

Investigation of the resilient behavior of granular base materials with simple test apparatus

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Abstract In many developing countries, where resources are at premium, thin asphalt layers or chip seals are widely used to provide a durable all weather pavement surfacing. In such pavements the role of granular layers is very important in the general performance of the structure. Pavement designs in these countries are empirical in nature and rely on simple input parameters like California Bearing Ratio (CBR) values. Although widely applicable the traditional CBR test does not provide the mechanical properties such as resilient and permanent deformation characteristics of granular road materials. This paper documents the characterization technique developed to determine the mechanical behavior of granular (sub-) base materials based on CBR test using repeated

load cycles. The confining pressure developed in the complex CBR stress state is estimated using strain gauges. Finite Element analysis has been attempted to model the repeated load CBR (RL-CBR) and derive an equivalent resilient modulus. Furthermore, a large scale cyclic load triaxial test was carried out on coarse unbound granular materials (UGMs) to validate the result of the RL-CBR. The RL-CBR test reasonably estimates the resilient modulus of UGMs which can be used as an input in mechanistic pavement design analysis in the absence of triaxial testing facilities.

Keywords Aggregates · Repeated load CBR · Characterization · Triaxial · Mechanical behavior

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1 Introduction

Since most developing countries lie in the tropics or sub-tropics the differences between pavement engineering in temperate industrialized countries and developing countries are often thought of almost exclusively in terms of climatic differences. Whilst these differences are substantial, more important differences between pavement engineering in developing countries and industrialized countries are the greater variability of construction materials, quality of construction, and the larger fluctuations in the volume and weight of road traffic that are typically encountered in developing countries [6].



An important aspect of pavement engineering in developing countries that has no parallel in most industrialized countries is the extent to which thin-asphalt surfaced and unsurfaced roads contribute to national road networks. In developing countries unsurfaced roads carrying several hundred vehicles per day are not uncommon, and these low-cost roads of all type play a vital role in the economic and social life of many of these countries. The techniques of designing, constructing and maintaining of thin-asphalt surfaced and unsurfaced roads are thus an important part of pavement engineering in developing countries.

In thin-asphalt surfaced and unsurfaced pavements the granular base and sub-base layers provide the bulk of the bearing capacity. Despite their extensive use, however, granular base and sub-base materials are often not used to their fullest extent. This is due to the fact that pavement designs in these countries are empirical in nature; moreover most of these design procedures originate from industrialized countries, where the main structural element is the asphalt layer and the significance of the granular base and sub-base are virtually reduced to that of a working platform. In many of the mechanistic–empirical (M–E) pavement design procedures used today too, granular materials do not feature strongly.

These design procedures focus on designing the asphalt layer, given the subgrade condition, the traffic loadings and the climatic conditions. To fully utilize the structural role of the granular layers and establish more rational pavement design and construction criteria it is essential that the response of granular layers under traffic loading is taken into consideration and thoroughly understood. It becomes very important to properly characterize the behavior of unbound aggregate layers and subgrade soils of the layered pavement structure in order to predict pavement responses, which is essential in the framework of the M–E pavement design approach.

On the other hand day-to-day engineering practice specifies and constructs roads based on a completely different set of parameters with very little correlation between the M–E design inputs and the common engineering parameters of the material. The factors impeding the more fundamental and mechanical approach of the behavior and performance of granular bases and sub-bases are basically related to the complexity of the characterization techniques, e.g.

cyclic loading triaxial tests, required to determine the stress dependent mechanical behavior of granular materials.

The aim of this research is, therefore, to develop a characterization technique for the mechanical behavior of unbound granular base and sub-base materials (mainly tropical and sub-tropical materials) that is more easily accessible to practice, in order to promote the introduction of M–E design methods in developing countries. Over the last four decades, many researchers have been investigating the resilient behavior of granular materials as the shift from the empirical to the mechanistic design of pavement gained popularity.

The resilient properties of unbound granular materials (UGMs) was first noted by Hveem in 1950s [16], who conclude that the deformation of such materials under transient loading can be treated as elastic in the sense that it is recoverable. The actual concept of resilient modulus was later introduced by Seed et al. [13] in characterizing the recoverable strain of subgrade soils and their relation to fatigue failures in asphalt pavements.

Granular materials are not truly elastic but experience some non-recoverable deformation after each load application [3]. In the case of transient loads and after the first few load applications, the increment of non-recoverable deformation is much smaller compared to the increment of resilient/recoverable deformation [17]. By studying the literature on earlier research Lekarp et al. [11] presented a “state-of-the-art” on resilient behavior of UGMs. Lekarp [10] found that the resilient behavior of UGMs was affected by several factors, like stress, density, moisture content, fines content, grading, aggregate type, number of load applications, stress history, load duration, frequency and load sequence. The state of stress was found to have the most influence on the resilient behavior. Several researchers [7, 8, 14, 16] have shown that the resilient modulus increases with an increase in confining pressure. On the other hand, Brown [2] reported a significant effect of the deviator stress, especially at high stress levels.

The method of characterizing the resilient behavior of UGMs, however, is commonly done using cyclic load triaxial tests which are considered to be advanced and unaffordable to implement in routine road construction projects in developing countries. On the other hand despite their worldwide acceptance and existence for a long time, index testing such as California Bearing Ratio (CBR), being too empirical,



have technical limitations to be used in the M–E design methods. An intermediate characterization technique, a repeated load CBR (RL-CBR) test, is used in the study to characterize the stiffness properties of unbound granular road materials, based on the standard CBR test using repeated load cycles.

This paper presents the characterization techniques of the RL-CBR and the results of the RL-CBR and large-scale triaxial tests on a high quality South African crushed rock (G1) base material. The following sections describe the material, experimental methodologies employed and the principle of the RL-CBR test. Further the resilient property from RL-CBR and triaxial tests will be compared and evaluated; and the effect of moisture content, degree of compaction and load level on the resilient characteristics of UGMs will be summarized.

2 Experimental

2.1 Material

The crushed rock base material is a crushed Hornfels rock which is obtained from a quarry in South Africa. Hornfels are a fine-textured metamorphic rock formed by contact metamorphism. The South African Hornfels is a type that is formed by contact metamorphism of a Greywacke sedimentary rock of mechanical origin. Mechanical origin refers to those sedimentary rocks that are formed by erosion of previously existing rocks (igneous or metamorphic) and their eventual deposition at some point from where they cannot be transported further (lake bottoms, plains, ocean floors).

The hard crushed rock is one of the best quality road base material and is classified as grade 1 (G1) crushed stone base course material according to the South African specification [4]. The crushed rock base coarse aggregate is produced from a hard rock and the fines are also crushed from the same sound rock. As this material is an aggregate crushed from sound rock the particles are characterized by angular spherical shape and rough surface texture, see Fig. 1. According to South African specification the grade 1 aggregate shall not contain any deleterious material such as weathered rock, clay, shale or mica. The wet sieve gradation of the material used lies within the South African standard specification [4] for grade 1

crushed stone base as shown in Fig. 2. Moreover the standard specifies compaction requirements of minimum 88% of apparent relative density, that is about 106–108% modified Proctor dry density (MPDD). The moisture–density relation as determined by means of the modified Proctor test demonstrates that, unlike fine subgrade soils, excessive water doesn't reduce its dry density instead there is a slight increment as show in Fig. 3a. For this reason road construction in South Africa with such high quality crushed rock base materials are compacted in the field by splashing a large amount of water during compaction to reach the high degree of compaction required.

However since such splashing during compaction couldn't be simulated in the laboratory compaction this requirement is not achieved in the experiments reported here. In the test program the compaction method employed for both the triaxial and RL-CBR specimens was vibratory compaction. The degree of compaction is varied from 98 to 102% MPDD. Increasing molding moisture content (MC), on the other hand, significantly reduces the CBR value of the material as shown in Fig. 3b for dry (2% MC), moderate (4% MC) and wet (6% MC).

2.2 Repeated load CBR test setup

The standard CBR test is a long established and extensively applied test, worldwide that yields an empirical strength property of granular road materials. The RL-CBR test is developed to take the advantage of the widespread familiarity of the standard CBR test and to exploit the already developed extensive experience particularly in developing countries. The purpose of the RL-CBR test technique is to estimate the resilient modulus of granular materials by using the standard CBR testing equipment with repeated load cycles.

However, coarse granular base and subbase materials with a maximum grain size of 45 mm cannot be tested in the standard CBR mould having a diameter of 152.4 mm. If these materials have to be tested using the standard mould, all particles coarser than 22.4 mm should be removed and replaced by materials in the 5.6–22.4 mm range. This changes the grading and characteristics of the material and therefore it is strongly advised to use a larger mould in order to tests the full gradation of coarse granular materials. The RL-CBR tests were, therefore, performed using a large

Fig. 1 South African crushed stone (G1) material details

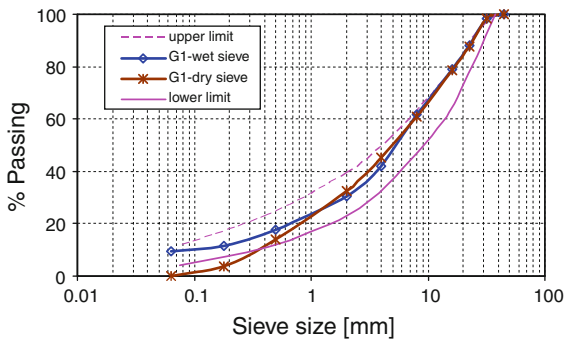


Fig. 2 Gradation of the G1 material and South African specification for class 1 crushed rock base materials

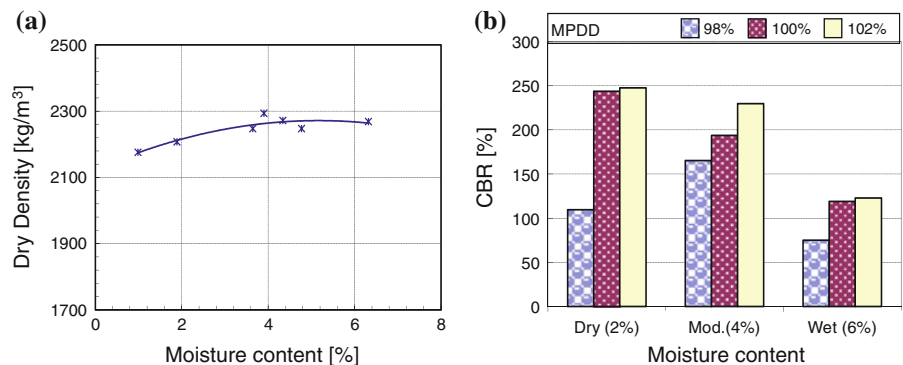
mould with a diameter of 250 mm and a height of 200 mm to accommodate the full 0/45 gradation.

Proportionally a bigger penetration plunger of 81.5 mm diameter is used instead of the standard CBR 49.64 mm diameter plunger. The principle of the RL-CBR test is simple. It is based on the concept that by measuring the load and deformation during loading and unloading cycles, the modulus can be estimated from the recoverable (elastic) deformation and the respective load. Upon multiple repetitions of

the same magnitude of loading granular materials comes to a state in which almost all strain under a load application is recoverable. The permanent (plastic) strain ceases to exist or becomes negligible and the material behaves with a stable recoverable deformation. From the applied load and the measured deformation an equivalent modulus (E_{equ}) of the bulk sample can be estimated. The term equivalent modulus is used as this reflects the overall stiffness of the bulk sample rather than the resilient modulus of the material.

Two test setups have been developed i.e. without and with strain gauges. The test set up is similar for both except for the latter in which a strain gauge is attached to the external surface of the mould so that the confining pressure developed in the complex CBR stress state is estimated by measuring the lateral strain of the mould. A CBR test specimen is prepared according to the prevailing specification (ASTM, AASHTO, BS, EN, etc.) with a surcharge load of 16 kg on top to simulate the overburden pressure from a thin asphalt layer about 80 mm thick surfacing. A load is applied then until an intended deformation, for instance 0.1 inch (2.54 mm), or a

Fig. 3 a Moisture-density relation, **b** effect of moisture content and compaction on CBR for South African G1 material



target plunger load is reached. It is a deformation controlled test so the loading is applied in a similar way to the standard CBR test at a rate of 1.27 mm/min (0.05 inch/min). After that the specimen is unloaded at the same rate of 1.27 mm/min to a minimum contact load of 0.1 MPa to keep the plunger in contact with the specimen. The loading and unloading cycles are generally repeated for about 50–100 load cycles at which time the permanent deformation due to the last five loading cycles will be less than 2% of the total permanent deformation at that point. The testing schedule is shown in Fig. 4.

This paper presents the RL-CBR tests with strain gauges. For tests without strain gauges reference is made to Araya [1] and Molenaar [12]. Four strain gauges capable of measuring in micro-strains, two at mid height of the mould and two near to the top, are glued on the external surface of the mould which measures the mould lateral deformation during the loading and unloading cycles. The strain gauges that measure the deformation of the mould provide information on the degree of confinement developed on the specimen by the steel mould. The stress dependent equivalent modulus is then estimated from the load, vertical elastic deformation and the lateral mould

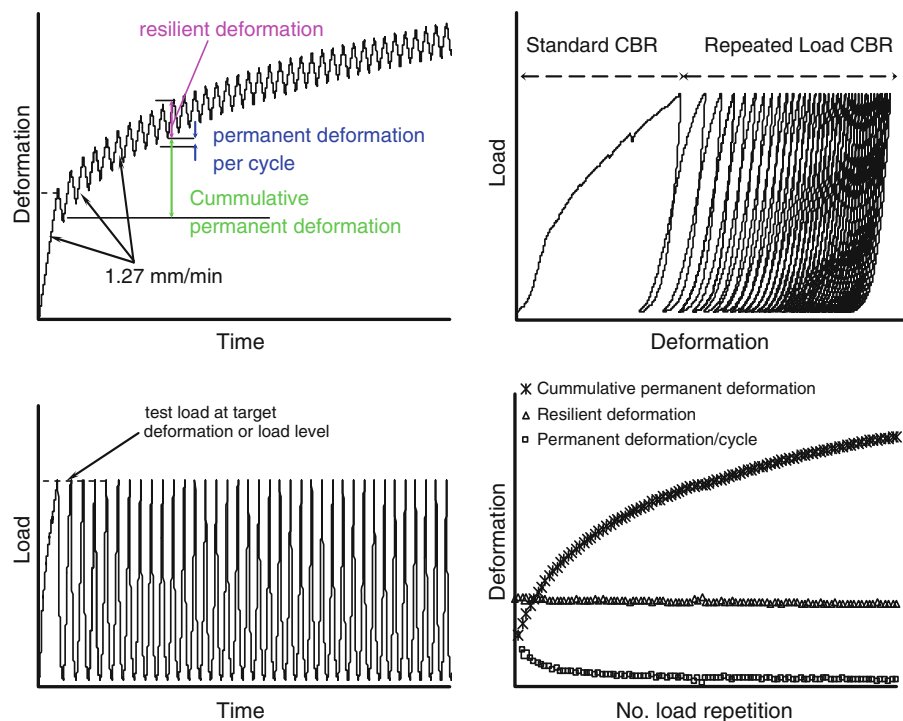
strain using a relation developed through a Finite Element analysis on a RL-CBR test model, as discussed in the following section. The vertical deformation is measured by an external linear variable differential transducer (LVDT) attached to the load cell or plunger through a magnetic stand. Schematic and test setup of the RL-CBR is shown in Fig. 5.

2.3 Monotonic and cyclic load triaxial test

The characterization of the mechanical behavior of the materials investigated is done by means of monotonic and cyclic load triaxial tests. The monotonic tests resulted in information with respect to the cohesion and the angle of internal friction, whereas cyclic load tests were performed to obtain information on the resilient modulus.

Details of the test configuration are given in Fig. 6. The specimens had a diameter of 300 and 600 mm high. The constant confining pressure (CCP) was realized by means of partial vacuum which can be adjusted theoretically up to 100 kPa but is practically limited to 80 kPa. The cyclic load signals used are a haversine at a loading frequency of 1 Hz with 100

Fig. 4 Repeated load CBR test schedule



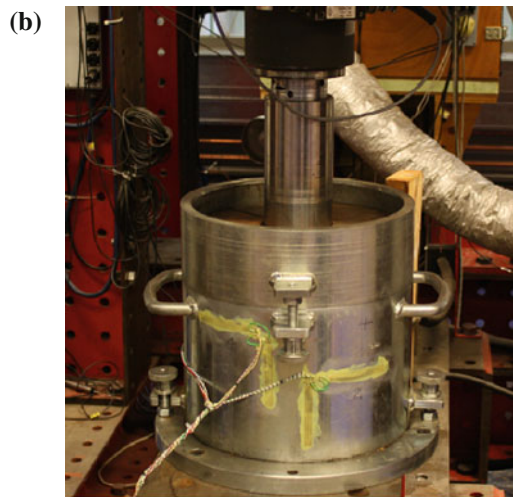
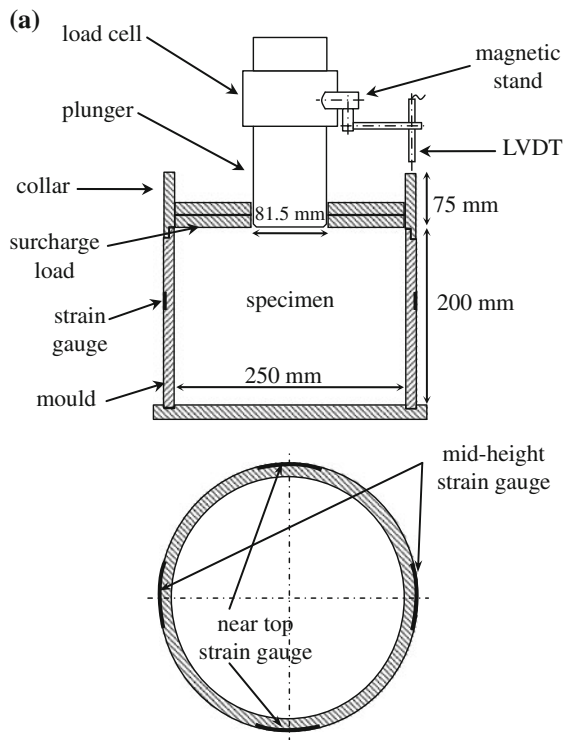


Fig. 5 Repeated load CBR **a** schematic diagram and **b** test setup

cycles for each load combination. Because of space limitations in this paper, no detailed description will be given of the specimen preparation procedure, the instrumentation, and the way that the tests were performed. For further detail reference can be made to Araya [1].

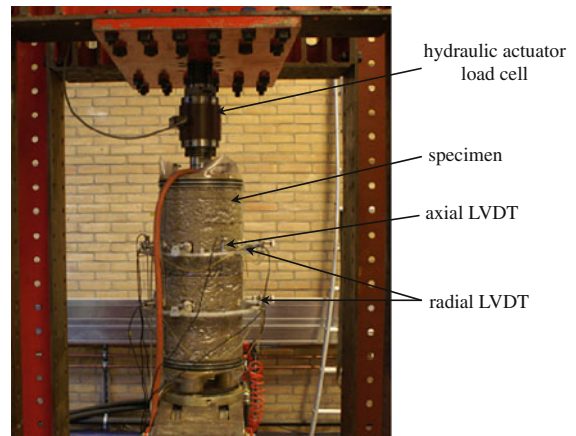


Fig. 6 Triaxial test setup

3 Finite element modeling

3.1 FEM model geometry

The commercial finite element modeling program ABAQUS has been widely applied for pavement analysis. Chen et al. [5] did a comprehensive study of various pavement analysis programs and showed that the results from ABAQUS program were comparable to those from other programs. Zaghoul and White [19], Kim et al. [9] simulated responses of flexible pavements using three-dimensional dynamic analysis in ABAQUS. The main capabilities of ABAQUS in solving pavement engineering problems include: linear and nonlinear elasticity, viscoelastic and elastoplastic material modeling. ABAQUS also provides two and three dimensional calculations and interface modeling with friction.

The main purpose of the finite element modeling in this research is to simulate the RL-CBR testing in order to develop a simplified relationship between the UGM elastic properties mainly the stiffness modulus and the stresses and deformations obtained. For this purpose a simple linear elastic material property is used in modeling both the granular material and the steel mould confining the granular specimen. The finite element mesh used in ABAQUS is shown below in Fig. 7. A three dimensional response is simulated using quasi three-dimensional Fourier analysis elements (CAXA) available within ABAQUS. The number of elements and nodes in the mesh are 730 and 2437 respectively. CAX8R, axis-symmetrical solid models 8 node quadratic rectangular elements

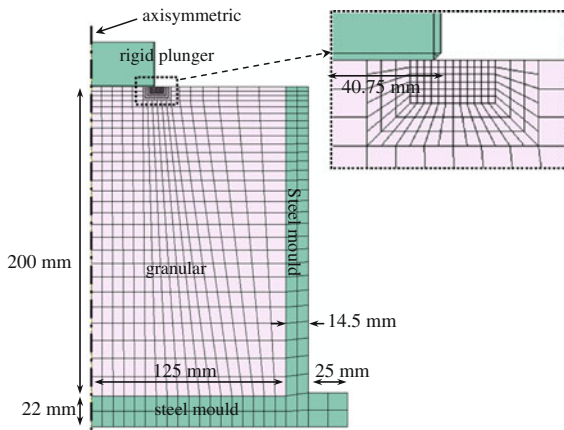


Fig. 7 Finite element mesh used in modeling the RL-CBR

with reduced integration, were used because of their ability to accurately predict the response of axially symmetric loaded models. They are used to give a simulated three-dimensional response by revolving a two-dimensional surface around the centerline of symmetry. The use of CAXA elements increases the efficiency of the model, when compared to a true three-dimensional model while still maintaining accurate results [15].

The granular base material dealt in this paper is a very high quality crushed stone (G1) base material, however the materials considered in this model is for various base and subbase materials ranging from high quality crushed stone to a rather marginal ferricrete material reported in Araya's PhD dissertation [1]. Thus the material properties for this modeling purpose include a wide range with elastic modulus 100–1000 MPa and Poisson's ratio 0.15–0.45 at various combinations. For the steel mould an elastic modulus of 210 GPa and Poisson's ratio of 0.2 is adopted.

3.2 FEM analysis and modulus prediction approach

For a given material property of the granular material a vertical displacement is applied on the rigid plunger, i.e. a displacement controlled test is simulated. As stated above the main purpose of the modeling is to find a relation between the modulus of the granular material and parameters that can be measured from the RL-CBR test; i.e. particularly from the average plunger stress, vertical plunger deformation and lateral

strain of mould mid-height. This relationship is developed as a set of transfer functions that relate material properties and the bulk stresses components of the specimen through a multidimensional least squares regression fitted to the FE analysis data.

First the vertical and lateral stresses of the bulk granular specimen are approximated by weighted average of vertical and radial stresses along the central axis (the axisymmetry) using the vertical deformation along the depth of the sample as weighting factor, as shown in Eqs. 1 and 2. This is based on the assumption that the granular material under the plunger is carrying most of the load, thus the stress and strains along the central axis are considered as representative of the bulk.

Second based on linear elastic theory for the axisymmetric condition, four transfer functions, Eqs. 3–6, were developed from the regression for the vertical stress, lateral stress, Poisson's ratio and elastic modulus. The regressions fit of the four transfer function to the FE data result a good fit of R^2 value of 0.99 except for the Poisson's ratio where the R^2 value is 0.95.

$$\sigma_v = \frac{\sum \sigma_{v,i} u_{v,i}}{\sum u_{v,i}} \quad (1)$$

$$\sigma_h = \frac{\sum \sigma_{h,i} u_{v,i}}{\sum u_{v,i}} \quad (2)$$

$$\sigma_v = k_1 \sigma_p \quad (3)$$

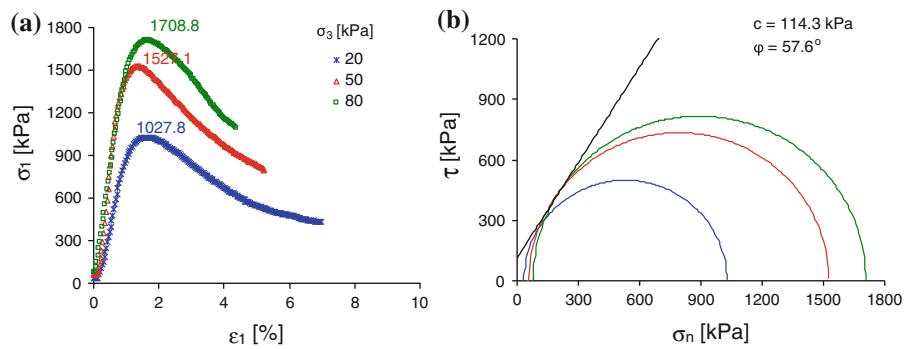
$$v = k_2 \left(\frac{\varepsilon_{hm}}{\sigma_p} \right) \quad (4)$$

$$\sigma_h = k_3 \varepsilon_{hm} \exp\left(\frac{k_4}{v}\right) \quad (5)$$

$$E = \frac{k_5 (\sigma_v - 2v\sigma_h)}{u_v} \quad (6)$$

where σ_v is the vertical stress of the sample as a bulk (kPa), σ_h the horizontal or lateral stress of the sample as a bulk (kPa), $\sigma_{v,i}$ the vertical stress of each element along the axis of symmetry (kPa), $\sigma_{h,i}$ the horizontal or lateral stress of each element along the axis of symmetry (kPa), $u_{v,i}$ the vertical deformation of each element along the axisymmetry (mm), σ_p the vertical plunger stress = total plunger load/plunger area (kPa), v the Poisson's ratio (–), E the stiffness modulus (MPa), ε_{hm} the horizontal or lateral strain at mid height of mould exterior (micro-strain), u_v the vertical plunger deformation (mm), and k_1 to k_5 is the model

Fig. 8 **a** Stress–strain in monotonic failure triaxial test, **b** Mohr–Coulomb failure criterion for G1 at 100% MPDD and moderate MC



parameters, where $k_1 = 0.368$ (–), $k_2 = -120.927$ (kPa), $k_3 = 43.898$ (kPa), $k_4 = -0.072$ (–), and $k_5 = 0.144$ (mm).

The stress dependent equivalent modulus of the RL-CBR test specimen as a bulk is estimated based on the elastic modulus of the finite element analysis given in Eq. 6. That is the equivalent modulus is expressed as a function of the vertical stress, lateral stress, Poisson's ratio and plunger vertical deformation. This expression is analogous with the resilient modulus of cyclic load triaxial test models such as the M_r – Θ model. In the next section the RL-CBR equivalent modulus will be compared and validated with triaxial test results of the G1 base material.

4 Results and discussion

4.1 Triaxial test results

4.1.1 Monotonic failure triaxial test results

Monotonic failure (MF) triaxial tests were performed on the G1 base materials at various compaction levels with three different confining pressures each. The results of the MF tests were described by the well-known Mohr–Coulomb failure criterion and plotted on a shear–normal stress (τ – σ_n) diagram as shown in Fig. 8. The failure behavior of the unbound base material is characterized in terms of the cohesion (c) and the angle of internal friction (ϕ). In Fig. 9 the results of 12 MF triaxial tests of the G1 base material at 4 MPDD with 3 confining pressure each all prepared at a moderate moisture content of 4% are presented. The effect of increasing compaction level is illustrated with an increase both the angle of friction and the cohesion except for the cohesion at 105% MPDD.

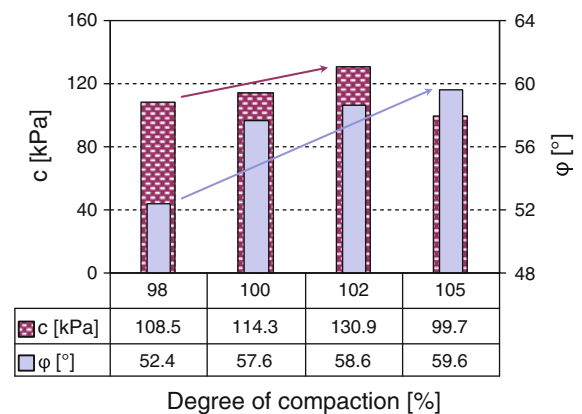


Fig. 9 c and ϕ values for G1 at various MPDD and moderate MC

4.1.2 Cyclic load triaxial test results

Similar to the MF triaxial test the resilient modulus cyclic load triaxial test is also carried out for the G1 base material at different mix and compaction condition that ranges from 98 to 105% MPDD. However, the RL-CBR with strain gauge for G1 is carried out at 100% MPDD with moderate moisture content. Therefore the result of the resilient modulus cyclic load triaxial test at 100% MPDD with moderate moisture content will be relevant in this paper.

The cyclic load triaxial compression test is currently the most commonly used method to measure the resilient (elastic) deformation characteristics of aggregates for use in pavement design [18]. For a cylindrical axial symmetrical triaxial specimen the lateral confining stress, σ_3 , and strain, ϵ_3 , are minor principal stress and strain; and the vertical axial stress, σ_1 , and strain, ϵ_1 , are the major principal stress and strain. For a CCP resilient deformation test, at any applied stress

combination σ_3 is constant and thus $\Delta\sigma_3 = 0$ and from Hook’s law elastic theory the resilient modulus M_r is expressed as Eq. 7 and computed from the measured stress and strains in the cyclic load triaxial test.

$$M_r = \frac{\Delta\sigma_1}{\Delta\varepsilon_{1r}} \tag{7}$$

The stress dependency of the resilient modulus was analyzed using the common isotropic non-linear M_r – Θ model, Eq. 8, for the purpose of comparing with the result of the RL-CBR tests with strain gauge. A plot of the measured M_r values against Θ , the sum of principal stresses, for the G1 base material at 100% DOC and moderate 4% MC is shown in Fig. 10. In this plot also the M_r – Θ model fit is given. In the figure increase in M_r at increasing Θ is observed for all σ_3 . At the σ_3 -level of 80 kPa increase in deviatoric stress, σ_d , an

increase in M_r —values at first and then stabilizes when the σ_d/σ_3 —ratio is getting higher.

$$M_r = k_1\theta^{k_2} \tag{8}$$

4.2 RL-CBR test results

To obtain an equivalent modulus from a RL-CBR test according to Eq. 6, three parameters are measured during the testing, shown in Fig. 11, the plunger load (average plunger stress σ_p), the vertical plunger deformation u_v and the lateral strain at the mid-height of mould exterior ε_{hm} . For the South African G1 base material the RL-CBR test with strain gauge is carried out for more than 20 different plunger load levels. The equivalent modulus is computed using average deviator values of σ_p , u_v and ε_{hm} between the maximum of loading and minimum of unloading of the last five cycles of the 100 load repetition in the Eqs. 3–6. The equivalent modulus is plotted in Fig. 12 against the sum of the principal stresses, $\Theta = \sigma_v + 2\sigma_h$, where the vertical σ_v and horizontal σ_h stresses in this case are in the absolute values of the stress state of a specimen under testing.

The stress dependent equivalent modulus, E_{equ} , for the G1 base material is presented in Fig. 12 along with the cyclic load triaxial resilient modulus test result from Fig. 10 as a function of Θ . It is observed that the RL-CBR test is more scattered and yield higher modulus values at higher stress levels than is achieved in the triaxial stress condition. The obtained equivalent modulus values, however, are under-predicted compared with those measured in the triaxial test. This

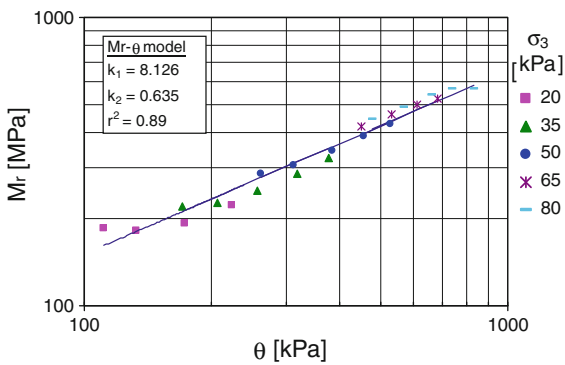
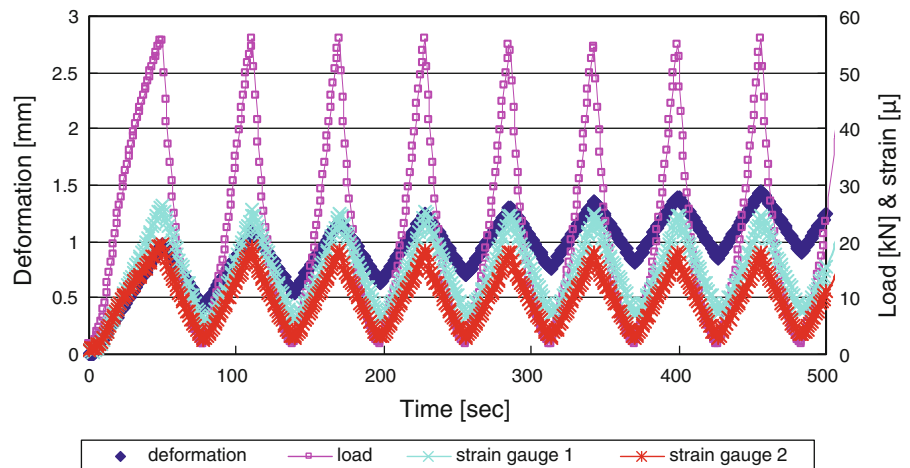


Fig. 10 M_r – Θ plot (data and model) for South African G1 base material at 100% MPDD and moderate MC

Fig. 11 RL-CBR measurements at particular test plunger load 55 kN



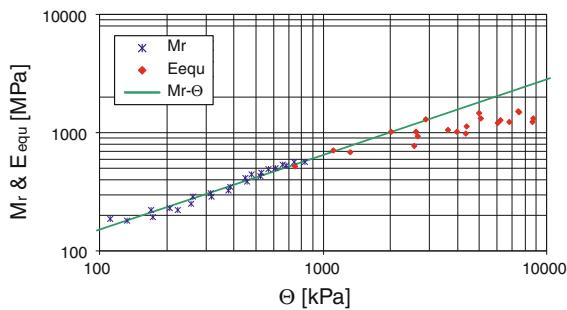


Fig. 12 Triaxial M_r and RL-CBR E_{equ} as a function of Θ

is due to the fact that most of the RL-CBR tests are carried out with very large plunger loads to show the stress dependency.

However, disregarding the M_r - Θ line, simple observation of the two (resilient and equivalent) moduli shows that the equivalent modulus perfectly follows the trend of the triaxial modulus which is becoming constant at its highest stress levels. Also, a bit of permanent deformation was observed during the 100 load cycles of the test at these high stress levels, indicating that the material is stressed beyond its elastic range. Moreover, the very slow rate of load application in the RL-CBR testing, compared to the 1 Hz cyclic triaxial load, might have an effect on the secant modulus obtained as an equivalent modulus. Further despite the use of larger mould and bigger plunger the granular arrangement or grain pattern in specimen preparation of the coarse granular material has an influence on the result of the RL-CBR test.

5 Conclusions

This paper presents information valuable to introduce mechanistic-empirical design procedures for pavements in developing countries. It discusses the characterization of the mechanical properties, failure and resilient modulus, of a high quality crushed stone base material as obtained by means of monotonic and cyclic load triaxial testing. The effect of compaction degree has been well illustrated by MF triaxial testing.

The usefulness and characterization techniques of an intermediate testing—the RL-CBR (less fundamental but better than the index tests) is demonstrated for approximation of mechanical behavior of UGMs employed in developing countries. It was shown that a good estimate of the stress dependent equivalent

modulus of the G1 base granular can be obtained with the RL-CBR with strain gauge testing.

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