FATIGUE AND DEFORMATION CHARACTERISTICS OF LARGE-AGGREGATE MIXES FOR BASES

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Abstract
As part of a study conducted for Sabita on Heavy Duty Asphalt Pavements (HDAPs), the CSIR Division of Roads and Transport Technology developed a comprehensive and practical mix design method for large-aggregate mixes. In this paper, a framework for linking mix design parameters with the structural design process is discussed, based on dynamic tests conducted in the laboratory, complemented by Heavy Vehicle Simulator (HVS) tests on pavements containing Large-Aggregate Mixes for Bases (LAMBS). Initial results indicate that LAMBS are less sensitive than conventional mixes to the magnitude of horizontal tensile strain and that pavements containing LAMBS should be able to carry traffic in excess of 50 million E80s.

1. INTRODUCTION

In view of the relaxation of economic sanctions against South Africa, the general upliftment of the world economy and of worldwide trends towards the endorsement of higher axle loads and higher tyre pressures, traffic loading on Southern African roads is expected to increase considerably in the near future. However, there is at present a shortage of funding for road maintenance, rehabilitation and especially for new construction. This results in increased demands for more economic designs and for optimization of the use of available resources.

In this framework, the CSIR Division of Roads and Transport Technology, on behalf of the Southern African Bitumen and Tar Association (Sabita), has developed and implemented technology related to the use of large aggregate mixes in bases. This new product, referred to as LAMBS (Large Aggregate Mixes for Bases), has been proven to be more economical and to perform better than conventional mixes. A new mix design methodology has been developed for LAMBS (Sabita, 1), which has been verified in a number of applications; in trial sections in the Western Cape and Northern Natal and in full scale implementation on Jan Smuts Airport and on the M2-Motorway in Johannesburg. Heavy Vehicle Simulator (HVS) testing conducted on trial sections has shown that LAMBS can indeed carry very high traffic -in excess of 50 million equivalent 80 kN axles.

However, the current process of relating structural design methodologies to mix design parameters was found to be unsatisfactory. A particular need was therefore expressed for the prediction of fatigue performance of LAMBS and of resistance to permanent deformation.

In this paper, a framework for linking mix design parameters to the structural design process will be discussed, focusing on the main parameters which need to be considered, such as stiffness, fatigue characteristics and resistance to permanent deformation. In addition, the results of work carried out to determine the fatigue properties and deformation characteristics of LAMBS are given and discussed. This work involved the use of the Sabita/CSIR third-point loading fatigue apparatus in order to determine fatigue criteria as well as the dynamic creep test combined with HVS results in order to verify permanent deformation criteria for LAMBS. Laboratory fatigue and deformation criteria for the structural design of pavements containing bases with large aggregate mixes are addressed and the effects thereof discussed in terms of economical design of asphalt bases.

2. BACKGROUND ON LAMBS

The use of LAMBS has arisen from the need for heavy duty pavements in South Africa for the following reasons:

- Increase in traffic volumes (>50 x 10^6 equivalent 80 kN axle loads (E80's))
- Possible increase of legal axle load to 9 or 10 metric tonnes (90 or 100 kN)
- Higher tyre pressures with new types of tyre

Heavy duty asphalt pavements can be classified into two categories, namely deep (composite) strength asphalt and full-depth asphalt. LAMBS would fall within the former category, in which a typical pavement structure would consist of an asphalt base (LAMBS) and a granular or cemented subbase.

The advantages of LAMBS include the improvement in the pavement's structural capacity at reduced cost resulting from:

- the increase in bearing capacity as aggregate size increases relative to layer thickness
- the increase in binder film thickness for a given binder content (by mass) as maximum size of aggregate increases, resulting in greater durability
- the increased resistance to indentation, abrasion and deformation as maximum stone size increases
- the decrease in material cost because of the savings in binder content on account of the smaller aggregate surface area which needs to be covered as aggregate size increases

The design of LAMBS is based on a three level rejection analysis of mixes manufactured with a grading selected based on available aggregate fractions and containing at least three different binder contents and two filler contents (Sabita, 1). The proposed tests to be conducted in each of the phases are summarized below. The design criteria of LAMBS are given in Table 1.

- *Phase I:* determination of bulk relative density, maximum theoretical bulk density, voids content, voids in mineral aggregate and voids filled with binder
- *Phase II:* determination of indirect tensile properties which include resilient modulus and indirect tensile strength
- *Phase III:* determination of resistance to permanent deformation by means of the dynamic creep test

TABLE 1: Design criteria of LAMBS (Sabita, 1)

Property	Criterion
Density	Aim for maximum
Voids	Minimum 3%, maximum 6%
Voids in mineral aggregate (VMA)	Dry side of minimum VMA vs binder content, minimum 12%
Voids filled with binder	Minimum 72%, maximum 80%
Resilient modulus @ 25°C/10 Hz	Minimum 2 000 MPa (stiff layer) 1 000 - 2 500 MPa (flexible layer)
Indirect tensile strength (25°C)	Minimum 800 kPa
Dynamic creep modulus (40°C)	Minimum 10 MPa

The pavement structure influences the structural response and performance of LAMBS as the response of underlying layers to loading influences the stresses and strains in the upper asphalt layers. During the design phase it is important to ensure that the structural behaviour of the pavement subjected to loading is incorporated in the mix design of LAMBS. Pavement design and mix design should, therefore, form an interactive process. If LAMBS are to overlay a flexible structure, the emphasis of the mix design should be on the provision of LAMBS of low stiffness, unless the thickness of the LAMBS layer is such that it can protect the underlying layers effectively. In the latter case, LAMBS should be designed to have great stiffness which can be achieved by selecting mixes with relatively high filler contents and low binder contents. If LAMBS are intended for use on a stiff supporting structure, such as on a cement treated layer, a mix of high stiffness should also be selected.

The constructibility of LAMBS is important as it influences the engineering properties of the pavement layer. Segregation in large stone mixes is a common problem, especially in mixes with discontinuous gradings (semi-gap or semi-open). Although LAMBS are not linked to a particular grading, the selection of a continuous grading would reduce the risk of segregation. The risk of segregation can be further reduced by proper control exercised at the mixing plant or by increasing both the binder and filler contents. As the latter would, however, result in an increase in cost, the process should be controlled during the mix design phase, where a balance between economic considerations and constructibility should be achieved.

3. DEVELOPMENT OF FATIGUE FAILURE CRITERIA

3.1 Introduction

The variables effecting fatigue response can be grouped into three sections:

- *load variables:* load history, state of stress, loading waveform, frequency of loading and rest periods
- *environmental variables:* temperature, moisture and time dependent effects causing changes to the material properties
- *material variables:* rheological properties of the binder, binder content, aggregate type, gradation, density and air voids content

As traffic loading usually has a variable nature, in which loading magnitude and frequency do not form a definite pattern, simulation of traffic-induced stresses or strains in the laboratory should ideally be of a compound nature which involves changing the testing conditions in a randomized fashion. This, however, makes the analysis of results and comparative studies conducted between different types of mix rather complex, unless use is made of the dissipated energy approach. In order to simplify the simulation process in the laboratory, fatigue tests are usually conducted under fixed testing conditions. The results of these tests are then related to actual traffic through the use of shift factors. These factors make provision for the effects of loading magnitude, frequency of loading and rest periods.

The state-of-stress at which fatigue tests are conducted in the laboratory depends on the behaviour of the structural component in the laboratory. Thin, flexible asphalt layers, whose fatigue life is dependent on the magnitude of horizontal tensile strains developing at the bottom of the layer, usually have to be tested in constant-strain mode. On the other hand, the constant-stress mode is usually required for the evaluation of thick, stiff asphalt layers. In the case of LAMBS, which are applied in thicknesses typically ranging between 100 mm and 300 mm, and whose supporting structures can either be flexible (as in the case of rehabilitation measures on a distressed pavement structure) or stiff (as in the case of a cement-treated subbase), the behaviour of the material in both states-of-stress modes has to be determined. Laboratory models should thus be developed in which both states-of-stress modes are incorporated and in which fatigue life of LAMBS is related to horizontal tensile strain.

Changes in the environment usually result in changes in the stiffness of visco-elastic materials such as LAMBS. Similarly, variations in the composition of the mix will result in mixes of different stiffnesses. Whereas the above variations can be characterized from the measurement of resilient modulus, their effects on horizontal tensile strain (asphalts) and on vertical compressive strain (granular materials) should be assessed through linear-elastic or elasto-plastic analysis of the pavement structure.

3.2 Laboratory modelling of fatigue

A wide variety of laboratory fatigue testing methods is available worldwide. These can be grouped as follows:

- simple or supported flexure
- direct axial
- diametral (indirect tensile)
- triaxial
- fracture mechanics
- wheel-tracking

Based on the findings of the Strategic Highway Research Programme (SHRP) (Rao Tangella et al, 2), in which the simple flexure test was identified as being that best suited to evaluate the fatigue resistance of asphalt mixes, the decision was taken to develop laboratory fatigue models for LAMBS using the third-point loading fatigue test. The testing device, shown in Figure 1, which is supported by a computer-controlled hydraulic testing facility, is enclosed in a constant temperature cabinet and enables the fatigue life of asphalt beams to be determined in either constant-strain or constant-stress mode, using different types of wave-shapes, frequencies, rest periods and temperatures. For the purpose of developing fatigue curves for LAMBS, the following testing parameters were used:

- state-of-stress: controlled-strain and controlled-stress
- loading waveform: sine
- loading frequency: 10 Hz
- testing temperature: 5°C

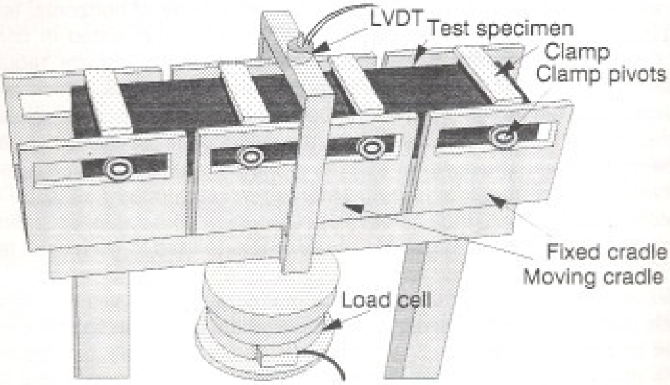

FIGURE 2: Third-point loading fatigue testing apparatus

For each fatigue test, the calculations of the maximum stress in the extreme fibre, σ, maximum initial strain in the extreme fibre, ϵ, and initial elastic modulus, E, are made in accordance with the following formulae (Irwin and Gallaway, 3):

$$\sigma = \frac{PL}{bh^2}$$

$$E = \frac{23PL^3}{108w_o bh^3}\left(1 + \frac{216h^2(1+\mu)}{115L^2}\right)$$

$$\epsilon = \frac{\sigma}{E}$$

where: P = amplitude of the dynamic load applied to a specimen (N)
L = beam span between reaction points (mm)
b = beam width (mm)
h = beam height (mm)
wo = centre deflection of beam (mm)
μ = Poisson's ratio

The number of strain or stress repetitions to failure is defined as the number of repetitions to crack initiation. In constant-strain mode, deflections remain constant while stiffness decreases gradually to the point of crack initiation whereafter it decreases rapidly until complete failure. The load which is applied in order to maintain a constant deflection follows a similar pattern. In controlled-stress mode, the applied load remains constant while deflections increase gradually as the fatigue resistance or the strength of the specimen decreases. At the point of crack initiation, deflections increase rapidly until complete failure.

The LAMBS subjected to the above fatigue tests were obtained from Heidelberg Road, Johannesburg, which was constructed to serve as an experimental section prior to the rehabilitation of the M2-Motorway in Johannesburg. Some of the engineering properties of the Heidelberg Road mix are given in Table 2. As can be seen from the results, this type of mix is ideally suited to overlay a stiff pavement structure as the mix has high stiffness and offers excellent resistance to permanent deformation.

TABLE 2: Engineering properties of LAMBS placed on Heidelberg Road

Property	Average	Specification
Resilient modulus		
25°C	3 300 MPa	Minimum 2 000 MPa
5°C	12 400 MPa	-
Dynamic creep modulus (40°C)	21 MPa	Minimum 10 MPa

The above mix has a continuous grading with a maximum stone size of 37,5 mm. The percentages passing the 4,75 mm and 0,075 mm sieves are 40 and 4 per cent respectively. A 60/70 penetration grade bitumen was used. The binder content was 3,5 per cent by mass of total mix. The mix was compacted to 98 per cent of maximum theoretical density to yield a mix containing 4 per cent air voids.

The fatigue lives of eight representative samples subjected to controlled-strain testing and those of six samples subjected to controlled-stress testing are given in Table 3 and shown in Figure 2. The results indicate that the fatigue curve obtained from tests conducted in controlled-stress mode is considerably more conservative than that obtained from tests conducted in the controlled-strain mode. Controlled-stress tests therefore result in a reduction in the number of load repetitions to failure by comparison with that of controlled-strain fatigue tests. This trend has been confirmed by other researchers (Monismith et al, 4). A possible reason for this is that controlled-stress testing results in a higher rate of crack propagation relative to that of tests conducted in controlled-strain mode. In controlled-strain mode, the load, and therefore the applied stress, is reduced as the test progresses in order to maintain a constant applied strain on the specimen. The induced energy thus decreases as testing progresses, with the result that the crack initiation phase may be diffused into the crack propagation phase without there being a clearly defined crack initiation point. This is contrary to what happens in controlled-stress testing where the applied stress remains constant throughout the test, thus resulting in a very high rate of crack propagation after its initiation. In fact, crack initiation and crack propagation occur almost simultaneously.

TABLE 3: Results of fatigue tests conducted on the Heidelberg Road LAMBS

Sample	Strain (με)	E-modulus (MPa)	Repetitions
Controlled-strain tests: $N_f = 1{,}01.10^{-13}\ \varepsilon^{-5{,}92}$ $R^2 = 0{,}87$			
1	720	4 400	670 000
2	860	4 900	100 000
3	860	4 800	75 000
4	990	4 600	34 000
5	1 010	4 600	90 000
6	1 160	4 000	31 000
7	1 170	4 600	34 000
8	1 400	4 000	6 000
Controlled-stress tests: $N_f = 5{,}22.10^{-20}\ \varepsilon^{-7{,}61}$ $R^2 = 0{,}90$			
1	570	4 700	210 000
2	600	5 000	161 000
3	640	4 800	131 000
4	680	5 100	62 000
5	800	4 600	34 000
6	840	4 700	7 500

Nf = fatigue life
ε = horizontal tensile strain
R = correlation coefficient

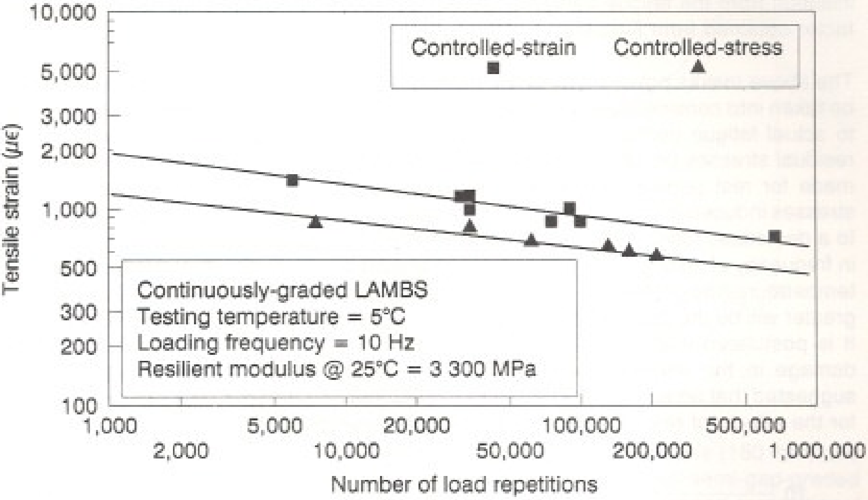

FIGURE 2: Fatigue curves for LAMBS

In Table 4, the slopes of the fatigue curves are compared with those obtained from a SHRP study on continuously-graded mixes (AC-DG) with a nominal stone size of 19 mm (Tayebali et al, 5) and from a study conducted by Freeme and Walker (6) on similar mixes used in thick bituminous bases. The results suggest that the LAMBS investigated in this study are less susceptible to horizontal tensile strain than conventional mixes manufactured with smaller nominal stone sizes.

TABLE 4: Slope of fatigue curves of conventional mixes and LAMBS

Type of mix	Mode of loading	Slope
19 mm AC-DG (Tayebali et al, 5)	controlled-strain controlled-stress	-4,01 -4,22
19 mm continuous (Freeme and Walker, 6)	controlled-stress	-4,43
LAMBS	controlled-strain controlled-stress	-5,92 -7,61

3.3 Relationship between test results and expected field performance

Since asphalt bases tend to be fairly thick and as fatigue cracking usually start at the bottom of the layer, extra traffic can be carried on the pavement structure before cracking propagates and becomes visible on the surface. The increase in the life of the pavement is thus a function of the thickness of the layer. The total life of the asphalt base is therefore determined by first determining the equivalent traffic to crack initiation from the fatigue curves (Figure 2) and then multiplying this value by a shift factor obtained from Figure 3 (Jordaan, 7).

The above makes provision for crack propagation. However, other factors should also be taken into consideration when fatigue lives determined in the laboratory are related to actual fatigue performance of the mix on the road. One of these is the effect of residual stresses on fatigue performance. In laboratory tests in which no provision is made for rest periods and where, therefore, there is no relaxation of the residual stresses induced in the specimens, these stresses build up with time, thus contributing to a decreased fatigue life. The build-up of these stresses increases with an increase in frequency of testing. Other factors which should also be taken into consideration are temperature (the greater the difference between ambient and testing temperatures, the greater will be the shift factor) and the effect of transverse distribution of wheel loads. It is postulated that only 40 per cent of the total number of wheels contributes to damage in the wheel track (Van Dijk and Visser, 8). Based on the above, it is suggested that an additional shift factor of between 20 and 30 be used to compensate for the effects of rest periods and of the transverse distribution of wheel loads.

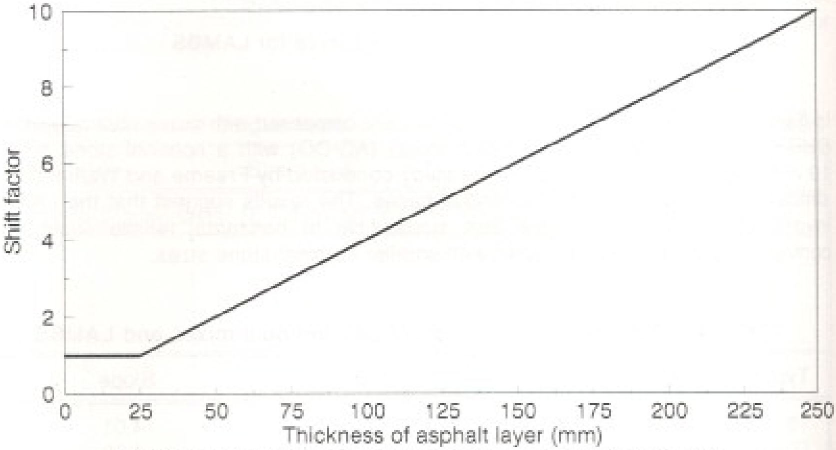

FIGURE 3: Shift factor for crack propagation (Jordaan, 7)

4. DEVELOPMENT OF FAILURE CRITERIA FOR PERMANENT DEFORMATION

In order to establish failure criteria for permanent deformation, three 100 m test sections of LAMBS were constructed near Dundee in Natal (Grobler et al, 9) and their performance evaluated by means of the Heavy Vehicle Simulator (HVS) (Horak et al, 10). A maximum aggregate size of 37 mm was used in these sections, the aggregate gradings being continuous, semi-gap and semi-open (Figure 4). The optimum binder content of the continuously- and semi-gap-graded mixes was 3,5 per cent by mass of total mix, while that of the semi-open-graded mix was 4,0 per cent. A 60/70 penetration grade bitumen was used in the manufacture of all three types of LAMBS.

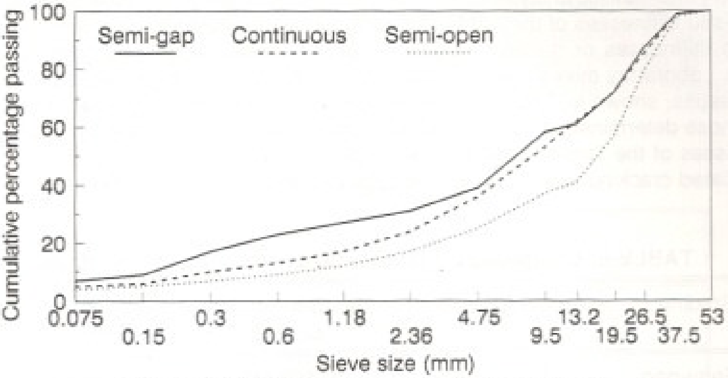

FIGURE 4: Gradings used in the Dundee trials

The pavement structure consisted of a fairly stiff lime-treated subbase (150 mm), the large aggregate asphalt base (150 mm LAMBS) and a conventional semi-gap-graded surfacing (40 mm). Rapid tests were conducted on all three sections and conventional HVS tests on the continuously-graded section. For the conventional tests, the HVS test section was divided into two subsections after an initial 500 000 repetitions under a 40 kN wheel load. The performance of one subsection was evaluated at ambient temperatures (15°C to 30°C) and that of the other section at an elevated temperature ranging between 40°C and 50°C. The test programme is shown in Table 5.

TABLE 5: Test programme for rapid and conventional HVS tests

Rapid tests:			Conventional test:
Semi-gap	Semi-open	Continuous	Continuous
18 000 reps @ 40 kN 22 000 reps @ 60 kN 110 000 reps @ 100 kN		18 200 reps @ 40 kN 61 800 reps @ 60 kN 88 200 reps @ 100 kN	1,5.10^6 reps @ 40 kN (one heated section)

During the HVS testing, surface rutting and deflections were measured continuously, as were deflections and permanent deformation within the LAMBS, by means of multi-depth deflection (MDD) measurements (de Beer et al, 11). The surface deflections prior to accelerated testing were in the order of 0,2 mm, which increased to a maximum of approximately 1,2 mm at the end of the test in the case of the semi-gap-graded LAMBS. The greater part of the increase in the deflections occurred in the in-situ material and in the layer beneath the subbase which had been ripped and recompacted as part of the construction process. After the LAMBS had been subjected to the equivalent of 4,4 million standard axles, no fatigue distress was observed.

By using mechanistic analysis models with measured multi-depth deflections as inputs, the in-situ stiffnesses of the LAMBS were determined and compared with the indirect tensile stiffnesses or resilient moduli of both cores and laboratory-compacted field mixes. Laboratory mixes were compacted according to the Hugo method (Hugo, 12). The results, shown in Table 6, indicate that in-situ stiffnesses compared favourably with those determined in the laboratory. From the results, it can also be seen that the stiffnesses of the Dundee LAMBS were low - contributing to the fact that no fatigue associated cracking was observed, in spite of the high surface deflections.

TABLE 6: Comparison between field and laboratory stiffness

Grading	In-situ stiffness	Resilient modulus of cores	Resilient modulus of Hugo/Lab mix
Semi-gap	1 140 MPa	1 300 MPa	1 369 MPa
Semi-open	1 360 MPa	1 380 MPa	1 470 MPa
Continuous	1 140 MPa	1 320 MPa	1 380 MPa

The rates of permanent deformation for the LAMBS layers in all the trial sections, under various conditions of loading and temperatures, were very low. These rates are summarized in Table 7. Also shown in the table are the permanent deformation characteristics of the different mixes assessed in the laboratory by means of dynamic creep tests (Cooper and Brown, 13). These tests were conducted during the design of the Dundee trial mixes.

TABLE 7: Deformation rates for LAMBS and average dynamic creep moduli

Grading	Rate of deformation (per 10^5 repetitions)	Dynamic creep modulus (40°C)
Rapid tests (100 kN)		
Semi-gap	1,8 mm	7,0 MPa
Semi-open	0,9 mm	10,6 MPa
Continuous	0,5 mm	12,4 MPa
Conventional tests (40 kN)		
Continuous (150 mm):		12,4 MPa
15°C to 30°C	0,040 mm (max)	
40°C to 50°C	0,090 mm (max)	

In Table 8, the expected lives (expressed in equivalent 80 kN axle load repetitions) of the different LAMBS are given, based on the measured rut rates, 20 mm rutting as a failure criterion and a damage factor of four. Based on the results obtained on continuously-graded LAMBS, indications are that these mixes should be able to carry traffic well in excess of 50 million standard axles without failure in terms of deformation within the base. It should, however, be realised that rutting rates might have been higher and therefore the expected life shorter, had the supporting structure been stiffer. Nevertheless, mixes with the minimum dynamic creep modulus of 10 MPa specified for laboratory-manufactured LAMBS should have long-term resistance to permanent deformation.

TABLE 8: Expected life of LAMBS

Grading	Expected life (20 mm rutting)
Semi-gap (rapid test)	43 million E80s
Semi-open (rapid test)	85 million E80s
Continuous (conventional test)	
15°C to 30°C	74 million E80s
40°C to 50°C	59 million E80s

5. CONCLUSIONS

A mix design method for LAMBS has been developed and successfully implemented in South Africa. It has, however, been found that the performance prediction models for conventional asphalt mixes are not always suitable for LAMBS. In order to predict the expected structural life span of LAMBS, new models thus needed to be developed. In this paper, initial prediction functions to evaluate the fatigue resistance of LAMBS were given. Based on the information given, the following conclusions can be made:

- LAMBS were found to be less susceptible than conventional mixes to the magnitude of horizontal tensile strain.
- Testing in controlled-stress mode provides a better indication of the number of load repetitions to crack initiation than does testing in controlled-strain mode.
- Fatigue tests conducted in controlled-stress mode resulted in shorter fatigue lives than tests conducted in controlled-strain mode.

Heavy Vehicle Simulator (HVS) tests conducted on the Dundee trial sections indicate that exceptional performance in terms of permanent deformation within the base layer can be expected when large-stone asphalt mixes (LAMBS), designed in accordance with the recommended mix design method, are used. If a minimum dynamic creep modulus of 10 MPa is specified for laboratory-manufactured samples, this will ensure that LAMBS subjected to traffic will perform satisfactory and it is expected that they should be able to carry traffic well in excess of 50 million standard axles without failure in terms of deformation within the base.

The stiffness of LAMBS can be predicted accurately. Stiffnesses measured in the field compare very well with the values measured in the laboratory on both cores and laboratory-manufactured samples.

ACKNOWLEDGEMENTS

The Director of the CSIR's Division of Roads and Transport Technology is thanked for the permission to publish this paper. The authors would also like to acknowledge the contribution made by the Southern African Bitumen and Tar Association (Sabita) towards the research project. The views expressed in this paper are those of the authors and do not necessarily reflect the standpoint of Sabita.

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