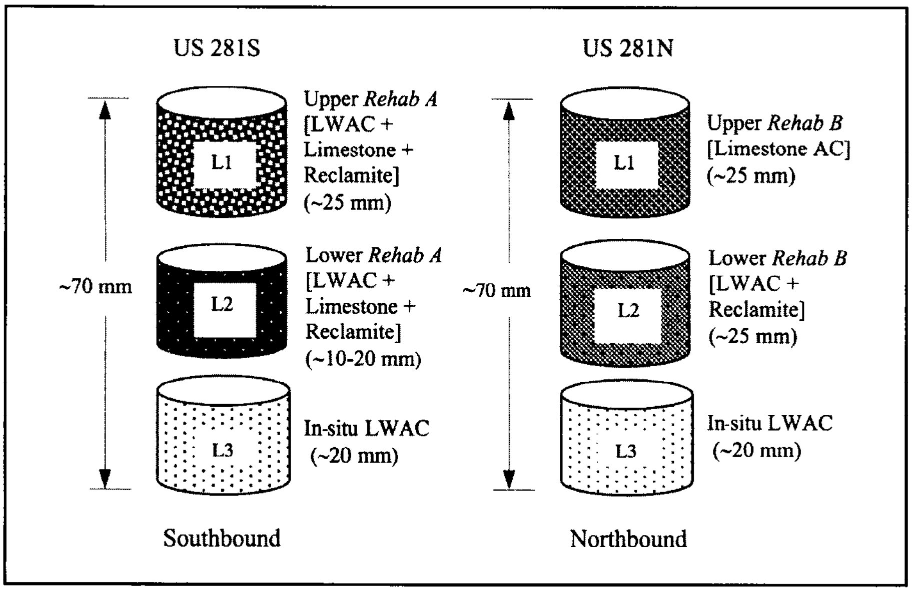

Figure 3 Core-specimens

trol, was also conducted on the northbound lane directly on the new limestone AC surface of *Rehab B*. The mean pavement temperature during MMLS3 trafficking for this test, measured at 25 mm depth, was 38°C (Smit *et al* 1999).

In addition, three wet tests were done with water applied on the pavement surface during trafficking. Two of these tests were conducted at 30°C on the surfaces of milled sections (lower *Rehab B* and lower *Rehab A*) of both the north- and southbound inner lanes, respectively. Hot water was applied on the pavement surface to maintain a constant temperature of 30°C at 25 mm depth during trafficking. The other wet test was conducted directly on the surface of the limestone AC layer of *Rehab B* on the northbound inner lane at ambient temperature without environmental control. The mean pavement temperature during MMLS3 trafficking for this test was 24°C at 25 mm depth (Smit *et al* 1999).

For all of the wet tests, an approximately 1 mm layer of water flowed across the test section surface during trafficking. This layer of water is equivalent to rain falling at a rate of approximately 5 mm per hour (Smit *et al* 1999).

In table 1, the test section notation '*n*' and '*s*' represents the northbound and southbound lanes, respectively. A test section is a marked out test pad on the pavement surface on which testing was done. The MMLS3 test section consisted of a rectangular grid 500 mm wide by 1 200 mm long, with a longitudinal centreline at 250 mm and transverse gridlines at 200 mm intervals.

The MMLS3 axle load for these tests was 2,1 kN, and the tyre pressure varied between 420 kPa (for the hot tests) and 690 kPa (for the dry and wet tests). The original intent was to use 690 kPa for all the tests, but the initial hot test was inadvertently conducted using 420 kPa. This tyre pressure was therefore retained for all the hot tests. No lateral wander was applied during any of the tests (Walubita *et al* 2000).

INDIRECT TENSILE FATIGUE TESTING

Field trafficking with the MMLS3 was done in Texas (USA), and fatigue testing of the cores was conducted at the University of Stellenbosch (Institute for Transport Technology [ITT]) in South Africa.

Coring and specimen preparation

A minimum of four cores were extracted from each trafficked test section along the centreline and each corresponding untrafficked section from both north- and southbound lanes. The cores were 100 and 150 mm in diameter, with a minimum length of 100 mm. These cores were cut to thicknesses corresponding to the pavement structure layer thicknesses up to 70 mm depth, with each layer or specimen approximately 20 mm thick, as shown in figure 3.

The core-specimens from the top surface layers were denoted 'L1' for layer 1. Core-specimens from layers 2 and 3 were labelled 'L2' and 'L3,' respectively. During the milling process on the southbound inner lane, as much as 40 mm of the upper *Rehab A* was unintentionally milled off on some parts of test sections s2 and s3. The layer and consequently the core-specimen thickness of the lower *Rehab A* varied between 10 and 20 mm with a mean of 15 mm. This, however, did not significantly affect the performance of this layer (lower *Rehab A*) in terms of temperature and moisture sensitivity according to the test results.

The specimen thicknesses used in this study were also within the range of those included in the indirect tensile strength (*ITS*) tests investigated in a study by Hugo and Schreuder (1993). According to them, the core-specimens used in this study are in fact more appropriate for assuming plane strain conditions in the analysis, since the results are less affected by thickness.

Test configuration

Fatigue testing was done in the indirect tensile (diametral) mode at 20°C with a haversine load at 10 Hz frequency with no rest periods until failure. Failure was defined as full crack propagation across the core-specimen. These loading conditions were chosen to simulate traffic loading on a pavement in the field.

The tests were stress controlled at stress levels approximately 20% of the maximum *ITS* of the corresponding MMLS3 untrafficked asphalt materials. Testing was done 90° to the direction of MMLS3 trafficking. At least four core-specimens were tested per test section per lane per layer.

Prior to testing, specimens were preconditioned at 20°C for a minimum period of two hours. Average time to fatigue failure was 20 hrs, with core-specimens from the hot trafficked test sections (trafficked at 50°C) taking the longest and having the highest residual fatigue life. Test results are presented in tables 2, 3 and 4 and will be discussed subsequently. Each result was obtained by electronically counting the number of load cycles to full crack propagation across the core-specimen. The crack failure criterion in the indirect tensile fatigue test is based on the development of tensile stresses in the centre zone of the specimen under repeated dynamic-compressive loading (SABITA 1997; Hugo *et al* 1992).

Supplementary measurements and tests

Non-destructive in-situ stiffness measurements were intermittently conducted in the field during MMLS3 trafficking to monitor the change in asphalt stiffness due to trafficking under different environmental conditions. The Portable Seismic Pavement Analyser (PSPA) and Seismic Measurements of Surface Waves (SASW) devices were used for the measurements of modulus that was equated to stiffness (Walubita *et al* 2000; Li & Nazarian 1994; Auoad *et al* 1993; Lee *et al* 1997.)

Ancillary laboratory tests (density, strength and moisture sensitivity) also provided supplementary information that was used to establish the ITS stress levels for the fatigue test (Walubita *et al* 2000).

The tests were conducted on core-specimens from both the untrafficked and trafficked test sections. At least four core-specimens were tested per test section per lane per layer. Moisture sensitivity tests involved determining the retained tensile strength of the untrafficked core-specimens after two hours wet conditioning (AASHTO 1998). The value obtained was compared with the tensile strength measured from the dry and untrafficked core-specimens to evaluate the moisture susceptibility of the asphalt. Strength tests were conducted in both ITS and semicircular bending (SCB) test modes at a test temperature of 20 °C. The application of the SCB test on asphalt is relatively new. The test involves determination of the maximum tensile stress (strength) at break (cracking) at the lower-middle zone of a three-point loaded semicircular shaped specimen as shown in figure 4.

The standard conventional equation used to calculate the strength in the SCB test is expressed as follows (Smit *et al* 1997):

$$\sigma_{t(SCB)} = \frac{(4{,}906P}{tD} \qquad (1)$$

where $\sigma_{t(SCB)}$ is the maximum horizontal tensile stress in MPa, P is the maximum failure load at break in N, t is the thickness of specimen in mm, D is the diameter of the semicircular-shaped specimen in mm and h is the specimen height in mm which is equal to half the diameter, D. In the event that 'h' is not equal to half the value of 'D', the equation is accordingly modified to account for the variation in 'h'. The maximum tensile stress $\sigma_{t(SCB)}$ calculated as a function of the maximum failure load is the measure of the material strength. Full details of the SCB test have been documented by Smit *et al* (1997).

TEST RESULTS AND ANALYSIS

The fatigue test results were evaluated in terms of the ratio of the residual fatigue life of core-specimens from trafficked sections ($N_{f(trafficked)}$) relative to the residual fatigue life of core-specimens from corresponding untrafficked sections ($N_{f(untrafficked)}$). This ratio of residual fatigue life was denoted RR_f, which is therefore defined as follows:

$$RR_f = \frac{N_{f(trafficked)}}{N_{f(untrafficked)}} \qquad (2)$$

where N_f is the number of load cycles to fatigue failure (full cracking).

Values of RR_f were determined for the respective environmental conditions during trafficking. The results are shown in tables 2, 3 and 4. These are representative of the mean value of test results of at least four core-specimens. By using a ratio (RR_f), the effects of material variability, including air void content, do not confound the comparison between environmental conditions during MMLS3 trafficking.

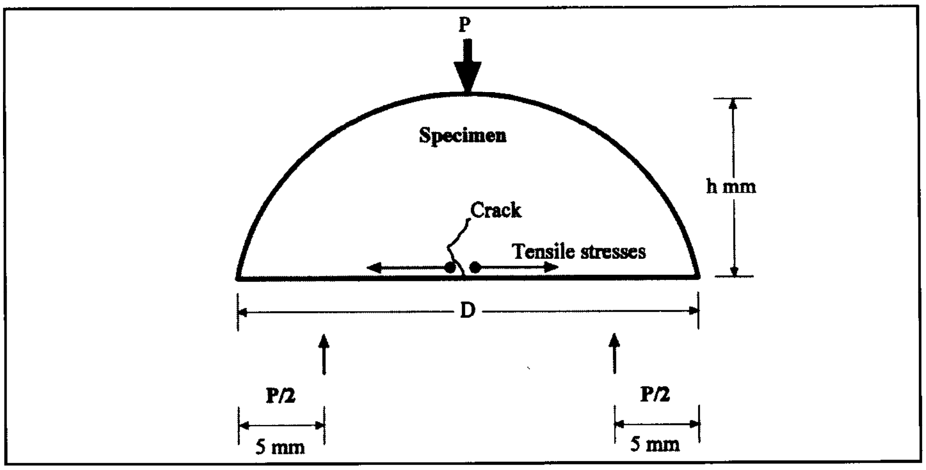

Figure 4 SCB test configuration

In the text 'k' represents one thousand. Standard deviations were calculated for each test section per lane per layer, and the values ranged between 204 and 836. Considering material variability within the same mix on the same section and experimental errors, the results are reasonable and within acceptable limits. Also in considering that N_f was measured in thousands, the standard deviations are relatively low and indicate that the deviation of the results from the mean was minimal and that the core-specimens gave a consistent picture of the material performance/damage under different MMLS3 trafficking conditions.

Trafficking under hot conditions with the pavement heated (@ 50°C)

With the exception of section *n2* layer 3, the results in table 2 show that the heated asphalt layers (sections *n1, n2, s1* and *s2*) generally exhibited increased fatigue life on the order of about 20% for the northbound and 13% for the southbound structures, probably because of MMLS3 traffic compaction. Epps (1969), Tangella (1990) and Raithby and Ramshaw (1972) also found that traffic compaction and an increase in asphalt stiffness increased fatigue life to the extent that it offset the effects of damage caused by traffic. However, in these tests it was also found that the fatigue life subsequently decreases with extended trafficking owing to damage without further compaction. The impact on fatigue performance in these sections was most significant in the layers immediately in contact with the trafficking tyre. The extent of the respective increases in terms of *RRf*, appeared to be proportional to the number of load applications.

Trafficking under dry conditions without heating (@ 38°C ambient temperature)

Relatively shorter fatigue lives were obtained from the *n4* section (Smit *et al* 1999) on both the untrafficked and trafficked core-specimens (table 3). This finding was ascribed to the poor quality material in this section. During diagnostic studies, cores from the top limestone AC surfacing layer were found to be highly inter-mixed with the underlying recycled LWAC. In general, the layer interfaces of the cores were not well defined. This appears to have contributed to the poor performance of the core-specimens from this section and hence the relatively shorter fatigue lives. The N_f of the *n4* core-specimens ranged from 200 k to 350 k load repetitions (table 3). In the case of the *n1* and *n2* core-specimens, the range was from 700 k to over 1 500 k. The untrafficked SCB strengths of the *n4* section were also lower than those of sections *n1, n2* and *n3* (see later). This lends sup-

Table 2 Fatigue test results - hot trafficking conditions (sections n1, n2, s1 *and* s2*)*

Lane	Material	N_f				RR_f	
		$n1_u$	$n1_t$	$n2_u$	$n2_t$	$n1_{tt} / n1_u$	$n2_t / n2_u$
North-bound	Upper *Rehab B*	884 800	1 519 800			1,70	
	Lower *Rehab B*	855 000	901 500	855 000	1 125 600	1,05	1,32
	In-situ LWAC	859 880	936 000	859 880	742 680	1,09	0,86
		$s1_u$	$s1_t$	$s2_u$	$s2_t$	$s1_t / s1_u$	$s2_t / s2_u$
South-bound	Upper *Rehab A*	892 740	1 150 000			1,29	
	Lower *Rehab A*	398 400	425 600	398 405	372 050	1,07	1,18
	In-situ LWAC	733 780	752 400	733 785	802 000	1,05	1,09

*u = untrafficked, t = trafficked

Table 3 Fatigue test results - dry trafficking conditions (section n4*)*

Lane	Material	N_f		RR_f
		$n4_u$	$n4_t$	$n4_t / n4_u$
Northbound	Upper *Rehab B*	271 375	311 345	1,15
	Lower *Rehab B*	268 815	277 225	1,03
	In-situ LWAC	233 365	336 850	1,43

*u = untrafficked, t = trafficked

Table 4 Fatigue test results - wet trafficking conditions (sections n3, n5 *and* s3*)*

Lane	Material	N_f				RR_f	
		$n3_u$	$n3_t$	$n5_u$	$n5_t$	$n3_t / n3_u$	$n5_t / n5_u$
North-bound	Upper *Rehab B*			884 800	785 533		0,89
	Lower *Rehab B*	855 000	488 600	855 000	186 437	0,57	0,22
	In-situ LWAC	859 880	340 000	859 880	171 420	0,40	0,20
		$s3_u$	$s3_t$			$s3_t / s3_u$	
South-bound	Upper *Rehab A*						
	Lower *Rehab A*	398 405	358 200			0,90	
	In-situ LWAC	733 785	512 600			0,70	

*u = untrafficked, t = trafficked

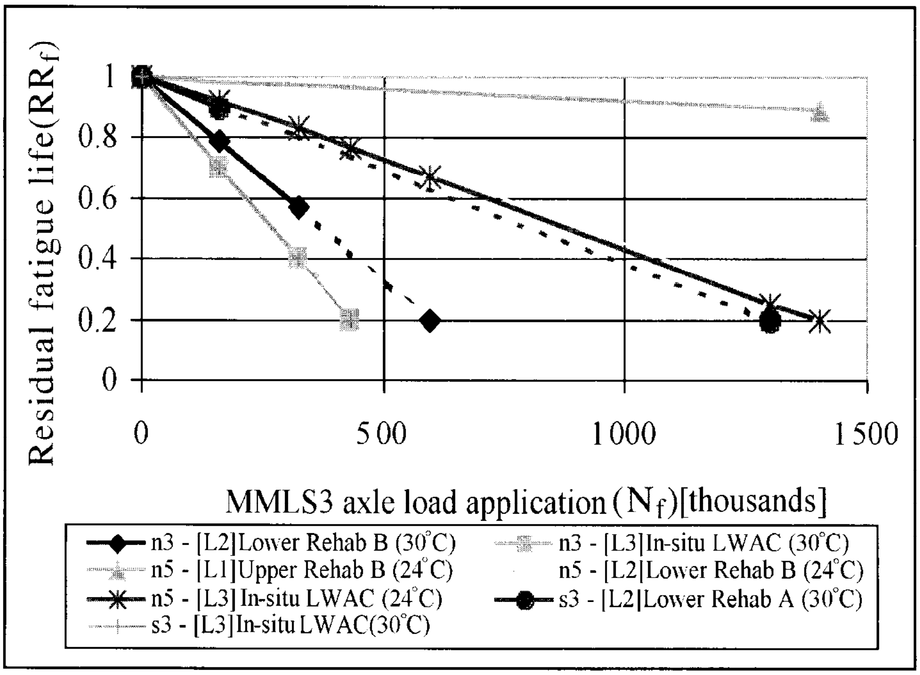

Figure 5 Relative fatigue life (N_f) after MMLS3 wet trafficking

port to the hypothesis regarding the poorer quality of the materials of section *n4*. Despite differences in quality, the RR_f values of the upper (layer 1) and lower *Rehab B* (layer 2) from the *n4* section exhibited similar trends compared to the results for section *n1*, albeit that their N_f values were smaller. This is most likely due to the lower temperature during trafficking.

On the other hand, it should be remembered that the N_f and the RR_f values of the *n4* section are indications of the comparable performance after extended trafficking (1,0 million axle loads were applied on this section) at ambient temperatures. Generally, all the *n4* layers exhibited an increase in fatigue life.

Trafficking under wet conditions with water on the pavement surface (@ 24°C and 30°C)

The results for the wet test sections are shown in table 4. The wet test sections showed a reduction in N_f relative to the untrafficked asphalt as well as in comparison to the heated test sections *n1, n2, s1* and *s2* (table 2). The reduction in RR_f in the wet tests was strongly affected by the number of load applications and material type. The limestone (upper *Rehab B*) was clearly superior to the other materials.

Figure 5 shows the relationship between RR_f and N_f for the wet tests graphically. The lower *Rehab B* (layer 2) on section *n3* had a reduction of about 43% (after 320 k), while the reduction for the lower *Rehab A* (layer 2) on section *s3* was about 10% (after 160 k). The hypothesis is that these reductions were due to the effects of water under trafficking. The in-situ LWAC (layer 3) on the southbound section had a loss of N_f of about 30% after 160 k, and the northbound had a loss of 60% for the LWAC (layer 3) after 320 k. Figure 5 shows that these changes fall on the same line and thus exhibit a degree and extent of water damage similar to the amount they would have exhibited had they been subjected to the same number of MMLS3 traffic axle loads. This finding was not surprising since it is virtually the same material.

The damage under extended trafficking for both the lower *Rehab B* and in-situ LWAC was far greater, as evident from the 21% residual fatigue life of section *n5* after 1,45 million axle load applications (table 4 and figure 5). However, the slope of the section *n5*-lower *Rehab B* and section *n5*-in-situ LWAC graphs (figure 5) is not as steep as that for the corresponding *n3* graphs. This difference shows that the progression of water damage was not as rapid and as intensive as that in the *n3* wet tests owing to the limestone AC (upper *Rehab B*) cover in the case of the section *n5* test. It should be noted that the top 25 mm limestone AC was milled off in the *n3* wet tests. If MMLS3 trafficking had continued in the *n3* and *s3* wet tests, the predicted extrapolation indicated that the lower *Rehab A*, the lower

Rehab B and the in-situ LWAC would probably have been reduced to about 21% residual fatigue life after approximately 1 300 k, 595 k and 420 k, respectively (figure 5).

The damaging effect of wet axle loads is apparent, and it is clear that the number of axle loads that can be carried is significantly reduced under wet conditions, even under the light wheel loads (2,1 kN) of the MMLS3. It is also clear that the damage increases with an increase in the number of axle load applications.

Both table 4 and figure 5 indicate that the upper *Rehab B* (limestone AC) in the northbound structure appeared to be less affected by water. This layer had a residual fatigue life of about 89% of the original untrafficked asphalt after 1,45 million MMLS3 axle loads. However, the AASHTO T283 moisture sensitivity test predicted otherwise. A tensile strength ratio *(TSR)* of 0,57 was measured, where *TSR* is defined as:

$$TSR = \frac{ITS_{wet\ conditioned\ specimen}}{ITS_{unconditioned\ specimen}} \qquad (3)$$

The measured mean *ITS* values were 1 202 kPa unconditioned and 685 kPa wet conditioned. Standard deviations were 39 and 57 kPa, respectively. Since the *TSR* value is less than the 0,8 limiting criteria (AASHTO 1998), this indicated possible moisture sensitivity and thus susceptibility to water damage.

From these results it appears that the AASHTO T283 specification does not necessarily guarantee that the asphalt will not be damaged by water nor stripping. Likewise, failure to meet the specification ($TSR<0,8$) may not necessarily mean that the asphalt will be damaged by water. Similar findings have been reported by Du Preez (2001) using MMLS3 tests.

It is important to note that in comparison to core-specimens from the heated test sections (*n1, n2, s1* and *s2*) which had indirect tensile fatigue lives in the order of approximately 400 k to more than 1 500 k load cycles, core-specimens from the wet test sections had between 170 k to 800 k. This is a further indication of the effect of moisture under wet MMLS3 trafficking. Core-specimens from the untrafficked sections sustained between 200 k to 900 k fatigue load cycles prior to failure.

Stiffness, SCB strength and density test results

The stiffness, strength and density results presented in this section are mean values of at least four measurements as for the fatigue tests. In considering the effect of trafficking on the performance of the different test sections, the difference in the number of applied axle loads had to be taken into account. Similar to what was found with fatigue performance, there was generally an increase in the extent of change that occurred in all three parameters (stiffness, SCB strength and density) with an increase in the number of load applications.

Table 5 In-situ asphalt stiffness measurements

Lane	MMLS3 trafficking conditions/ section	MMLS3 axle loads	Asphalt stiffness (MPa)		RR_{stiff}
			Untrafficked	Trafficked	Trafficked/untrafficked
			n_u	n_t	n_t / n_u
North-bound	Hot (*n1*)	320 000	2 870	2 866	1,00
	Hot (*n2*)	160 000	3 060	3 136	1,02
	Dry (*n4*)	1 000 000	2 998	3 700	1,23
	Wet (*n3*)	320 000	3 034	2 019	0,67
	Wet (*n5*)	1 450 000	3 040	1 200	0,39
			s_u	s_t	s_t / s_u
South-bound	Hot (*s1*)	180 000	3 123	3 596	1,15
	Hot (*s2*)	80 000	3 058	3 120	1,02
	Wet (*s3*)	160 000	2 997	2 670	0,89

*u = untrafficked, t = trafficked

Table 6(a) SCB strength test results - hot trafficking conditions (sections n1, n2, s1 and s2)

Lane	Material	SCB strength (kPa)			RR_{tSCB}	
		Untrafficked	Trafficked		Trafficked/untrafficked	
		n_u	$n1_t$	$n2_t$	$n1_t / n_u$	$n2_t / n_u$
North-bound	Upper *Rehab B*	2 450	2 500		1,02	
	Lower *Rehab B*	2 035	2 090	2 050	1,03	1,01
	In-situ LWAC	1 950	1 960	1 860	1,01	0,95
		s_u	$s1_t$	$s2_t$	$s1_t / s_u$	$s2_t / s_u$
South-bound	Upper *Rehab A*	2 330	2 530		1,09	
	Lower *Rehab A*	2 070	2 080	1 850	1,05	0,89
	In-situ LWAC	1 910	1 930	1 950	1,01	1,02

*u = untrafficked, t = trafficked

Table 6(b) SCB strength test results - dry trafficking conditions (section n4)

Lane	Material	SCB strength (kPa)		RR_{tSCB}
		Untrafficked	Trafficked	Trafficked/untrafficked
		$n4_u$	$n4_t$	$n4_t / n4_u$
North-bound	Upper *Rehab B*	1 260	2 000	1,59
	Lower *Rehab B*	1 140	1 290	1,13
	In-situ LWAC	938	1 615	1,72

*u = untrafficked, t = trafficked

Table 6(c) SCB strength test results - wet trafficking conditions (sections n3, n5 and s3)

Lane	Material	SCB strength (kPa)			RR_{tSCB}	
		Untrafficked	Trafficked		Trafficked/untrafficked	
		n_u	$n3_t$	$n5_t$	$n3_t / n_u$	$n5_t / n_u$
North-bound	Upper *Rehab B*	2 450		2 720		1,11
	Lower *Rehab B*	2 035	1 690	1 720	0,83	0,85
	In-situ LWAC	1 950	1 180	1 280	0,61	0,66
		s_u	$s3_t$		$s3_t / s3_u$	
South-bound	Upper *Rehab A*	2 330				
	Lower *Rehab A*	2 070	1 930		0,93	
	In-situ LWAC	1 910	1 650		0,86	

*u = untrafficked, t = trafficked

Table 5 shows a summary of the average composite stiffness of the in-situ asphalt in terms of SASW-determined modulus measured to a depth of approximately 70 mm and normalised to 21°C and 30 Hz (Walubita *et al* 2000). The standard deviation for the measurements ranged between 6 and 127 MPa. In comparison to the untrafficked sections based on the stiffness ratios (RR_{stiff}) (trafficked/untrafficked) in table 5, the results show that there was an increase in in-situ asphalt stiffness under dry and hot MMLS3 trafficking conditions and a decrease under wet conditions (ascribed to moisture damage).

It is important to appreciate that the stiffness reflects the condition in the composite upper layers. Generally, the change in stiffness in terms of RR_{stiff}, was as marked as the changes in RR_f, especially with increased trafficking.

A summary of the SCB strength test results for the wet MMLS3 trafficking conditions at 30°C (test sections *n3* and *s3*) is shown in table 6 (Walubita *et al* 2000). The standard deviation ranged from 14 to 177 kPa.

The changes in ratios of SCB strength (RR_{tSCB}) (trafficked/untrafficked) followed the same pattern as the RR_f and the RR_{stiff}. As the number of load applications increased, the effect increased.

The RR_{tSCB} values in table 6(c) show a reduction in strength of the asphalt from the wet trafficked sections compared to the untrafficked, except in the case of the upper *Rehab B*, which had an increase of 11%. These strength reductions were ascribed to the effect of moisture under wet MMLS3 trafficking conditions. The upper *Rehab B* layer that had an increased RR_{tSCB}, was the one that was only slightly affected by the wet trafficking in all respects. By contrast, the measured SCB strength of the core-specimens from the hot MMLS3 trafficked sections in table 6(a) ranged between 1 939 and 2 540 kPa, with a mean strength ratio of 1,02. The RR_{tSCB} values for the dry section *n4* exhibited considerable increases with the RR_{tSCB} for the in-situ LWAC equal to 1,72 and the upper *Rehab B* equal to 1,59.

Density measurements (trafficked and untrafficked) are presented in tables 7(a), (b) and (c) (Walubita *et al* 2000). The standard deviation for these tests ranged from 7 to 73 kg/m^3. The density ratios were much closer to unity than the other parameters that were monitored RR_f and the RR_{stiff}. However, the trends were once again generally the same, with increases in the hot and dry tests, and decreases in the wet tests. There were some minor exceptions such as the in-situ LWAC on the southbound lane (section *s3*). The increase in density under dry and hot conditions was ascribed to material densification under MMLS3 trafficking compaction, and the decrease under wet conditions was assumed to be due to moisture damage.

Table 7(a) Density test results - hot trafficking conditions (sections* n1*,* n2*,* s1 *and* s2*)

Lane	Material	Density (kg/m^3)			Density ratios	
		Untrafficked	Trafficked		Trafficked/untrafficked	
		n_u	$n1_t$	$n2_t$	$n1_t / n_u$	$n2_t / n_u$
North-bound	Upper *Rehab B*	2 153	2 258		1,05	
	Lower *Rehab B*	1 664	1 770	1 736	1,06	1,04
	In-situ LWAC	1 659	1 664	1 668	1,00	1,01
		s_u	$s1_t$	$s2_t$	$s1_t / s_u$	$s2_t / s_u$
South-bound	Upper *Rehab A*	1 961	1 984		1,01	
	Lower *Rehab A*	1 712	1 724	1 749	1,01	1,02
	In-situ LWAC	1 616	1 680	1 680	1,04	1,04

*u = untrafficked, t = trafficked

Table 7(b) Density test results - dry trafficking conditions (section* n4*)

Lane	Material	Density (kg/m^3)		Density ratios
		Untrafficked	Trafficked	Trafficked/untrafficked
		$n4_u$	$n4_t$	$n4_t / n4_u$
North-bound	Upper *Rehab B*	2 160	2 205	1,02
	Lower *Rehab B*	1 718	1 685	0,98
	In-situ LWAC	1 673	1 670	1,00

*u = untrafficked, t = trafficked

Table 7(c) Density test results - wet trafficking conditions (sections* n3*,* n5 *and* s3*)

Lane	Material	Density (kg/m^3)			Density ratios	
		Untrafficked	Trafficked		Trafficked/untrafficked	
		n_u	$n3_t$	$n5_t$	$n3_t / n_u$	$n5_t / n_u$
North-bound	Upper *Rehab B*	2 153		2 353		1,09
	Lower *Rehab B*	1 664	1 605	1 653	0,96	0,99
	In-situ LWAC	1 659	1 645	1 661	0,99	1,00
		s_u	$s3_t$		$s3_t / s3_u$	
South-bound	Upper *Rehab A*	1 961				
	Lower *Rehab A*	1 712	1 686		0,98	
	In-situ LWAC	1 616	1 656		1,02	

*u = untrafficked, t = trafficked

It was apparent that the high temperature of the hot tests had a more pronounced effect. The upper *Rehab B* layer of the northbound wet trafficking section also experienced an increase in density which was unexpected. It could be that this was related to the resistance of the material to water damage. The effect of the lower temperature in the dry test was also noticeable, with a smaller impact on the density despite the high traffic volume.

DISCUSSIONS AND SYNTHESIS OF THE FINDINGS

Fatigue performance under dry and hot MMLS3 trafficking conditions

An overall increase in residual fatigue life owing to heating and MMLS3 traffic consolidation was evident in the dry and hot test sections. Density measurements of core-specimens from these test sections indicated an increase in density of slightly more than 2% due to MMLS3 compaction. This appears to have improved the indirect tensile fatigue performance of the asphalt from these sections. In addition, in-situ asphalt stiffness measurements showed an increase in stiffness on the northbound and southbound lanes. The increase was, in fact, substantial in the case of the dry test, with RR_{stiff} equal to 1,23, representing an increase of 23%.

This indicates that with the limited axle loads applied, there was no measurable material damage imparted by MMLS3 trafficking on these sections. In fact, it is apparent that material densification and increased stiffness, resulting from MMLS3 trafficking under dry and hot conditions, offset the effects of traffic damage to such an extent that it increased the residual fatigue life of the asphalt layers. This phenomenon has also been reported by Epps (1969), Tangella *et al* (1990) and Raithby and Ramshaw (1972). With extended trafficking, damage is expected to occur once compaction ceases and stresses are no longer dissipated.

Fatigue performance under wet MMLS3 trafficking conditions

On the wet sections there was an overall average decrease of 35% in fatigue life of sections *n3* and *s3* due to water damage under MMLS3 trafficking with water on the pavement surface. In the case of section *n5*, the overall average decrease was 56%. The moisture damage was also indicated by the in-situ asphalt stiffness measurements. In the case of the northbound lane, the reduction in stiffness of section *n3* was 33% while it was 61% in the case of section *n5*. In the southbound lane, the average decrease was 11%. All of these changes were ascribed to degradation under wet MMLS3 trafficking.

Likewise, losses indicative of moisture damage were measured in the SCB strengths of both lanes after wet trafficking. An average loss of 21% was measured in the SCB strength tests of the lower *Rehab* and the in-situ LWAC layers of sections *n3*, *n5* and *s3*. On test sections *n3* and *n5*, the SCB strength loss was 16% for layer 2 (lower *Rehab B*) and 36,5% for layer 3 (in-situ LWAC). On the southbound section *s3*, this loss was 7% for the lower *Rehab A* and 14% for the in-situ LWAC. Stripping also occurred, with visual evidence of small loose aggregate particles found on the test sections at the termination of trafficking. Micro cracks were visible on these test sections, and this correlates with the decrease in density that was measured in most of the layers. It is apparent that all these factors contributed to the loss in residual fatigue life of the asphalt in the wet trafficked test sections.

Effects of the air voids on the asphalt performance

According to the retained mix strength-air void relationship developed by Terrel *et al* (1993), the 12,5% and 9,3% air void contents of the *Rehab A* and *Rehab B*, respectively, fall within the 'pessimum void range'. In this air void content range (7,5% to 13%), the highest water damage is experienced and the asphalt strength is significantly reduced after wetting or in the presence of water. As mentioned earlier, the lightweight aggregate has a porous structure by nature, which contributes to the higher than normal void content of the LWAC. This appears to have facilitated moisture damage and subsequent poor performance of test sections *n3*, *n5* and *s3* under wet trafficking, resulting in substantial loss of fatigue life evident from the laboratory test results.

By contrast, the pessimum voids did not impact significantly on the performance of the asphalt under dry and hot MMLS3 trafficking conditions. In fact, there was an increase in residual fatigue life for core-specimens from test sections that were trafficked under dry and hot MMLS3 conditions, despite the high void content. This indicates that in the absence of water with MMLS3 trafficking under dry and hot conditions, the pessimum voids have little or no damaging effect on the asphalt in terms of indirect tensile fatigue performance.

The results do show that the effect of high voids on asphalt performance is much more pronounced in the presence of water. Nonetheless, the effect of air void content was not a primary variable investigated in this study, since in any case, all materials tested (wet, dry, hot and untrafficked) generally had air void contents within the critical range for water damage. Therefore, no detailed evaluation of the effects of the voids was conducted. Also, by using the RR_f as the method of performance evaluation and analysis in this study, the effects of material variability, including air void content, do not confound the comparison between environmental conditions during MMLS3 trafficking. Additionally, the saturated surface dry (SSD) method employed may not have been a very accurate method for measuring high air void contents. For a detailed air void content analysis, better methods should be utilised.

However, it must also be noted that air voids of this nature (high) may not be uncommon especially with poor construction practices and/or poor quality control processes.

Comparison of material performance

In comparing the different pavement materials, the upper *Rehab B* (limestone AC) proved to be water resistant while the lower *Rehab B* showed an increased susceptibility to temperature damage and water damage. The lower *Rehab A* of section *s3*, despite being a relatively thin layer after unintentionally milling off approximately 40 mm of the upper *Rehab A*, was nevertheless found to be less prone to water damage than the lower *Rehab B*. It was also less temperature susceptible than the in-situ LWAC (Walubita *et al* 2000). The in-situ LWAC in both the northbound and southbound structures exhibited a similar degree and extent of water damage at equivalent MMLS3 axle loads. The in-situ LWAC also appeared to have been the most affected by water in terms of damage. It had the lowest residual fatigue life.

CONCLUSIONS

From the findings, the following conclusions were drawn:

- Under dry and hot MMLS3 trafficking, the asphalt exhibited an improvement in fatigue performance due to material densification under MMLS3 compaction. However, the performance of the sections under wet trafficking was adversely affected. There was a substantial decrease in residual fatigue life of some sections relative to the untrafficked asphalt due to water damage. The noteable exception was the limestone (upper *Rehab B*). From this finding, it is apparent that for asphalt materials susceptible to moisture damage, the fatigue life expectancy is significantly reduced by wet trafficking, such that even light axle loads (2,1 kN) with high tyre pressures (690 kPa) may cause substantial damage.
- The hypothesis is that the damage to the asphalt was caused by degradation, loss in strength and stiffness, micro-cracking and stripping due to wet trafficking with the MMLS3. This resulted in a decreased residual fatigue life of the asphalt evident from the laboratory test results. The high void content might have been a contributing factor, but this was not investigated in depth.
- Although the effects of voids on asphalt performance were not investigated in greater detail, the results showed that the effect of high voids on asphalt performance in terms of residual fatigue life under MMLS3 trafficking is much more pronounced in the presence of water.
- With regard to the fatigue performance of the different asphalt materials/pavement layers, the following findings were observed:
  - *Rehab A* exhibited worse fatigue performance compared to *Rehab B* under dry and hot trafficking conditions.
  - The upper *Rehab B* (limestone AC) and the lower *Rehab A* layers were less susceptible to water damage than were the lower *Rehab B* layers.
  - In both the northbound and southbound structures the underlying in-situ LWAC exhibited a similar degree of water damage at equivalent MMLS3 axle loads. These layers were most affected by water in terms of damage followed by the *Rehab B* layers.
  - The indirect tensile fatigue and SCB testing used in this study proved to be valuable tools for monitoring progressive performance/damage of asphalt due to traffic and to environmental factors such as elevated temperatures and water. The tests have indicated that it is feasible to relate residual indirect tensile fatigue life of asphalt to different environmental conditions during trafficking (dry, hot and wet). This offers a sound base for developing a means of predicting remaining fatigue life of surface layers of in-situ pavement sections.

Overall, the study demonstrated that the MMLS3 used in conjunction with laboratory fatigue testing is a valuable APT tool. It can be used to evaluate the response and performance of the surface layers of full-scale, in-service asphalt pavements under different environmental conditions, supplementing full-scale APT devices. The device can also be used to evaluate the performance of different pavement materials. In order to determine appropriate limits for the ancillary laboratory tests in terms of performance, further research is needed.

RECOMMENDATIONS

The following recommendations can be made from the findings of this study:

- In consideration of the test and analysis methodology utilised in this study, a limiting criterion (such as a percentage or ratio) needs to be established to define asphalt failure, moisture sensitivity and/or damage in terms of indirect tensile fatigue testing. For example, at a given temperature and number of load applications, does 30% or 50% decrease (or loss) in residual fatigue life under MMLS3 trafficking constitute failure and/or moisture damage susceptibility? Establishment of such a limiting failure criterion will create a formidable basis for the continued use of the MMLS3 along with indirect tensile fatigue testing as APT analysis tools.
- In view of the impact of wet trafficking on pavement performance, data on trafficking under such conditions (pavement temperature, loading parameters – axle load and tyre pressure, pavement structural details and material characteristics) should be collected for consideration when evaluating the performance of in-situ pavements.
- The residual fatigue life test results of core-specimens from the wet trafficked test sections also served as indicators of moisture sensitivity. The conflicting results with the AASHTO T283 moisture sensitivity test need to be further investigated.
- In comparative studies of this nature, all factors that affect material performance need to be considered during analysis. Parameters such as the material mix design characteristics (binder type and content, aggregate type, size and gradation, air void content etc), age and actual traffic per lane were not fully taken into account in the analysis. These could have had a profound effect on the material performance/damage.

CLOSURE

The findings reported in this study relate to the materials tested, and further testing is needed to validate the general applicability of the test methodology.

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