A Realistic Method of Characterizing Granular Materials for Low-Cost Road Pavements

A. Araya, A. Molenaar & L. Houben
Road and Railway Engineering Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherland

ABSTRACT: Cyclic load triaxial testing is becoming nowadays a more accepted test method for mechanical behavior of unbound granular materials. This testing method is, however, not readily available and not an easy test to be done especially in developing countries for design of low-cost roads that for their bearing capacity heavily rely on granular base and subbase layers. Even in developed countries triaxial tests are mainly used for research and academic purposes. On the other hand, the characterization of the unbound granular base and subbase materials in low-cost roads is still done using empirical methods such as California Bearing Ratio (CBR). A more realistic and relatively simple testing technique is developed, based on the widely practiced CBR test, to characterize the mechanical behaviors of granular materials for low-cost pavements. The repeated load CBR test provides a realistic estimate of the stress dependent resilient modulus of unbound granular materials, which can be used for mechanistic design analysis of low-cost pavements. Furthermore, the effect of degree of compaction and moisture content on the resilient modulus and permanent deformation is investigated for different unbound granular materials, ranging from the high quality crushed rock (G1) base material from South Africa to rather marginal materials such as Ferricrete from South Africa and weathered basalt from Ethiopia.

KEY WORDS: Granular materials, repeated load CBR, triaxial, low-cost pavements.

1 INTRODUCTION

Most road pavements in developing countries and rural roads in the developed world are unpaved low-cost roads or paved with thin asphalt surface. The base and subbase layers are the main load bearing structures in such pavements. Those layers are mostly built from locally available natural granular materials and crushed rocks. Proper utilization and characterization of these materials results in developing sustainable and economical low-volume road pavements.

Historically, flexible pavement design practices were typically based on empirical procedures, which recommend certain base, subbase and surface layer types and their thicknesses based on the strength of the subgrade. The often-used soil strength parameters in these empirical pavement design practices are California Bearing Ratio (CBR), Hveem R-value and Soil Support Value (SSV). All these soil parameters are based on failure of subgrade soil specimens in laboratory conditions (Huang 1993, NCHRP 2008). Most flexible pavements, however, fail owing to either excessive rutting or cracking of pavement layers as a result of fatigue, temperature and moisture changes and/or softening caused by the surface layer cracking (Barksdale 1972, Brown 1974). Because flexible pavements do not fail as a result of soil strength failure, the 1986 AASHTO and subsequently the 1993 AASHTO Pavement design guide recommended the use of a soil parameter known as Resilient Modulus (M_R) to replace strength based parameters such as CBR and SSV (Brickman 1989). Several other investigations also refer to this modulus parameter as M_R in their studies.

The main reason for using the resilient modulus or stiffness as the parameter for subgrade, subbase and bases is that it represents a basic material property and can be used in mechanistic analyses for predicting different distresses such as rutting and roughness. The major drawback of empirical based design of pavements and characterization of materials is that the performance of the materials under different or changing conditions (climate, increasing traffic loads, tire pressures, etc) and applications (other type of pavement structures) is uncertain. Furthermore the advantage of using such mechanical properties of materials enables to introduce alternative or marginal but possibly suitable materials and use to their fullest extent, which in itself will play a significant role in optimizing the use and conservation of natural resources.

The method of characterizing the mechanical behavior of unbound granular materials such as the resilient modulus, however, is commonly done using cyclic load triaxial tests which are considered to be advanced and costly to implement in routine road construction projects particularly in developing countries. The repeated load CBR test is therefore introduced to provide a more practical and simpler method for characterization of unbound materials. The following sections describe the principle of the test, the materials and methodologies used as well how the test technique is effective in determining the effect of moisture content, degree of compaction and load level on the resilient and permanent deformation characteristics of unbound granular materials.

2 MATERIALS

The materials used in the study range from a very good quality Grade 1 (G1) crushed Hornfels rock base course material of South Africa to a recycled mix granulate of the Netherlands. This paper however will deal mainly about three of the materials i.e. crushed rock (G1) base material from South Africa, weather basalt (WB) natural gravel subbase material from Ethiopia and ferricrete (FC) natural gravel subbase material from South Africa.

The materials were first examined for their gradation (Figure 1) and their basic physical properties such as modified Proctor density, apparent (pycnometer) density, their soaked and unsoaked CBR strength etc. The modified Proctor dry density (MPDD) vs. moisture content curve and the standard CBR for unsoaked and soaked samples for these materials are shown in Figure 2. The CBR values for the crushed stone G1 material are extremely high in a range of 350 - 450% at the moderate moisture content of 4%. As a reference the modified Proctor dry density at their respective moderate moisture content is chosen to be 1950 kg/m^3 at 7% moisture content (MC) for the WB, 2173 kg/m^3 at 7.5% MC for the FC and 2293 kg/m^3 at 4% MC for the G1. These dry densities are considered to be 100% degree of compaction (DOC) and are taken as reference for the variation of DOC of each material.

3 TEST SETUP AND METHODS

Specimens are prepared for both the repeated load CBR (RL CBR) and triaxial testing in a similar way using a vibratory compaction hammer which better simulates the vibration compaction in the field. For both tests the granular materials at required grading were obtained by recombination of various fractions of sieved materials to the grading shown in Figure 1. The required quantity of water to bring the material to the required level of moisture content were added and mixed using a mechanical mixer. Having obtained the sample material at the target moisture content, the RL CBR specimens were compacted in three layers in a 250 mm dia. 200 mm height mould, whereas the triaxial specimens were compacted in four layers in a 300 mm dia. 600 mm height split mould. For each layer the exact amount of material is weighed to obtain the target degree of compaction (measured in terms of modified Proctor dry density, % MPDD) after compaction. The material of the first layer is pre-compacted by hand tamping then by means of the vibratory compactor to the required density until the target layer thickness is achieved. The same procedure is followed for the subsequent layers. The surface of each layer was mechanically scarified before adding the next layer on top to obtain a good layer interlock and a homogeneous sample.

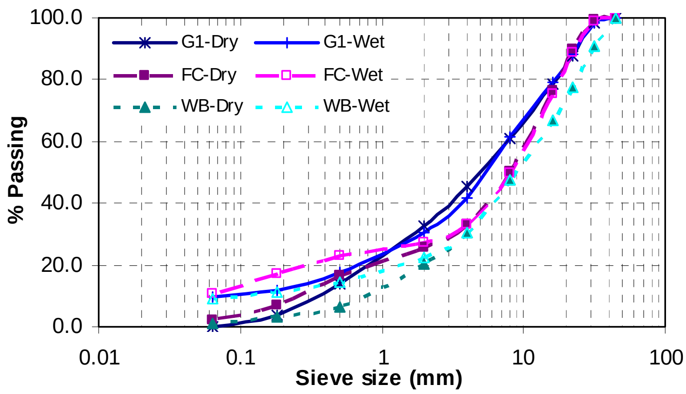

Figure 1: Dry & wet sieving particle size distribution of the three materials.

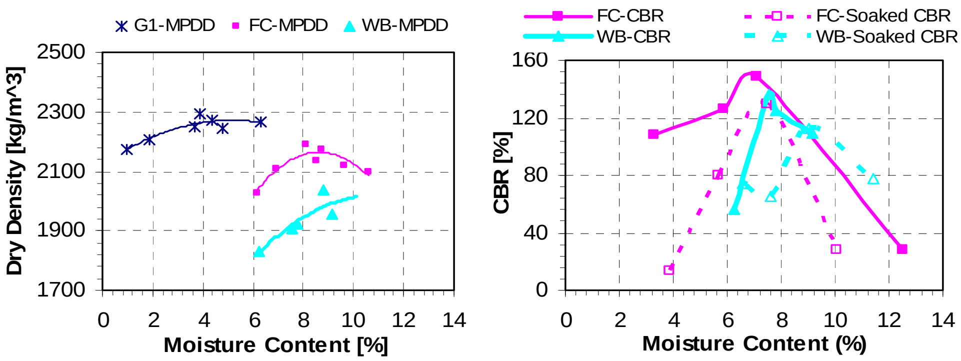

Figure 2: Modified Proctor dry density and CBR vs. moisture content.

3.1 The Repeated Load CBR (RL CBR) Test

As shown in Figure 1 the grading of all the materials used in this project is 0/45 mm. For such coarse granular material the standard 150 mm dia. mould is not suitable unless the material is downgraded. To avoid downgrading of the material, which completely changes the gradation of the material commonly used in the field, a bigger mould 250 mm (10 inch.) diameter and 200 mm height is adopted for all the repeated load CBR tests in this project. Proportionally a bigger penetration plunger of 81.5 mm dia. is used instead of the standard 49.64 mm dia. plunger.

To apply the test method in a standard CBR test machine in routine road project tests the standard CBR loading rate i.e. 1.27 mm/min is adopted for both loading and unloading and the following procedure is used:

- The specimen is loaded, at the standard CBR test rate (1.27 mm/min), to a predetermined load level or deformation (for e.g. 2.54 mm). The load is recorded and unloaded to a minimum contact load of 0.1 to 0.3 MPa.
- The specimen is re-loaded to the same load at the same rate of loading 1.27 mm/min, and released once more to the minimum contact load. The load level for each cycle is therefore kept constant.
- These cycles are repeated for about 60 – 100 load cycles at which the permanent deformation due to the last 5 loading cycles will be less than 2% of the total permanent deformation at that point. The elastic and plastic deformation is measured as shown in Figure 3.

The test loading system is equipped with an actuator (MTS controller) so that the increase and decrease of load and development of deformation can be monitored along with a work station for storing and retrieving the test data.

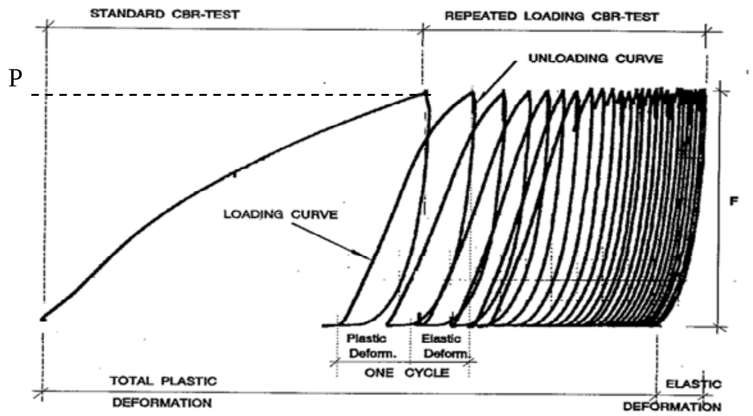

Figure 3: Repeated load CBR test principle.

The equivalent modulus E_{equ} is computed from the stabilized elastic deformation after 100 cycles. The term equivalent modulus is used because it reflects the overall stiffness of the sample as a bulk rather than the resilient modulus of the material. A Finite Element analysis is carried out on a model of the CBR mould with ABAQUS assuming linear elastic behavior of the granular material. A wide range of material stiffness 100 – 1000 MPa and Poisson's ratio 0.15 - 0.45 was used for the granular material with different deformation and force levels in a total analysis of 240 combinations. From these analyses equation 1 has been developed that relates the elastic modulus of the material tested (referred as equivalent modulus of the whole sample) and the load and elastic deformation that were measured from the RL CBR tests.

$$E_{equ} = \frac{1.513(1-\upsilon^{1.104})\sigma_p \cdot a}{u^{1.012}} \tag{1}$$

Where:	E_{equ}	= Equivalent modulus	[MPa]
	ν	= Poisson's ratio	[-]
	σ_p	= Plunger average stress	[MPa]
	u	= elastic deformation	[mm]
	a	= radius of the load circle/the plunger = 81.5	[mm]

When using this equation one has to make an estimate for the Poisson's ratio ν. Normally a value between 0.35 and 0.45 is taken. The choice depends on the type of material (fine grained soil or granular) and moisture conditions (Molenaar 2008). Equation 1 is an improved version of a similar equation developed by Opyio (1995) with less model parameter by replacing the two extreme conditions of full friction and full slip with a better contact behavior between the granular material and the mould.

3.2 Resilient Deformation Triaxial (RDT) Test

Similar to the RL CBR test a large scale triaxial setup with a diameter of 300 mm and a height of 600 mm was used in the study for testing the full 0/45 mm coarse materials. The triaxial apparatus is equipped with a hydraulic loading system actuator and MTS controller capable of cycling the axial stress and with a constant confining vacuum pressure (CCP). The loading signals used are a haversine at a loading frequency of 10 Hz for the first 20,000 load cycles of conditioning phase and 1 Hz for the series of short loadings 100 cycles each. The stress range used is a ratio of axial stress to their respective failure axial stress, $\sigma_1/\sigma_{1,f} = 0.05$ to 0.6 for all the materials. The objective of the cyclic conditioning is to stabilize the permanent strains of the material and attain a practically elastic behavior. Generally the conditioning is performed with a stress level corresponding to the maximum stresses applied in the test. The triaxial cell is equipped with transducers measuring the axial and radial strains on the middle third of the specimen, see Figure 4. The resilient modulus is then expressed as:

$$M_r = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \tag{2}$$

Both the RL CBR and RDT testing were carried out for the three materials WB, FC and G1 in a similar way with varying the moisture content (MC) and degree of compaction (DOC as % MPDD) conditions.

Figure 4: RL CBR specimen during compaction (left), RL CBR during testing (middle) and instrumented triaxial specimen ready for testing (right)

4 RESULTS AND DISCUSSION

4.1 Repeated Load CBR (RL CBR)

Most of the RL CBR specimens are tested first at a load level, P, which results in a 2.54 mm (0.1 in) penetration from the first loading cycle similar to the standard CBR and repeated the loading cycles with the same load. However as granular materials are known for their stress dependent behavior, the tests at various material conditions are carried out with different load levels on a virgin specimen. Figure 6 shows the resilient deformation of six Ethiopian weathered basalt (WB) specimens with varying material condition and tested at two load levels, 32 kN for varying the DOC and 15 kN for varying the MC. The resilient deformation decreases for the WB with moderate MC and increase of the DOC at the same load level, 32 kN. At 95% DOC and 15 kN load the resilient deformation increases with the increase of the MC.

To obtain stress dependent behavior from the RL CBR, large numbers of tests have been carried out at various plunger load levels. The equivalent modulus is estimated using equation 1 developed by the author from finite element modeling of the RL CBR. Figure 7 shows stress dependent equivalent modulus of the three materials analyzed using a Poisson's ratio of 0.35. It is to be noticed that the RL CBR equivalent modulus is stress dependent and generally the stiffness of the WB and G1 increases with an increase in DOC and decrease in MC. However for the FC it is with more scatter and relatively sensitive when compacted in outer ranges of the MC and DOC. The equivalent modulus of the ferricrete is relatively higher at the moderate MC than wet as well as dry, and it shows better performance at 98% DOC than 95% and 100%. Over compaction, 100% DOC, of the FC shows poor performance in the RL CBR as a result of crushing of aggregates during compaction and weakening the material.

In the results presented here for each individual loading, the value of the resilient strain and stress are the average of the last ten load cycles. The values of Mr are not generally very sensitive to MC and DOC except for the ferricrete where it is sensitive with both the MC and DOC. When we compare per material the Mr values, the range is 100 – 500 MPa for the WB and FC and 100 – 650 MPa for the G1.

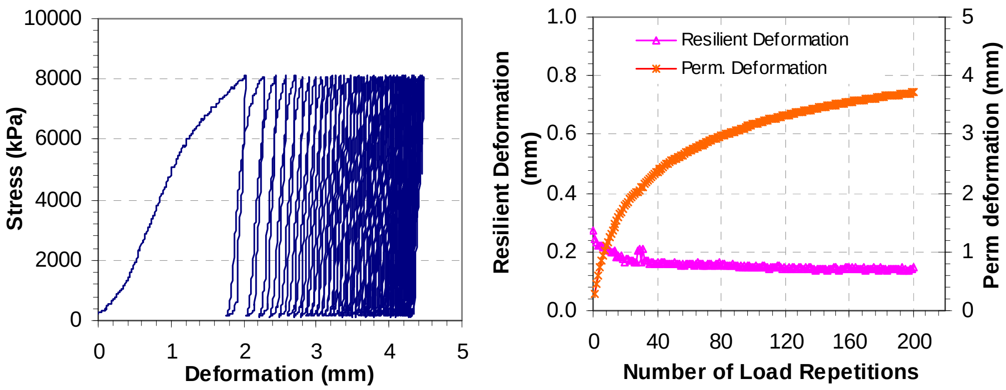

Figure 5: Measured stress-deformation pattern and deformations in a typical RL-CBR test

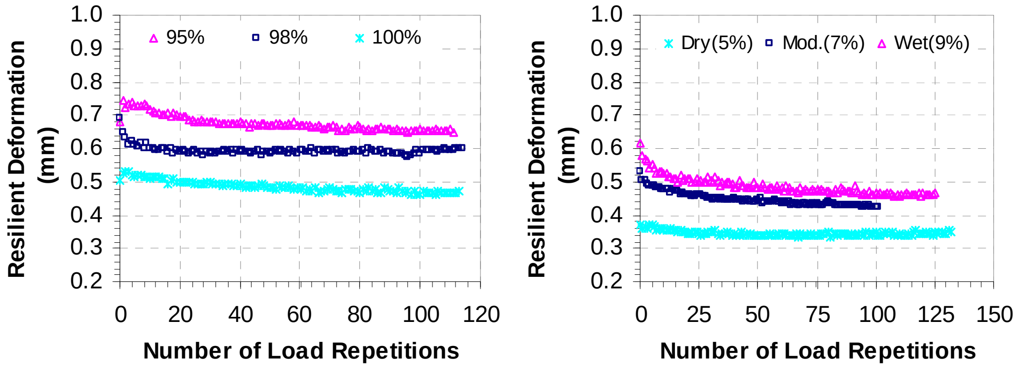

Figure 6: Effect of DOC at moderate MC and effect of MC at 95% DOC for WB material

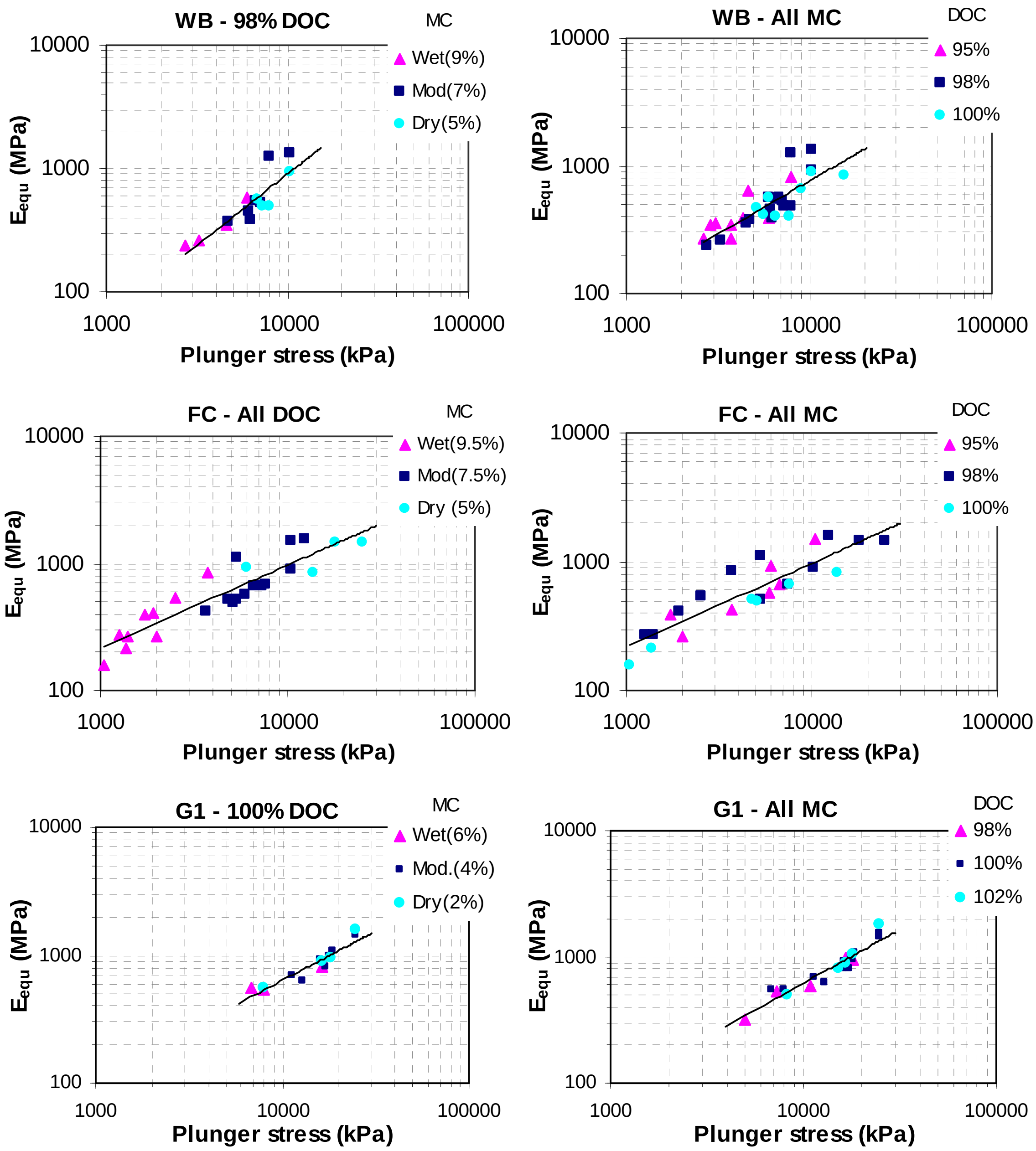

Figure 7: Stress dependent equivalent modulus for the three materials at various MC & DOC

4.2 Resilient Deformation Triaxial (RDT)

The resilient modulus triaxial testing has been carried out for the three materials at varying mixture and compaction condition. The stress dependency of the resilient modulus was analyzed using different models, however for comparison with the result of the RL CBR tests the simple and well known isotropic non-linear $M_r - \theta$ model is presented in Figure 8.

$$M_r = k_1\theta^{k2} \qquad (3)$$

Where:
- M_r = resilient modulus [MPa]
- θ = sum of principal stresses ($\sigma_1+\sigma_2+\sigma_3$) [kPa]
- k_1 & k_2 = model parameters

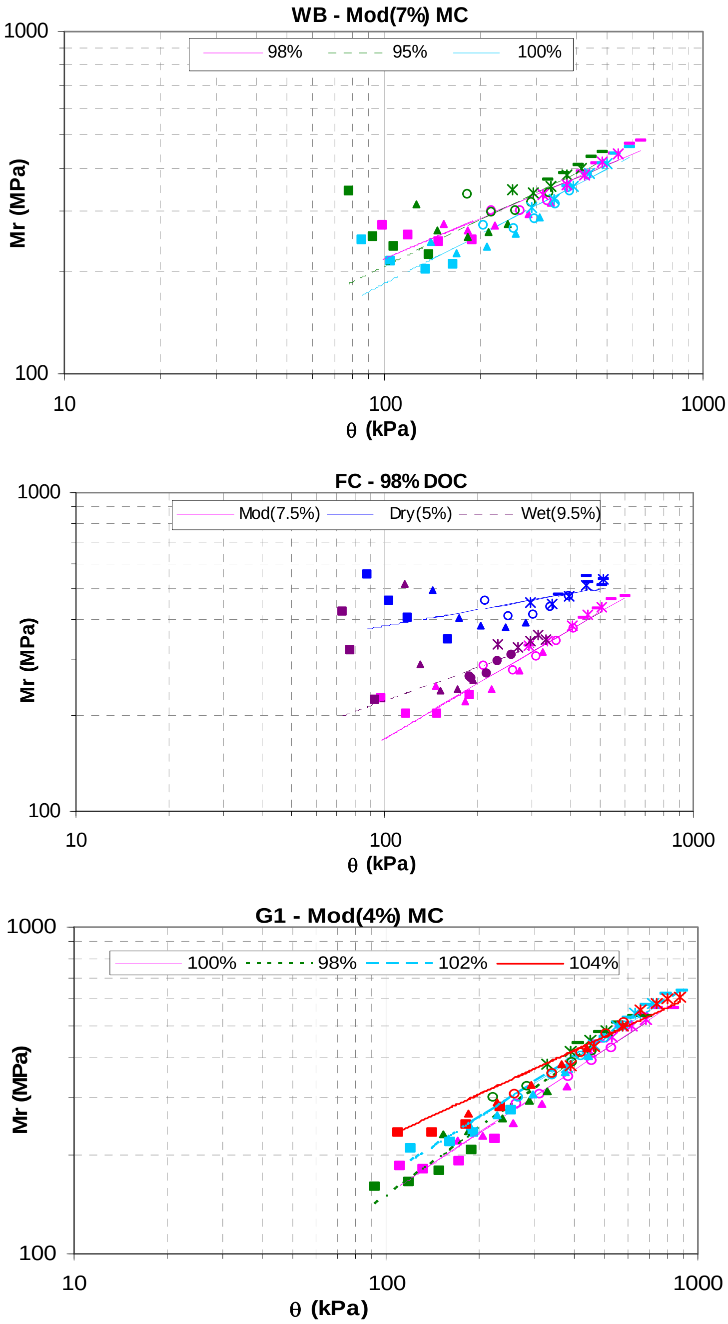

Figure 8: Examples of resilient modulus behavior; variation of M_r with bulk stress θ, DOC and MC.

5 CORRELATING RL CBR EQUIVALENT MODULUS WITH TRIAXIAL RESILIENT MODULUS

The equivalent modulus obtained from the RL CBR test can't be used directly for analysis and design of pavements as the test load level and the stresses in the specimen are quite high compared to the triaxial test loadings and practical traffic loading. Figure 9 shows the trend how the modulus varies with their respective stress levels (bulk stress for the triaxial and plunger stress for the RL CBR) for a typical example. Thus to use the output of the RL CBR test for pavement analysis and design a correlation to the triaxial test results of the same material and test condition is necessary. Araya et. al. (2009) has made a correlation between the results of the two test techniques for a single material. Here similar approach is used for all the materials by finding a corrected or reduced plunger stress to get a modulus that is comparable to the triaxial test result and that can be used for lost-cost pavement design and analysis.

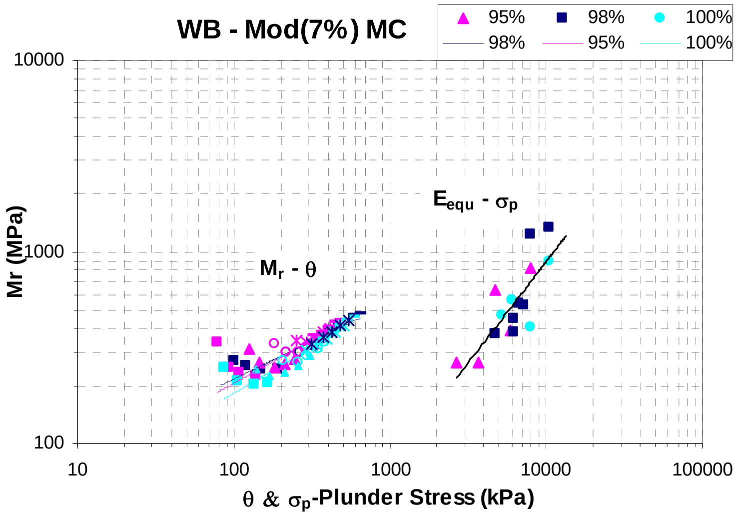

Figure 9: Comparison of resilient modulus vs. equivalent modulus typical example

For $E_{equ} \cong M_r$ from equations (1) and (3):

$$\frac{1.513(1-\nu^{1.104})\cdot\sigma_p\cdot a}{u^{1.012}} = k_1\theta^{k_2} \qquad \text{for } \nu = 0.35 \qquad \sigma_p = \frac{u^{1.012}\cdot k_1\theta^{k_2}}{42.312} \tag{4}$$

The corrected plunger stresses were computed for different triaxial bulk stress levels, θ, 100 – 800 kPa, and the effect of DOC and MC were better expressed by void ratio (e) and degree of saturation (S) as the relative particle densities are known for the three materials from Pycnometer measurements. Using a non linear multidimensional least square regression technique, equation 5 was developed for estimation of the corrected plunger stress for the three materials. The regression analysis was done for each of the three materials individually and for all the materials as a whole to obtain a general representative equation. However the correlation of the regression fit for the general one is smaller as shown in table 1.

$$Log(\sigma_p) = a_1 + a_2S + a_3e + a_4Log(\theta) \tag{5}$$

Where σ_p = corrected plunger stress [MPa]
S = degree of saturation [-]
e = void ratio [-]
θ = bulk stress ($\sigma_1+\sigma_2+\sigma_3$) [kPa]
a_1 to a_4 = model parameters [-]

In practice to get an equivalent modulus comparable to the triaxial resilient modulus one can conduct a RL CBR test at different load levels and carrying out a pavement analysis for an assumed modulus to estimate the stress level in different layers. The corrected equivalent modulus, comparable to the triaxial resilient modulus, can then be estimated in an iterative way from RL CBR test.

Table 1: Model parameters for equation 5

Material	a_1	a_2	a_3	a_4	R^2	No. data
G1	-1.069	0.072	1.030	0.641	0.962	64
FC	1.504	-1.860	-2.150	0.375	0.706	90
WB	-0.241	0.025	-1.101	0.469	0.634	130
All material	0.164	-0.668	-1.317	0.479	0.681	284

6 CONCLUSIONS

- The RL CBR test is a realistic and affordable technique and gives a reasonably good estimate of the resilient modulus, when large scale triaxial testing for coarse granular materials is too complex to be used in low-cost road pavements.
- The resilient modulus measured from both the RL CBR and triaxial testing for all the three different materials gives almost in the same range, where as the CBR values are much higher for G1 similar to the actual superior behavior of the G1 material in practice. This is due to the fact that CBR measures resistance to penetration (i.e. related to permanent deformation) but it is not a suitable indicator of stiffness behavior.
- The RL CBR test is a useful technique to evaluate the effect of moisture, compaction and stress level on the modulus; however some materials such as the FC and WB are not always consistent to such conditions.

REFERENCES

Araya, A.A., Molenaar, A., and Houben, L., 2009. *Characterization of Unbound Granular Materials Using Repeated Load CBR and Triaxial Testing*. Accepted for publication in the proceedings of GeoShanghai International Conference 2010, Shanghai, China. June 3 -5, 2010.

Barksdale, R.D., 1972. *Laboratory Evaluation of Rutting in Base Course Materials*. Proc., 3rd International Conference on Asphalt Pavements, University of Michigan, Ann Arbor, pp. 161-174.

Brickman, A., 1989. *An Overview of Resilient Modulus Test Systems*. Workshop on Resilient Modulus, Corvallis, Ore.

Brown, S.F., 1974. *Repeated Load Testing of a Granular Material*. Journal of the Geotechnical Engineering Division, Vol. 100, No. 7, pp. 825-841.

Huang, Y.H., 1993. *Pavement Analysis and Design*. Prentice Hall, Inc., Englewood Cliffs, N.J.

Molenaar, A.A.A., 2008. *Repeated Load CBR Testing, A Simple but Effective Tool for the Characterization of Fine Soils and Unbound Materials*. Transportation Research Board, TRB 2008 Annual Meeting CD-ROM. No. 08-0516, Washington DC.

NCHRP, 2008. *Estimating Stiffness of Subgrade and Unbound Materials for Pavement Design*. NCHRP Synthesis 382, Transportation Research Board, National Research Council, Washington, D.C.

Opiyo, T.O., 1995. *A Mechanistic Approach to Lateritic-based Pavements*. MSc. thesis IP 047, International Institute for Infrastructure, Hydraulic and Environment Engineering (IHE), Delft, Netherlands