EVALUATION OF DEFORMATION RESPONSE OF HMA UNDER APT AND WHEEL TRACKING TESTS

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ABSTRACT

South Africa has experienced rapid economic growth over the past years. As a result the freight traffic on the country's roads has increased steeply. In the same time the legal axle load for trucks has increased and so did truck tire pressures. This combination of factors places high demands on the country's road network. Existing local Hot-Mix Asphalt (HMA) design guidelines were found lacking in light of this new reality by industry stakeholders. More reliable design procedures are required to combat premature rutting (especially at intersections) and fatigue cracking of HMA surfacing. Thus, under auspices of the Gauteng Department of Public Transport, Roads and Works (GDPTRW), a research project was started to update HMA design methods.

This paper is based on a study into the rutting performance of HMA which forms part of the larger research initiative. The objective of this phase is to identify and develop appropriate test protocols and associated acceptance criteria for the assessment of rut resistance of HMA. A road test section, surfaced with a standard continuously graded medium HMA material, was subjected to full scale Heavy Vehicle Simulator (HVS) and scaled Model Mobile Load Simulator (MMLS) testing. A laboratory test program to characterize the material was conducted as well. This paper contains a comparison between the Accelerated Pavement Testing (APT) in the field and wheel tracking tests performed as part of the laboratory study (Hamburg Wheel Tracking Tests and Transportek Wheel Tracking Test). The method of analysis of the creep curves is presented as well as the method used for comparing measured permanent deformation with mechanistically determined elastic strain values. The average elastic shear strain at the edge of the tire over the full thickness of the HMA layer was found to be the best indicator of plastic deformation potential at different temperatures.

INTRODUCTION

In South Africa, Hot-Mix Asphalt (HMA) is typically used as thin (< 50 mm) surfacing layers for road pavements. During normal service life the HMA surfacing is exposed to various vehicular and environmental loads, causing gradual deterioration in the condition of the layer. The behavior of the HMA is generally expressed in terms of the number of load repetitions the material is able to carry before the acceptable level of either fatigue cracking, or permanent deformation is transgressed. These acceptable levels are typically defined in terms of both structural and functional properties of the pavement structure and layer. In order to ensure reliable pavement design and maintenance, it is necessary to obtain a sufficient understanding of the behavior of pavement layers and pavement structures under varying vehicular and environmental loads. In South Africa a research effort is underway to improve the understanding of both the permanent deformation and fatigue cracking behavior of HMA, and to improve the prediction models for these distress types in the HMA design guidelines.

The first phase of the research project consisted of a state of the art survey and a forensic investigation. The forensic investigation in particular provided direction for the later research phases. One of the conclusions of the study was that: *Too often, "off the shelf" standard HMA mixes are used in high demand situations that call for individually designed solutions."* (*1, p10*). The main aim of the second phase of the project, which focuses on permanent deformation of HMA, is therefore to provide engineers with reliable tools to assess the rutting potential of mixes and confidently select suitable mix designs for specific conditions. The permanent deformation study will be followed by a study aimed at increasing the understanding of fatigue performance of HMA.

In this paper a discussion is provided on the permanent deformation behavior of HMA, at different temperatures, as monitored under Accelerated Pavement Testing (APT) and various laboratory wheel-tracking tests. First, the research project on which the paper is based is discussed in broad terms. This is followed by a summary of the permanent deformation (creep) mechanism in materials and more specifically HMA. Deformation data obtained from APT and wheel tracking tests in the laboratory are presented next, followed by the analysis of the data using linear elastic theory. Finally, conclusions are presented.

Objectives and scope

The primary objectives of the current HMA permanent deformation study are to use APT coupled with a laboratory-testing program, to identify and develop appropriate test protocols and associated acceptance criteria for the assessment of permanent deformation of HMA. The test protocols should be such that they can be used reliably and accurately to forecast the potential for permanent deformation on a specific site where HMA is applied, taking cognizance of mix composition, the pavement structure, climate (specifically pavement surface temperature) and traffic.

As indicated, the focus of this paper is on comparing the creep behavior of the standard HMA mix under the HVS to the behavior under wheel tracking tests. The discussion is limited to the response to changes in temperature only. The influence of changes in material thickness, magnitude of loading and load rate, which also form part of the study do not form part of the paper. The data obtained from the wide range of other laboratory tests included in the study (e.g. detailed binder analysis, static creep, dynamic creep, repeated simple shear at constant height, etc.) are also outside the scope of this paper.

METHODOLOGY OF HMA PERMANENT DEFORMATION STUDY

Following the forensic study an experiment was designed incorporating APT and laboratory evaluation of a standard continuously graded medium HMA mix that is widely used in South Africa. The aim was to provide benchmark data mapping the performance of the standard mix for the various tests. This is to be followed by the evaluation of rut resistant mix designs proposed by industry using a similar protocol. A challenge was put to industry to develop mix designs that can be applied on specific problematic areas where high levels of permanent deformation would typically be experienced (i.e. interchanges, steep inclines etc).

Site condition and material characteristics

Test sections for evaluation with the Heavy Vehicle Simulator (HVS) were constructed on Road P159/1 on the western side of Pretoria. As part of the broader study a Long Term Pavement Performance (LTPP) section was constructed as well. The data on the performance of the HMA under the HVS will eventually be compared to performance under normal traffic on the LTPP section when this data become available over time. The climatic conditions at the site in terms of pavement temperature were determined using locally developed pavement temperature prediction equations as described by Denneman (*2*). In terms of the SUPERPAVE design method for HMA, the mean 7-day maximum average pavement temperature at 20 mm depth at the site is 54ºC, with the 98th percentile confidence limit at 58ºC. The mean minimum surface temperature is 2.5ºC, with a 98th percentile confidence limit at -0.6ºC.

Before placement of the HMA layer, the pavement structure consisted of a stiff crushed stone base and subbase on top of selected layers and a relatively strong subgrade. Figure 1 shows a cross section of the pavement structure as observed in a test pit at the test section. The elastic surface deflection under Falling Weight Deflectometer (FWD) testing before construction of the HMA layer ranged between 0.20 and 0.25 mm, indicating a very stiff pavement structure. Stiffness values assigned to the different layers as shown in Table 1 were found to provide the best fit to the FWD deflection bowls and are used in present paper for pavement response analysis.

FIGURE 1: Cross section of test section pavement structure.

TABLE 1: Back calculated layer stiffness.

The existing structure was surfaced with the selected HMA mix at three thicknesses often used in South Africa (i.e. 25 mm, 40 mm and 60 mm). The 40 mm section was viewed as the standard for the experiment with the 25 mm and 60 mm sections providing information specifically around the cost benefit ratio of using thicker and thinner HMA layers than the standard 40 mm. The outcomes of the comparisons of different thicknesses are not covered in this paper.

The coarse aggregate for the HMA mix consists of a crushed dolerite while the sand fraction consists of a combination of crushed dolerite and dolomite as well as mine sand. An unmodified 60/70 penetration grade bitumen was used. According to the SUPERPAVE performance grade classification, the binder is a PG64-x (the minimum temperature value of the PG was not determined). The design gradation of the mix, as well as the gradation of the material recovered from field cores (for 40 mm section) are shown Table 2. The recovered values are within the tolerances allowed in terms of local specifications.

TABLE 2: Mix design information.

HVS testing

In South Africa the Heavy Vehicle Simulator (HVS) is primarily used for APT of full scale pavement test sections (*3*). Currently there are two operational HVSs in South Africa. The HVS used for the research is operated through funding from the Gauteng Department of Public Transport, Roads and Works (GDPTRW). The machine is capable of applying a range of full-scale loads to a pavement section using truck tires mounted on essentially a half-axle. During the test program followed for these tests (consisting of a planned number of load applications at a selected axle load and tire inflation pressure) the deterioration of the pavement was monitored through measurements of the surface and in-depth permanent deformation, visual condition and various environmental parameters in the pavement. The HVS test program is usually supported by a laboratory test program.

During HVS testing the various vehicular and environmental load parameters can be selected to enable a controlled experiment that can meet the desired objectives. In the specific tests conducted in this research a standard legal axle load (40 kN on a dual set of 11R22 tires at 620 kPa inflation pressure) was applied in a uni-directional channelized mode for all the HVS tests. The uni-directional mode was selected over faster bi-directional testing, because the former is expected to provide a better simulation of the situation under real life uni-directional traffic on the road. Novak et al (*4*) have shown fundamental differences in the longitudinal shear stress patterns between uni-directional and bi-directional HVS operation on HMA. The evaluation of a comparison between the uni- and bi-directional performance of thin asphalt layers is part of the larger research program.

Tests at different load levels will be conducted later in the test program. The surface temperature of the HMA surfacing was kept at four specific temperatures during the various phases of the test (using an environmental control box and an array of heaters as described by Steyn and Denneman (*5*)). The selected temperatures were 40°C, 50°C, 55°C and 60°C (*5*). Tests were conducted starting at initial surface temperatures of 40°C, 50°C and 60°C for each new test and increased to the higher temperatures after a pre-set number of load repetitions. The analysis in this paper is based on the deformation behavior of the material at the initial temperature levels only.

Model Mobile Load Simulator

The MMLS Mark 3 is a wheel tracking device that can be used both in the laboratory, on slabs or cylindrical specimen, and in the field. The machine has four bogies with 300 mm diameter pneumatic tired wheels, operating uni-directionally. The typical speed used by commercial laboratories for testing is 7 200 repetitions per hour. The maximum achievable tire inflation pressure is 800 kPa and the maximum achievable load is 2.9 kN. In the course of the present study MMLS testing was done in the field as well as in the laboratory. Load conditions and speed were varied, but the majority of tests were performed at a 2.9 kN load level with a 750 kPa tire inflation pressure that was validated using the Stress-In-Motion (SIM) device to most closely resemble the contact stresses selected for the HVS. The MMLS testing was performed at 7 200 repetitions per hour, which is the standard used by local industry.

Transportek Wheel Tracking Test

The Transportek Wheel Tracking Test (TWTT), shown in FIGURE 2, is an adaptation of the TRL slab compactor. The equipment can be used to compact 655 mm x 345 mm slabs using a segment of a steel wheel roller. The resulting compaction action resembles the compaction effort in the field. The machine can be transformed to evaluate rutting potential of HMA by means of wheel tracking with a loaded solid rubber wheel. The wheel diameter is 400 mm with a width of 100 mm. The contact stress can be varied from 600 kPa to 900 kPa, which is achieved by varying the load. The temperature is controlled by means of a temperature cabinet. The speed of the wheel can be adjusted, but is typically set at 2 500 passes per hour. The tests described in this paper were performed at a standard 900 kPa contact stress generated by a 6 kN load.

FIGURE 2: Transportek Wheel Tracking Test device.

Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Test, in which deformation in HMA under loading with a steel wheel is measured, was performed in accordance with AASTHTO T324-04.

PERMANENT DEFORMATION (CREEP) OF MATERIALS

Materials subjected to constant or repeated loading deform over time to relieve stress. In Material Science this phenomenon is known as creep. Material deformation occurs as a result of long term exposure to levels of stress that are below the yield or ultimate strength of the material. The rate of this damage is a function of the material properties and the exposure time, exposure temperature and the applied stress (*6*).

If a material is loaded with a stress that is above the flow strength of the material at that temperature the material will start to deform. Figure 3 (*7*) shows a typical stain-time curve for material deformation. First the material will deform rapidly, then, after some strain hardening has taken place, the material gets to a stage with a lower creep rate. This stage is known as secondary creep, or steady state creep. In the third stage the material becomes unstable and rapid collapse is the result.

FIGURE 3: Typical creep deformation curve (from *7*).

Creep in HMA

The development of permanent deformation in HMA follows a trajectory similar to the general material creep curve shown in Figure 3. The dominant damage mechanisms in the different phases are also similar to those seen in other materials such as metals. For dense graded mixes, traffic load induces an initial densification phase after construction. During this phase the mix stabilizes, the traffic action results in aggregate particles moving into their preferred orientation and, if properly designed, the void content is reduced to the design void content. If a mix is not well designed the void content may drop below a critical level, which can result in the aggregate floating in the binder and HMA mix becoming unstable. For such mixes the rapid deformation continues and the serviceability is compromised prematurely.

The proportion of permanent deformation taking place in the different creep phases is important. The critical rut depth is generally set at 10 mm, if this depth is reached in the first phase or in the first part of the second phase, the functional life of the HMA layer is reduced drastically.

In Phase II, the rate of deformation slows down considerably. The dominant mode of deformation is caused by shear stress overcoming flow strength of the material. The flow strength consists of two components, i.e. friction and cohesion. The deformation takes place in small iterations with each load application. Figure 4 shows the results of Phase II creep in HMA at an HVS test section. Eventually the void condition and the level of permanent strain will cause the HMA to enter the third phase and rapid unstable shear failure occurs (*8*).

FIGURE 4: Phase II creep under HVS testing.

Well designed HMA mixes will reach the permanent deformation failure criteria well into the steady state creep phase. The permanent deformation at failure therefore consists of an initial settlement component and a secondary creep phase component. Under normal application, HMA material is not expected to reach the tertiary creep phase. Many publications on the use of APT and wheel tracking tests for permanent deformation prediction use a model akin to the one proposed by Monismith et al (*9*) shown in Equation 1. This approach is useful, but if the aim is to model the transition between initial and secondary creep in detail more advanced models will generally be required. The model of German and Lytton (*10*) can be mentioned as one such approach. In the present study the creep curve is modeled using the function in Equation 2, and shown in Figure 5 proposed by Theyse (*11*) for permanent deformation of the subgrade. The steady state creep rate and the initial settlement are the primary design parameters in HMA permanent deformation modeling. When relating the results of creep testing methods, the slope under the creep curve during the secondary creep stage is of more importance than the total permanent deformation. As most of the permanent deformation takes place in the secondary creep stage, the slope or the creep rate is the primary rut prediction parameter. The creep rate can be obtained by taking the first derivative of the permanent deformation model as shown in Equation 3. As the number of repetitions increases the second term in Equation 3 approaches 0 and the creep rate of the secondary creep phase becomes equal to model parameter *m*. For the secondary creep phase the prediction of total rut can than be simplified as shown in Equation 4. In the present study the slope of the steady state deformation phase (*m)* and the initial deformation value (*a)* are used to compare the results of the different laboratory tests to the shape of the deformation curves obtained under APT in the field. For the results of the bulk of the tests contained in this paper the difference of the value *a* and the initial settlement is negligible. In many instances the value *a* will therefore be assumed to be equal to the initial settlement, although mathematically incorrect.

$$PD = AN^{B} \qquad [1]$$

$$PD = mN + a(1 - e^{-bN}) \qquad [2]$$

$$\Delta PD = m + \frac{ab}{e^{bN}} \qquad [3]$$

$$PD = mN + a \qquad [4]$$

Where:

PD = Permanent deformation
A = Regression coefficient
B = Regression coefficient
m = model parameter (equal to the steady state creep rate)
N = Number of load repetitions
a = model parameter (equal to the initial densification)
b = model parameter (defining shape of initial densification line)

FIGURE 5: Mathematical representation of creep curve.

For a given HMA material, creep slope *m* is a function of a number of variables all impacting on the rate of deformation. The variables investigated in this study are the layer thickness, age of the binder, pavement temperature, tire pressure, magnitude of the load and loading speed. Only the influence of temperature is covered in this paper.

RESULTS AND ANALYSIS

Empirical deformation data

Figure 6 shows the steady state creep slope (*m*) at temperature for the APT tests performed at the test section and under wheel tracking tests in the laboratory. The wheel tracking tests, as well as other permanent deformation tests such as the repeated simple shear test at constant height (RSST-CH), showed an exponential change in the deformation rate with change in temperature. This exponential growth was absent from the MMLS data, which showed little difference in deformation rate between the tests performed at 50°C and 60°C. It was suspected that the speed of 7 200 repetitions / hour (which is used as a standard for this test in South Africa) was too high for realistic plastic deformation to occur. When the test was repeated at a lower speed of 2 400 repetitions / hour, the permanent deformation rate increased and the total permanent deformation after 150 000 repetitions increased from 1.4 mm to 3.2 mm.

FIGURE 6: APT and laboratory wheel tracking tests, creep slope at temperature for standard mix.

Based on the values for creep slope *m* shown in Figure 6 and the initial deformation (*a*) data, the relationship between temperature and total rut depth can be described for the steady state creep phase using Equation 4. Based on the analysis of a larger dataset including result not covered in this paper, no statistical relation between temperature and the initial rut depth *a* was found and therefore an average of this value is used. Creep rate *m* is modeled as an exponential function of the temperature *t*. The growth function for permanent deformation of this particular HMA under the HVS is represented by Equation 5.

$$PD = 5\times10^{-8} e^{0.1907t} N + 0.60 \qquad [5]$$

Exponential growth functions were determined based on the MMLS data obtained for the standard tests run at 7 200 repetitions / hour and 2.9 kN load. For reasons stated earlier, the reliability of the MMLS data and as a consequence the reliability of the exponential growth functions determined based on this data shown as Equation 6 and 7 is limited.

Deformation standard HMA mix under MMLS testing in the field:

$$PD = 4\times10^{-7} e^{0.0439t} N + 0.41 \qquad [6]$$

Deformation standard HMA mix under MMLS testing in the laboratory:

$$PD = 8\times10^{-9} e^{0.1059t} N + 0.69 \qquad [7]$$

The slope of the curve in Figure 6 for the deformation response of the HMA under the Hamburg Wheel Tracking Test (HWTT) bears close resemblance to the curve for the material response under HVS testing. This provides confidence that linear relationships between deformation under the HWTT and full scale testing may be drawn. The function for the rut growth under the HWTT is shown as Equation 8.

$$PD = 5\times10^{-8} e^{0.1907t} N + 3.16 \qquad [8]$$

The TWTT results also compare well to the deformation under the HVS. The prediction for the permanent deformation under the TWTT at temperature *t* and repetition *N* is shown in Equation 9.

$$PD = 6\times10^{-7} e^{0.1319t} N + 2.04 \qquad [9]$$

Mechanistic analysis of strain in thin asphalt layer

Efforts are underway to create nonlinear visco-elastic response models for HMA. These models are extremely complex as they have to cater for the effect of temperature, load rate, variation of material characteristics with depth and time dependent material properties. Although future work may include this type of advanced analysis, this first effort to increase the understanding of the stress and strains state of the material under the different tests is limited to linear elastic methods. Denneman (*12*) provided an approximation of the linear elastic material properties for the HMA reference mix as shown in Table 3. Note that the characterization is based on tests run at a load frequency of 10 Hz. The material will react stiffer for wheel load rates of a frequency higher than 10 Hz and less stiff for wheel load rates of lower frequency.

TABLE 3: Stiffness values of reference mix at different temperatures.

The elastic response of the pavement structure in Table 1, incorporating the characteristics for the HMA layer at different temperatures as per Table 3, under loading with the HVS and MMLS was determined using *Me*PADS software. The *Me*PADS linear pavement analysis functionality has been benchmarked against a range of well known international packages by Maina et al (*13*). In the same publication the reliability of the new Finite Element Method for Pavement Analysis (FEMPA) software was shown. FEMPA was used to determine the stresses and strains in the HMA material in laboratory testing under MMLS and TWTT. The HWTT test was not modeled as reliable data on the contact area between the steel wheel and the HMA samples were not available.

Figure 7 shows the shear stress distribution in the top 200 mm of the pavement structure (Figure 1) under APT tests at different temperatures. It can be seen that the maximum shear stresses in the pavement structure for this load of HVS and MMLS are similar (the load conditions were selected for this reason). The maximum shear stress under the HVS load is located deeper in the asphalt layer and migrates deeper into the pavement with a decrease in stiffness of the layer at higher temperatures. The maximum shear stress under MMLS loading is located near the surface.

FIGURE 7: Shear stress distribution at outer edge of tire under APT tests.

The stress and strain distributions in the asphalt material in the various tests and at various critical positions (e.g. at the centre of the load, at the outer edge of the tire, etc) were assessed. It was found that the plastic strain rate for the different tests is approximately proportional to the elastic strain condition. A similar observation was made drawn by McLean and Monismith (*14*). The elastic shear strain at the outer edge of the tire provides the best fit to the plastic deformation data from the various tests (Figure 8). Shear strain has been used to predict rutting performance by other researchers. Deacon et al (*15*) use the elastic shear strain at the edge of the tire at a depth of 50 mm to predict rutting. In the South African situation the thickness of asphalt layers is limited. The position of the maximum shear strain in the layer may vary as can be seen from Figure 7. Therefore, rather than taking the shear strain at a set depth as a parameter for deformation potential, the average shear strain over the thickness of the layer was used to compile Figure 8. It is proposed that for thin layers the deformation potential may be considered constant over the full thickness of the layer.

FIGURE 8: Comparison between permanent deformation rate and average elastic shear strain over depth of the thin asphalt layer.

CONCLUSIONS AND RECOMMENDATIONS

The reader is reminded that the results presented in this paper were determined for a single HMA design only. The results presented were obtained for a single layer thickness and at fixed loading conditions. Notwithstanding these limitations the following conclusions are drawn:

- The methodology for analyzing permanent deformation rate under testing was applied successfully to HVS data and wheel tracking test data;
- The trends in permanent deformation rate at temperature under the wheel tracking tests discussed in this paper compare well to the results obtained under full scale HVS testing;

- The standard loading speed of 7 200 repetitions per hour used for MMLS testing may be too high to invoke the same response from the material as exhibited under the other tests, and
- The average elastic shear strain at the outer edge of the tire over the depth in the thin asphalt layer, determined using elastic layer theory for the field tests and finite element method for the laboratory tests provides the best fit to the plastic deformation data.

It is recommended that:

- The methodology presented in this paper be applied to the results of other test methods, load conditions and material thicknesses that form part of the research project. The methodology will also be applied to the data from the rut resistant mix designs that will be tested in the next phase of the HMA research project;
- It is recommended that the influence of speed on MMLS results is studied in more detail, and
- The methodology and results presented in this paper can be used as a starting point for the prediction of permanent deformation field performance of HMA designs using wheel tracking tests coupled with linear pavement structure analysis.

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TABLE 4: **Back calculated layer stiffness.**

Layer	**Material**	**Thickness [mm]**	**Stiffness [MPa]**	**Poisson's ratio**
1	HMA	40	varies	varies
2	Granular	150	830	0.35
3	Granular	100	830	0.35
4	Granular	150	640	0.35
5	Granular	200	640	0.35
6	subgrade	∞	550	0.35

TABLE 5: Mix design information.

Sieve size [mm]	**Mix design**	**Recovered (average)**
13.2	100	99.9
9.5	99	98.8
6.7	86	89.6
4.75	71	74.8
2.36	43	46.5
1.16	26	30.1
0.600	18	21.2
0.300	13	15.7
0.150	8	9.6
0.075	5.4	5.2
Binder content [%]	5.0	5.1
Air void content [%]	4.3*	5.7**
Voids in Mineral Aggregate (VMA) [%]	15	
Marshall Stability [kN]	10.7	
Marshall Flow [mm]	3.0	
Gyratory voids at N = 300	2.4	
Indirect Tensile Strength at 25 °C [kPa]	1180	

* Design air void content at standard 75 blows Marshall compaction effort per face

** Air voids at field compaction (before trafficking)

TABLE 6: Stiffness values of reference mix at different temperatures.

Temperature [°C]	E* [MPa]	Poisson’s ratio
25	4000	0.35
40	2000	0.40
50	1000	0.45
60	500	0.48

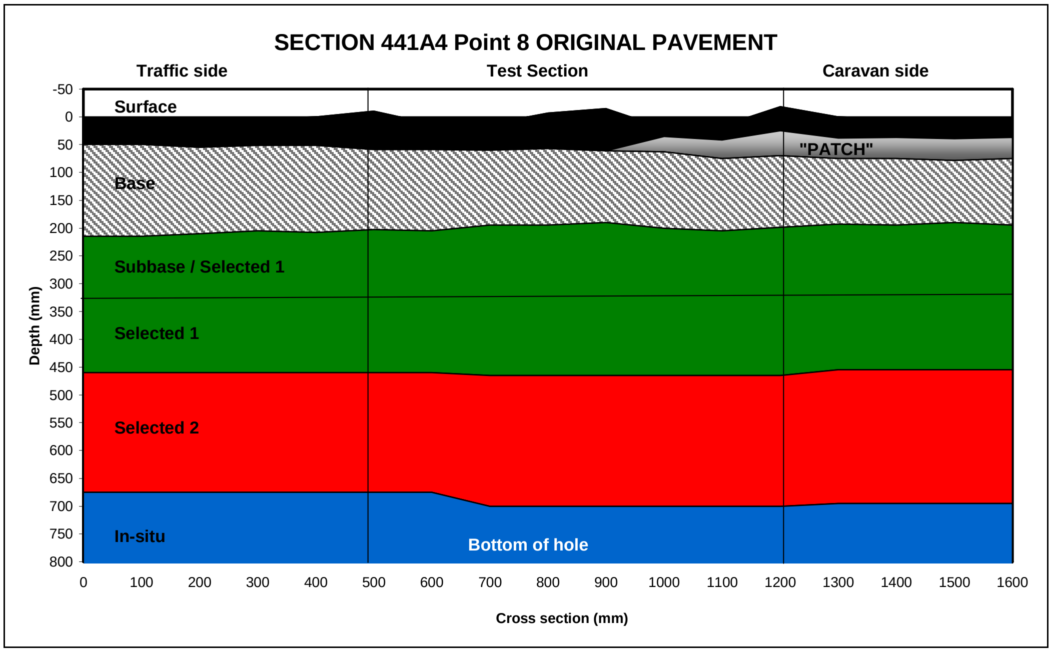

FIGURE 9: **Cross section of test section pavement structure.**

FIGURE 10: **Transportek Wheel Tracking Test device.**

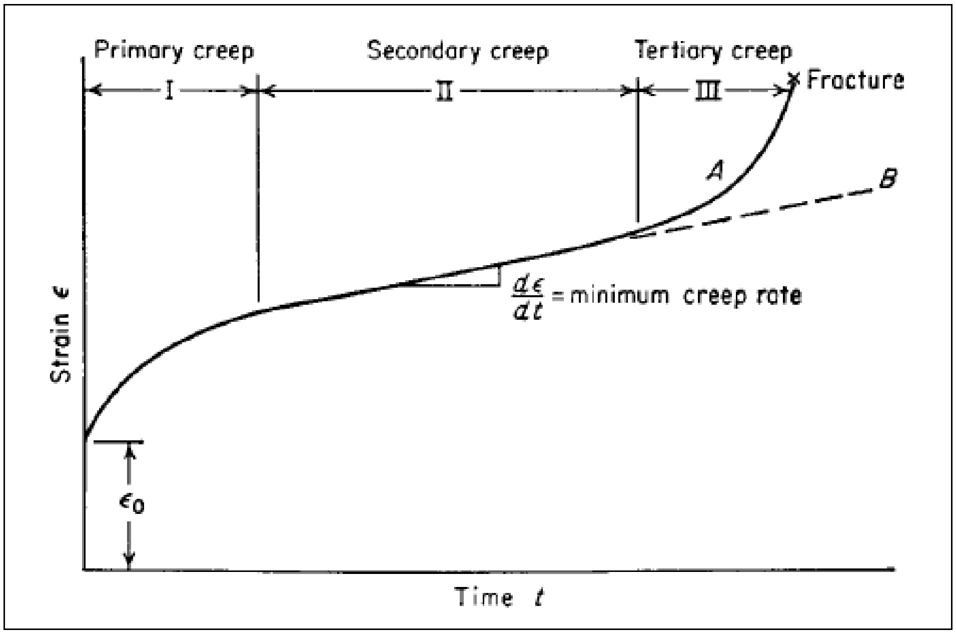

FIGURE 11: Typical creep deformation curve (from *7*).

FIGURE 12: Phase II creep under HVS testing.

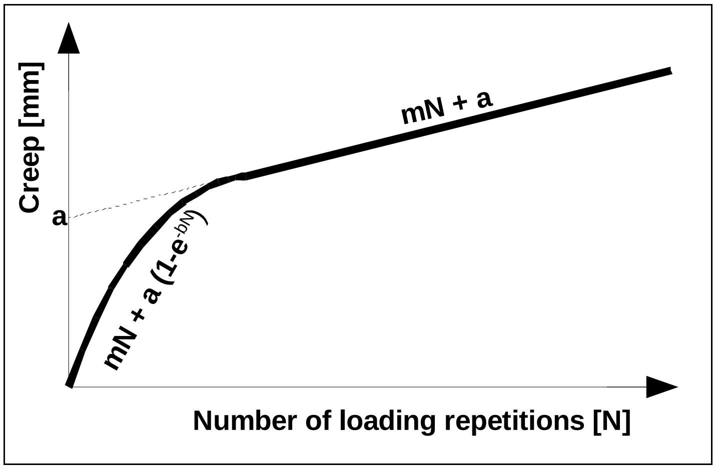

FIGURE 13: **Mathematical representation of creep curve.**

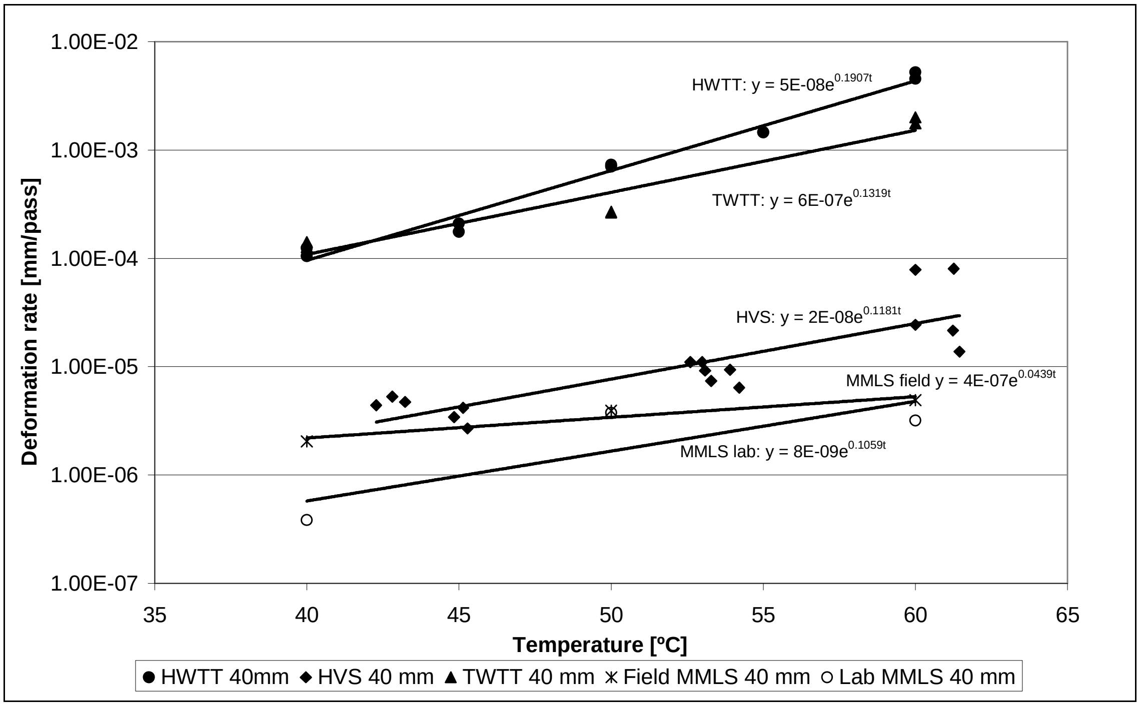

FIGURE 14: APT and laboratory wheel tracking tests, creep slope at temperature for standard mix.

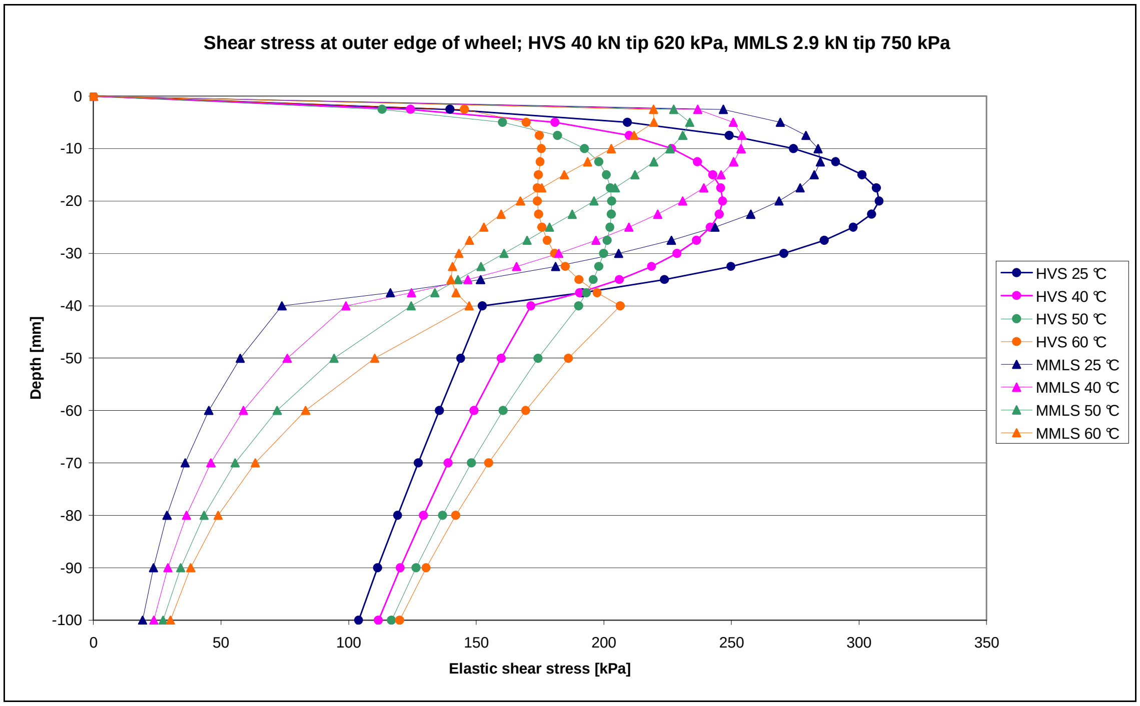

FIGURE 15: Shear stress distribution at outer edge of tire under APT tests.

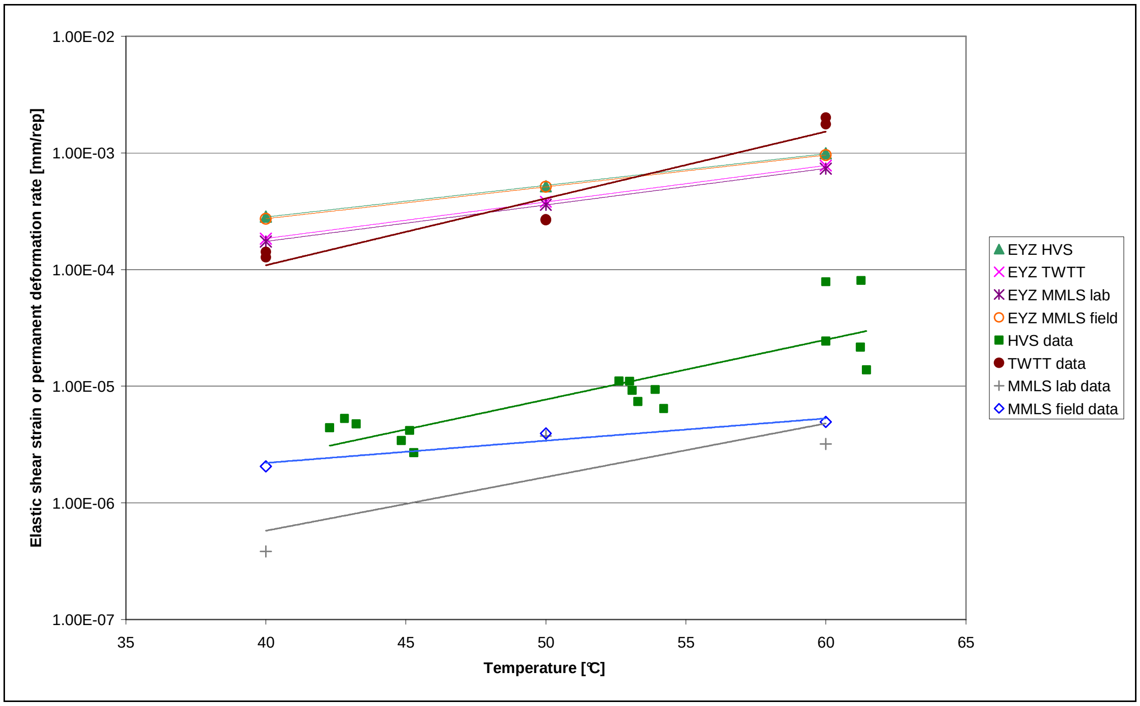

FIGURE 16: **Comparison between permanent deformation rate and average elastic shear strain over depth of the thin asphalt layer.**