

# Permanent deformation testing for a new South African mechanistic pavement design method

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## ABSTRACT

The South Africa National Road Agency Limited together with the CSIR are undertaking a research and development project to support the revision of the South African mechanistic-empirical pavement design method. An important part of this project is to develop test protocols for hot-mix asphalt materials. To date, no permanent deformation test is incorporated into South African pavement design guides. The objective of this paper is to present the development process of a repeated load axial permanent deformation test protocol and models using a standard South African hot-mix asphalt material. The developed test protocol and models provide guidelines, and make a significant contribution to pavement design in South Africa.

*Keywords: Asphalt mixtures, Permanent deformation, Repeated load test, Axial stress, Temperature, Mechanistic pavement design*

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## **1. Introduction**

The current South African mechanistic-empirical design method (SAMDM) for flexible pavements has over the years, formed the backbone of pavement design methods used in South Africa and it is recognized worldwide [1-3]. The SAMDM has been widely adopted in the southern Africa region. However, this method is mainly based on technology and pavement material performance models that were developed during the 1970s and 1980s. The new traffic realities (increased truck volumes, truck masses, tire inflation pressures) and the need for utilizing unconventional materials (new generation materials, recycled, cementitious stabilized, industrial wastes, marginal materials) have rendered important parts of the method obsolete and in dire need of serious revision and updating for road design and construction in South Africa.

A major shortcoming of the SAMDM is the lack of permanent deformation characterization of hot-mix asphalt (HMA) materials. One plausible explanation is perhaps the lack of laboratory test procedures or equipment capable of simulating permanent deformation behavior of asphalt mixes under repeated loading. The South African National Road Agency Limited (SANRAL), together with the Council for Scientific and Industrial Research (CSIR), are funding development of a new mechanistic-empirical pavement design guide for flexible road pavements [4]. An important part of the project is the development of improved and new test procedures/protocols for HMA testing, which is funded by the CSIR strategic research panel (CSIR SRP) project. The new design guide, referred to as South African Pavement Design Method (SAPDM) will use permanent deformation in addition to fatigue characteristics to model damage of HMA materials [5].

Permanent deformation properties determined from repeated load uniaxial or triaxial tests are key parameters used to model rutting potential of HMA in the current Mechanistic Empirical Pavement Design Guide (MEPDG) sponsored by American Association of State Transportation Officials (AASHTO). In the SAPDM, repeated load permanent deformation test parameters are alternative to shear permanent deformation properties.

The overall objective of work reported in this paper was to develop a repeated axial load permanent deformation test protocol that takes into consideration field loading conditions including

different stress and temperature levels to realistically characterize rutting behavior of HMA mixes in South Africa. A comprehensive laboratory testing was conducted on a standard South African HMA that is mainly used as a surface course material. The laboratory test data established were used to develop material characterization models for the mix tested. The developed test protocol and models will be validated when more test data on HMA materials become available.

## **2. Materials and mix design**

### ***2.1. Materials and properties***

The hot-mix asphalt used for this study is continuously graded (dense graded) mix with a maximum aggregate size of 13.2 mm. The mix was manufactured according to South Africa standards (TMH1: Standard Methods for Testing Road Construction Materials [6]). The raw materials (aggregate and binder) were sampled at the asphalt plant in accordance with TMH5: Sampling Methods for Road Construction Materials [7]. The aggregate used was a 100 % crushed dolomite with mine sand, and lime stone dust filler. Table 1 shows the grading analysis results of the blended aggregate.

The bulk relative density (specific unit weight) of the aggregate was 2.912 g/cm<sup>3</sup>, the water absorption was 0.42 %, sand equivalent of 78 and flakiness index of 12.3. The bitumen was a 60/70 penetration grade binder with penetration (25°C, 100 g, 0.1 mm) of 64, and softening point after Rolling Thin Film oven (RTFO) aging at 49°C. All the above tests were performed in accordance with TMH1.

Typically some characterization of the bituminous binder used for the protocol development would be expected. However, this was not the case for this study because the purpose was not to evaluate the binder but instead to develop a test protocol for HMA mixes in South Africa.

**Table 1**  
Aggregate grading

Sieve size (mm)	Percent passing
13.2	100
9.5	99
6.7	88
4.74	68
2.36	45
1.18	30
0.600	21
0.300	16
0.15	9
0.075	5.5

## ***2.2. Mix design***

The HMA used for the permanent deformation test protocol development was obtained from an asphalt plant in South Africa. The mix design was done by the asphalt plant based on the Marshall mix design method. The mix design results indicated an optimum binder content of 4.9 %, and air voids content of 5 % to produce a continuously graded mix with a 60/70 pen grade binder. The average voids in mineral aggregate (VMA), voids filled with asphalt (VFA) and asphalt film thickness for the samples were 16.6%, 70.0 % and 8.7 $\mu$ m, respectively.

## ***2.3. Mix sample preparation***

A loose continuously graded HMA with 60/70 pen grade binder was obtained from the asphalt plant. The AASHTO gyratory compaction procedure was adopted for this protocol. Details of gyratory compaction procedure for cylindrical specimens can be found in the AASHTO T312 [8]. The mix was manufactured at the mixing temperature of 150°C and compacted at 135°C for the preparation of the samples tested.

A short-term aging was performed on the loose HMA from the plant before any compaction took place using the Superpave short term aging procedure. The purpose was to simulate the short-term aging (STA) that takes place during the production process of HMA in the asphalt plant, transport, placement and compaction in the field. The STA method, as described by Von Quintus et al. [9], consists of placing the prepared loose mix back into the oven for 4 hours at 135°C before compaction.

A Superpave Servopac gyratory compactor designed and manufactured by the Industrial Process Controls (IPC) Company in Australia was used to produce the cylindrical specimens. Loose short-term aged HMA samples were compacted to a height of 170 mm and a diameter of 150 mm, and close to 8 % air voids, i.e., 3 % above the target (design) air voids content of 5 %. A trial and error method was used to obtain the excess air voids content of 3 %. The aim was to obtain target air voids of 5 % after the compacted specimen is cored and cut for the permanent deformation testing. Samples whose air voids content differ by more than  $\pm 0.5$  % of the design air voids (5 %) were discarded. Compaction to the target specimen height and air voids was, typically, achieved after 90 to 120 gyrations. After compaction, the specimens were allowed to cool for approximately 10 minutes, extruded from the mold, and then cored and cut to produce samples for the permanent deformation test. A total of 36 samples were prepared for the protocol development.

### **3. Laboratory testing program**

#### ***3.1. Development of test protocol***

During the past decades, several permanent deformation test protocols have been proposed for HMA characterization. A lot of these procedures are described extensively, and are available in the literature [10-13]. However, most of these tests are still under investigation, and are yet to be accepted as standard tests. It was found that due to several limitations in some of these tests methods, most researchers, agencies, and the industry are currently considering modifications/developing new repeated load test procedures for their local use. For instance, the low applied stress level of 69 kPa in the AASHTO T320 could result in an insignificant permanent strain in the asphalt mixes tested, and also limited data to develop permanent deformation model for asphalt mixes. In this study, the NCHRP simple performance test on permanent deformation was used as the basis for developing the repeated axial load permanent deformation test protocol for SAPDM [12, 13].

Several research studies conducted by Witczak et al. [14], used a test temperature of 37.8°C or 54.4°C at different axial stress levels to conduct repeated axial load permanent deformation tests on asphalt mixes. Denneman [15] reported that the maximum surface temperature of road pavements in

South Africa is generally between 45°C and 55°C although it can be as high as 70°C for few days of the year. Also, the average road pavement temperature in the asphalt surface course in South Africa was found to be about 25°C. Accordingly, three test temperatures at different stress levels were used to develop the repeated axial load permanent deformation protocol for SAPDM.

### ***3.2. Repeated axial load permanent deformation test protocol for SAPDM***

The proposed protocol for the repeated axial permanent deformation test for SAPDM is to conduct the test at four axial stresses levels and three temperatures. Details of the procedures to be followed are summarized below:

- Condition specimens until the test temperature is uniform throughout the mass. A dummy specimen prepared from the mix to be tested with thermocouple attached in its centre should be placed close to the test specimen to verify a uniform temperature distribution in specimen;
- Heat the temperature chamber and check the response of the equipment before testing, especially, the linear variable displacement transducers (LVDT's);
- Perform the test at temperatures of 25, 40 and 55°C, and axial stress (differential stress) levels of 69, 138, 207, and 276 kPa. Each temperature and stress pair require a news specimen to be used, because permanent deformation test is destructive, and samples are usually assumed to be damaged after testing;
- Conduct test to collect permanent strain accumulation data up to 20,000 load cycles. If needed, data for computing resilient modulus can be collected first at 100 load cycles;
- Apply a haversine load waveform of 0.1 seconds followed by 0.9 seconds rest periods;
- Apply contact stress of not more than 5 % of the axial stress to the specimen before testing. Ensure that test specimen is not damaged with the contact stress;
- Observe cumulative axial permanent strain of the specimen not to exceed 5 % at any stage of testing;
- Permanent axial deformations ( $\delta_p$ ) are recorded throughout the test, and the corresponding plastic strains ( $\epsilon_p$ ) are computed.

It should be noted that the highest stress level proposed for this test protocol is three times of the

stress level used in the standard AASHTO T320 test method in order to induce a high permanent strains that closely simulates typical rutting in the field. Also, the approach of using the last five load cycles of the applied 100 cycles from repeated load testing to determine the resilient modulus properties of pavement materials is under investigation as part of this protocol. When completed, resilient properties of asphalt mixes under repeated axial loading conditions could also be obtained from the permanent deformation testing.

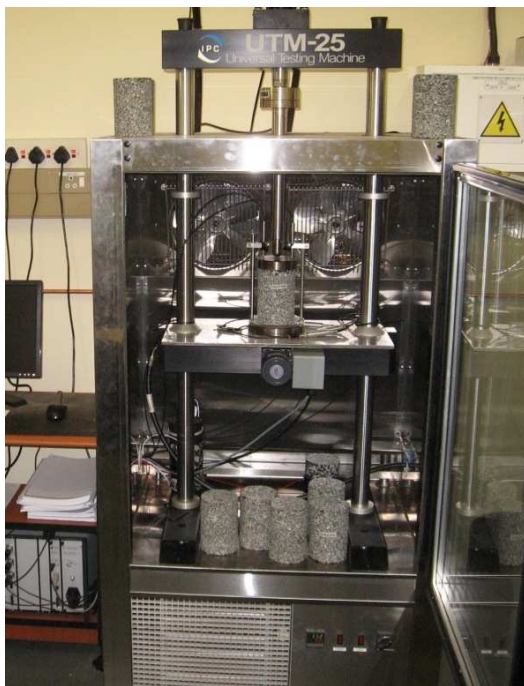
### ***3.3. Permanent deformation testing on the standard HMA***

A laboratory testing program was conducted on the prepared samples of the continuously graded asphalt mix to verify the proposed permanent deformation test for SAPDM. Three replicate samples were tested at the four stress levels and three test temperatures to complete a factorial testing of 36 samples. A commercially available Universal Testing servo-hydraulic 25 kN Universal Testing Machine (UTM-25) at the CSIR advanced pavement materials testing laboratory, designed and manufactured by IPC in Australia was used to conduct the tests. The UTM-25 test setup includes an integrated windows-based PC software, a separate control and data acquisition system and a temperature environmental chamber, which is capable of controlling the test temperatures of the specimen.

Although the UTM-25 testing system has been widely used in major pavement design projects for repeated axial load permanent deformation testing of HMA and complies with several international standards for pavement materials including AASHTO, British Standards Institution (BSI) and the European Committee for Standardization (CEN), this protocol does not impose a particular type of testing device. The authors however, recommend that selection of the equipment and loading conditions should be based on the capabilities of the device and flexibility of the software associated with the testing system. Figs. 1 and 2 show the cylindrical test specimens of the asphalt mix tested, and the IPC UTM-25 test setup at the CSIR, respectively.



**Fig. 1.** Cylindrical 100 mm diameter by 150 mm high specimens.



**Fig. 2.** Permanent deformation test setup for IPC UTM-25 at CSIR.

## **4. Discussion of test results**

### ***4.1. Temperature and stress effects***

Figs. 3 and 4 show typical effects of increasing dynamic/axial stress and temperature on permanent strain accumulation of the sample at the stress levels of 69, 138, 207, and 276 kPa, and temperatures of 25, 40 and 55°C. Fig. 3 shows the typical effects of increasing temperature on permanent strain, whereas Fig. 4 shows the effects of increasing axial stress on permanent strain accumulation at different temperatures.



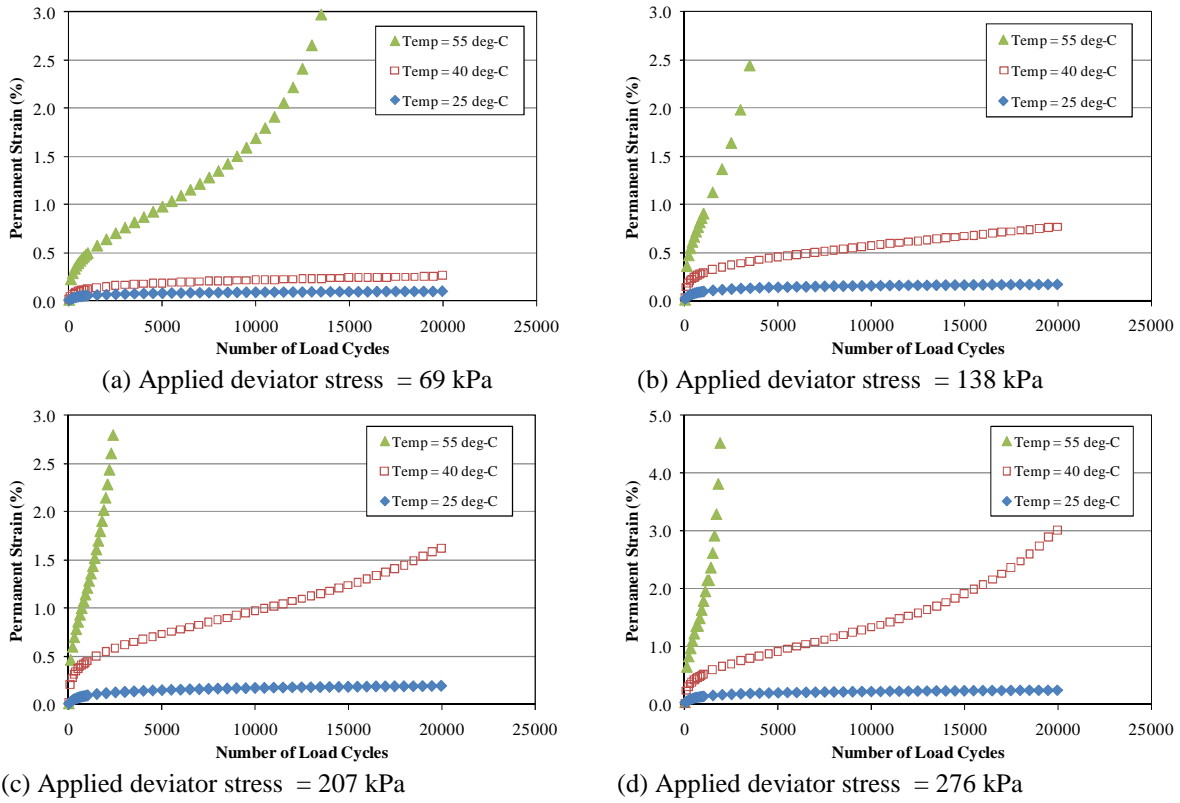


Fig. 3. Effect of temperature on permanent deformation.

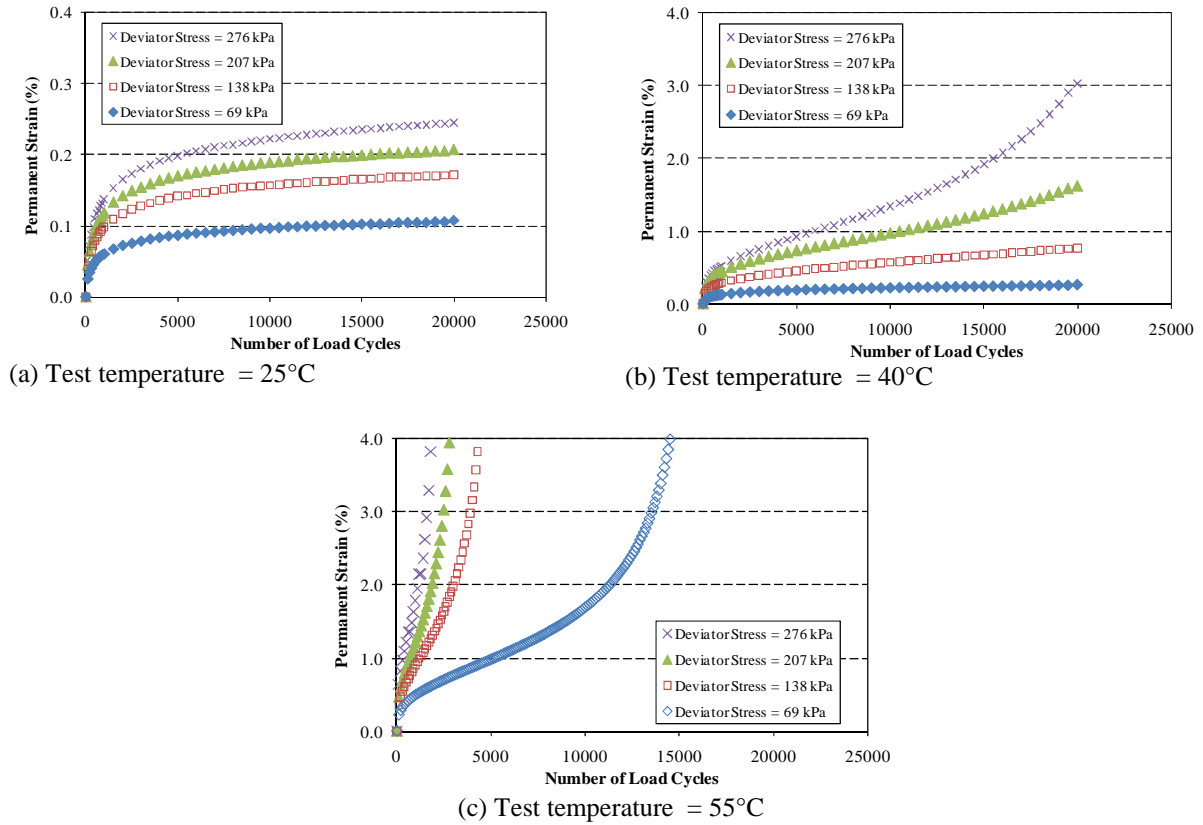


Fig. 4. Effect of applied axial stress on permanent deformation.

As expected, as the applied axial stress increased, the magnitude of the axial permanent strain accumulation increased. The increase in strain was very significant at high stresses and high temperatures, whereas low strains were accumulated at low stress levels and temperatures. This implies that the asphalt mix would experience considerable amount of permanent deformation under high wheel loads from vehicles at high temperatures in the field, hence significant rutting is expected under such a condition.

It should be noted that limited discussions are presented in this paper since only one asphalt mix is used. Moreover, the focus of this paper is to start the protocol development process by establishing the reasonableness of the selected loading conditions that could be used to test various types of HMA materials in South Africa.

#### **4.2. Precision**

The accepted practice for determining the precision of a test method is given in the ASTM [16]. This practice recommends inter-laboratory study to establish precision for test methods. The precision statement for permanent deformation tests (repeated shear/repeated axial) of asphalt mixtures has not been established. Anderson et al. [17] reported from an extensive study that a single laboratory precision (repeatability) of repeated shear permanent deformation test at constant height was within 10%. The multi-laboratory precision (reproducibility) for the test was much high at 70%.

Inter-laboratory comparison tests on commonly used South African HMA mixes are needed to establish precision for the developed test protocol. Repeatability and reproducibility will be determined according to South Africa national standards.

Table 2 shows the statistical analysis results of permanent axial strain (%) at 5000 cycles for the three replicates tested at the four stress levels and three test temperatures. The results indicate that although there were variability between the replicate samples, the values were generally quite reasonable. Bonaquist [18] suggested that the coefficient of variation (CoV, %) for permanent deformation before flow in the flow number test is approximately 15 %. The coefficient of variation for the flow number is approximately 20 %.

**Table 2**

Statistical analysis results for permanent axial strain (%) at 5000 cycles

Stress State (kPa)	25°C			40°C			55°C		
	Mean	STDEV	CoV	Mean	STDEV	CoV	Mean	STDEV	CoV
69	0.07	0.01	16.2	0.19	0.01	5.2	0.981	0.098	9.9
138	0.14	0.01	5.7	0.46	0.04	7.8	*	*	*
207	0.15	0.02	13.2	0.69	0.02	3.4	*	*	*
276	0.20	0.03	13.8	1.19	0.01	0.9	*	*	*

\*: test could not reach 5000 cycles before failure

## 5. Permanent deformation modeling

### 5.1. Permanent deformation models

The purpose of pavement response model is to determine the structural response of the pavement system due to traffic loads and environmental influences. Usually the HMA layer in the pavement is affected by temperature, stresses due to traffic loading and number of load applications.

Permanent deformation relationship relating asphalt mix temperature and number of loading applications has been an integral part of several mechanistic-empirical pavement design procedures throughout the world. It is well known that permanent strains typically accumulated in HMA mixtures follow the trend of power functions with increasing number of load applications.

A number of parameters describing the accumulated permanent strain response from the repeated axial load permanent deformation test, include the “intercept” and “slope” parameters. These parameters have been widely used as input for predictive design procedures [19]. These intercept and slope parameters are obtained from a log-log relationship between the permanent strain and the number of load cycles, which is expressed by the classical power model:

$$\varepsilon_p = k_1 \times N^{k_2} \quad (1)$$

where  $\varepsilon_p$  is the accumulated plastic strain at N number of load cycles;  $k_1$  and  $k_2$  are non-linear regression constants ( $k_1$  represents the intercept;  $k_2$  represents the slope).

In the new United States mechanistic-empirical pavement design guide (MEPDG) proposed by the National Cooperative Highway Research Project 1-37A, however, the plastic and resilient strains ratio

as a function of number of load applications and temperature are used to characterize asphalt mixes permanent deformation [10]. The final form of the MEPDG permanent deformation model is expressed as follows:

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \times N^{k_2} T^{k_3} \quad (2)$$

where  $\varepsilon_p$  is the accumulated plastic strain at N number of load cycles;  $\varepsilon_r$  is the resilient strain of the asphalt mix as a function of the mix properties, temperature and time rate of loading;  $T$  is temperature;  $k_i$  are non-linear regression constants.

It is worth mentioning that the on-going discussions on the effect of the resilient strain included in this model is inconclusive because of the small contribution it makes to the correlation. A comprehensive but yet practical permanent strain model of asphalt mixes should also account for the additional effects of stresses in the asphalt pavement. Uzan [20] suggested a confining stress-dependent parameter in addition to temperature and the number of load applications to characterize asphalt mixes.

In this paper, a proposed plastic strain model for SAPDM is presented in Eq. 3.

$$\varepsilon_p = k_1 \times N^{k_2} T^{k_3} \sigma_d^{k_4} \quad (3)$$

where  $\varepsilon_p$  is the accumulated plastic strain at N number of load cycles;  $\sigma_d$  is the repeated/dynamic axial stress;  $T$  is temperature;  $k_i$  are non-linear regression constants.

## ***5.2. Permanent deformation models for SAPDM***

The objective was to develop a practically predictive equation to estimate permanent deformation behavior of asphalt mixes used in South Africa. Results from all the 36 samples tested at different stress levels and different test temperatures were used to develop the permanent deformation models. As shown in Figs. 3 and 4, the results indicated that there is an effect of stress states and test temperature on permanent deformation accumulation on the mix tested.

Combined data sets obtained at all the loading conditions were used to obtain permanent deformation characterization model for the asphalt mix. The SAS statistical software [21] was used to perform multiple regression analyses on the data sets to obtain the model parameters. Table 3 lists the permanent strain models developed using the combined test data and gives the model parameters obtained from stepwise multiple regression analyses. A very weak correlation was obtained when only the number of load repetitions are used to model the asphalt mix tested (i.e., coefficient of correlation,  $R^2 < 0.1$ ). However, the inclusion of temperature and stress significantly improved the  $R^2$ -values (see models 2 and 3), thus indicating stress and temperature dependency had the predominant role in predicting permanent strain accumulation.

**Table 3**  
Permanent strain models studied for the asphalt mix.

Model 1	$\varepsilon_p = k_1 \times N^{k_2}$					
Model 2	$\varepsilon_p = k_1 \times N^{k_2} T^{k_3}$					
Model 3	$\varepsilon_p = k_1 \times N^{k_2} T^{k_3} \sigma_d^{k_4}$					
Model	Model parameters					
	$k_1$	$k_2$	$k_3$	$k_4$	$R^2$	RMSE
1	$7.779 \times 10^{-2}$	0.165	-	-	0.04	0.457
2	$5.726 \times 10^{-7}$	0.302	3.022	-	0.67	0.266
3	$1.139 \times 10^{-9}$	0.333	3.372	0.860	0.89	0.156

Since a comprehensive but yet practical model should account for the additional effects of temperature and applied stresses in the hot-mix asphalt mixes, model 3 in Table 3 can be verified using both laboratory and field testing if more data becomes available for routine use in the estimation of permanent deformation behavior of the standard asphalt mix tested. The proposed model for the mix tested, is represented by Eq. 4.

$$\varepsilon_p = 1.139 \times 10^{-9} N^{0.333} T^{3.372} \sigma_d^{0.950} \quad (4)$$

It can be seen from Eq. 4 that increasing the number of load cycles, axial stress and temperature should produce high accumulation of permanent strain in the asphalt material. This implies that, the exponents of these parameters should always be positive in the model. It is worth mentioning that the proposed model in its current form under-predicts permanent deformation at high temperatures and axial stresses. As mentioned earlier, Denneman [15] reported that the maximum surface temperature of road pavements in South Africa is generally between 45°C and 55°C. There is an on-going research investigation by the authors about the need to select the highest test temperature below 55°C in order to achieve at least 5000 cycles before the sample fails. It can be seen from Table 2 that majority of the samples tested at 55°C could not reach 5000 cycles before the test was terminated at the failure condition of 5% strain.

## **6. Conclusions**

SANRAL together with the CSIR are currently funding a number of projects to revise the existing mechanistic-empirical pavement design guide for road pavement design in South Africa. An important part of the revision is the development of new or improved test protocols to characterize HMA mixes commonly used in South Africa road pavements.

This paper presented the development process of repeated axial load permanent deformation test protocol for the revised South African pavement design method. The test protocol was used to conduct a comprehensive laboratory testing program on a standard South African hot-mix asphalt with 60/70 penetration grade bituminous binder. Although the test results indicated that the asphalt mix tested depends on the axial stress levels, test temperatures, and the number of load repetitions, it should be noted that only one mix type and one binder has been addressed for the protocol development process. The models developed would therefore, need improvements through calibration/validation for final implementation in the SAPDM. This would require additional permanent axial deformation properties of asphalt mixes and binder types. Based on the material presented in this paper, the following important conclusions can, however, be made.

- A new permanent deformation test protocol, which provides ability to better predict permanent deformation behavior of HMA mixes over a wider range of stress levels and temperatures has been

developed using typical road pavement conditions in South Africa. This test protocol will support the revision of the South African mechanistic-empirical pavement design method.

- Permanent strain accumulation model that is based on temperature, applied stress and number of load applications has been developed for South African pavement design method. The models will provide the basis to improve HMA performance models for future implementation in the new SAPDM when more laboratory and field data become available.

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