REPEATED LOAD CBR TESTING A SIMPLE BUT EFFECTIVE TOOL FOR CHARACTERISING SOILS AND UNBOUND GRANULAR MATERIALS

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Abstract

Proper characterization of unbound granular materials and soils is particularly important for the design of pavements with thin asphalt layers since the bearing capacity of those pavements heavily relies on the quality of the granular base and subbase layers. Cyclic load triaxial testing is nowadays the most favoured test method for the characterization of the mechanical behavior of unbound granular materials and soils. This testing method is, however, not readily available and not an easy test to be done especially in developing countries. Even in developed countries, triaxial tests are mainly used for research and academic purposes. On the other hand, characterization of the unbound granular base and subbase materials is still mainly done using empirical methods such as California Bearing Ratio (CBR).

In this paper a more realistic and relatively simple testing technique is presented, which is based on the widely practiced CBR test. The repeated load CBR test provides a realistic estimate of the stress dependent resilient modulus of unbound granular materials and soils, which can be used for mechanistic design analysis of pavements in which the bearing capacity is mainly determined by the granular layers and subgrade soil. Furthermore, the effect of degree of compaction and moisture content on the resilient modulus and permanent deformation is investigated. Different soils and unbound granular materials are tested, ranging from sand and expansive clay to high quality crushed rock (G1) base material from South Africa and rather marginal materials such as Ferricrete from South Africa and weathered basalt from Ethiopia.

Relationships between the results of repeated load CBR tests and those obtained by means of cyclic load triaxial tests are presented.

It has to be mentioned that a major part of the paper was already presented at the 2010 ISAP conference in Nagoya. This paper however contains information on the use of the repeated load CBR test which was not presented at the Nagoya conference. Furthermore it is believed that this paper contains important information for the African region since extensive testing was performed on materials coming from this continent. Therefore it was decided to offer this paper as well to the CAPSA conference.

1 INTRODUCTION

Many road pavements all over the world and especially in developing countries are roads made of granular materials with only a 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 as well as of the subgrade soils is essential in order to be able to build sustainable and economical road pavements.

Historically, flexible pavement design practices are 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 the 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 result of fatigue, temperature and moisture changes and/or softening caused by the surface layer cracking (Barksdale 1972, Brown 1974). In the 1986 AASHTO and subsequently the 1993 AASHTO Pavement design guide the use of a soil parameter known as Resilient Modulus (M_R) is recommended rather than strength based parameters such as CBR and SSV (Brickman

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 which 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 material performance 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 is that it enables the designer to introduce alternative or marginal but possibly suitable materials and use them to their fullest extent in pavement structures, 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 too advanced and costly to be implemented in routine road construction projects particularly in developing countries but also in many developed countries. The repeated load CBR test is therefore introduced to provide a more practical and simpler method for the characterization of unbound materials and soils. 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 sand and an expansive clay to very good quality Grade 1 (G1) crushed Hornfels rock base course material of South Africa, a weathered basalt (WB) natural gravel subbase material from Ethiopia and ferricrete (FC) natural gravel subbase material from South Africa. A short description of the materials will be given hereafter.

2.1 Sand

The sand that was tested in this research is typical for the types of sand used for hydraulic fills in the Netherlands. Because of the very weak subsoil, significant sand fills have to be made in the western part of the country for the construction of the major road network. This implies that this sand fill is taken as the subgrade in pavement design analyses. Figure 1 shows the gradation of the sand that was tested, while Figure 2 shows the moisture – density – CBR relationship.

2.2 Expansive clay

The expansive clay that was tested in this research program was so called “Black Cotton” clay from Ethiopia. The gradation of this A-7-5 clay is shown in figure 3. The material has a swell potential of 24% a liquid limit of 99% and a plasticity index of 54%. Figure 4 shows the moisture – density – CBR relationship. The figure clearly shows that this material has a very low bearing capacity when wet.

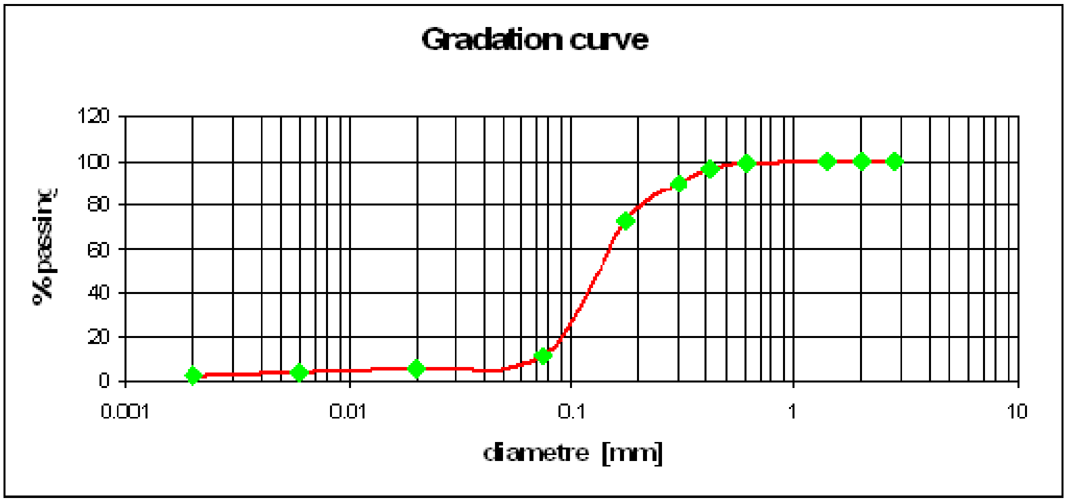

Figure 1. Gradation of the tested sand.

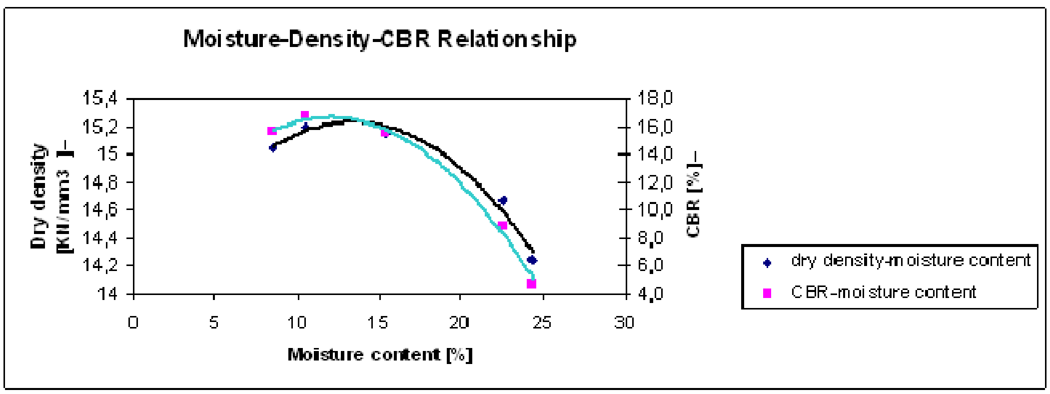

Figure 2: Moisture – density – CBR relationship for the tested sand.

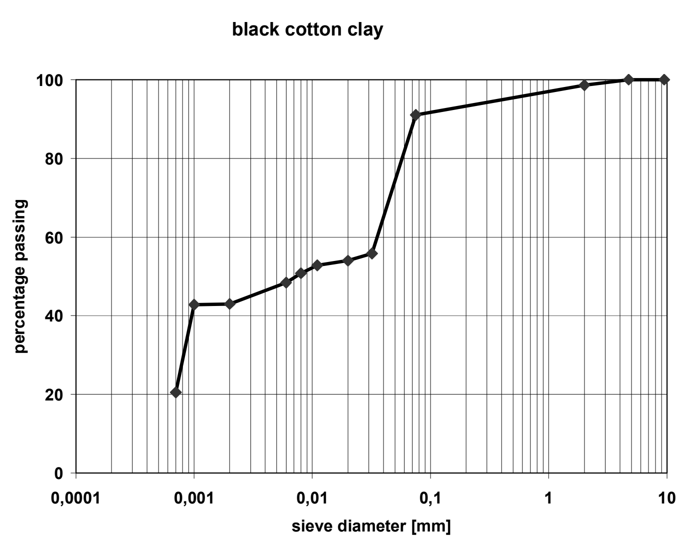

Figure 3. Gradation of the black cotton clay.

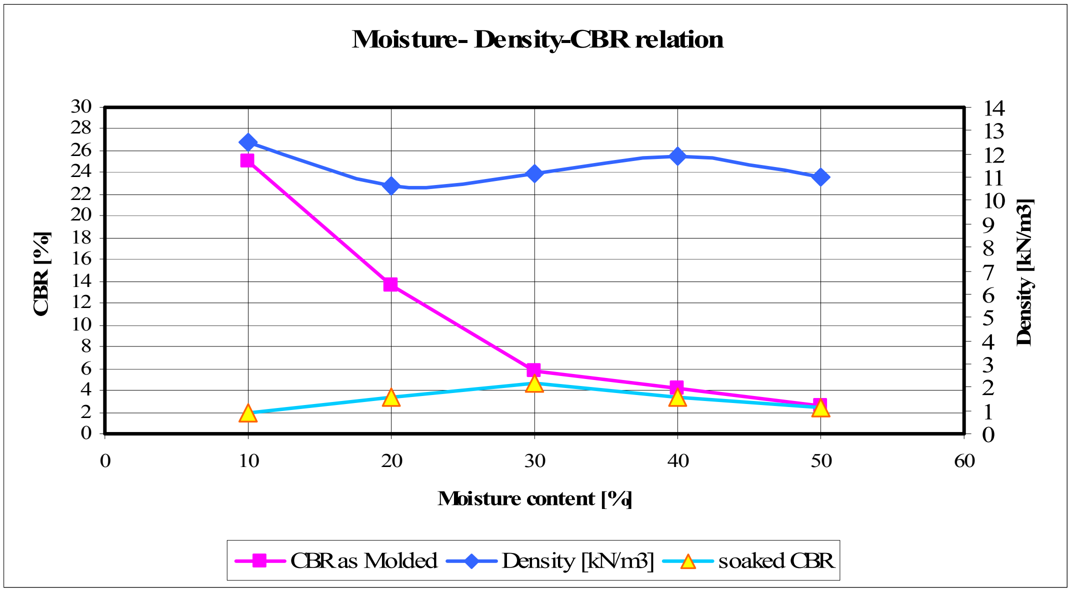

Figure 4. Moisture – density – CBR relationship for black cotton clay.

2.2 Granular materials

The granular materials used in the study were a very good quality Grade 1 (G1) crushed Hornfels rock base course material of South Africa, a ferricrete (FC) natural gravel subbase material from South Africa and a weathered basalt (WB) being a natural gravel subbase material coming from Ethiopia

The materials were first examined for their gradation (Figure 5) 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 6. 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%. The modified Proctor dry density at their respective moderate moisture content is 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 REPEATED LOAD CBR TEST

The repeated load CBR test can be performed in two ways. For fine grained materials like the sand and the expansive clay that were tested in this research project, the standard CBR equipment can be used. Samples are compacted in the usual way and the following test sequence is applied.

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:

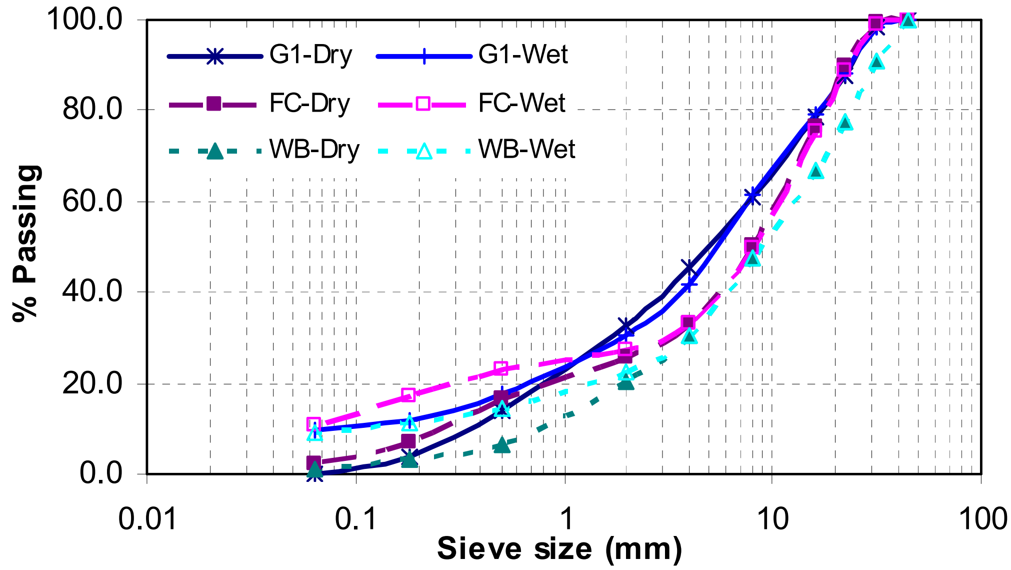

Figure 5. Gradation curves of the tested granular base and subbase materials.

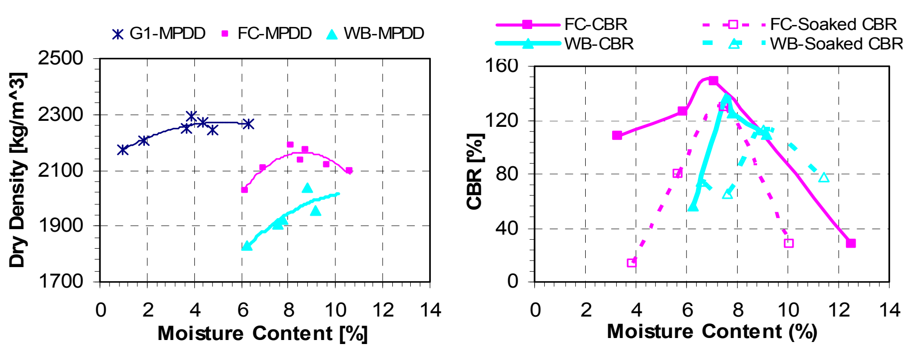

Figure 6. Moisture – density – CBR relationships for the tested granular base and subbase materials.

- The specimen is loaded, at the standard CBR test rate (1.27 mm/min), to a predetermined load or deformation level (for e.g. 2.54 mm). The load is recorded and the specimen is 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 7.

Another way of doing the repeated load CBR test is by doing the test at different load levels. In this way the stress dependency of the material can be determined. This will be described in greater detail later on in this paper.

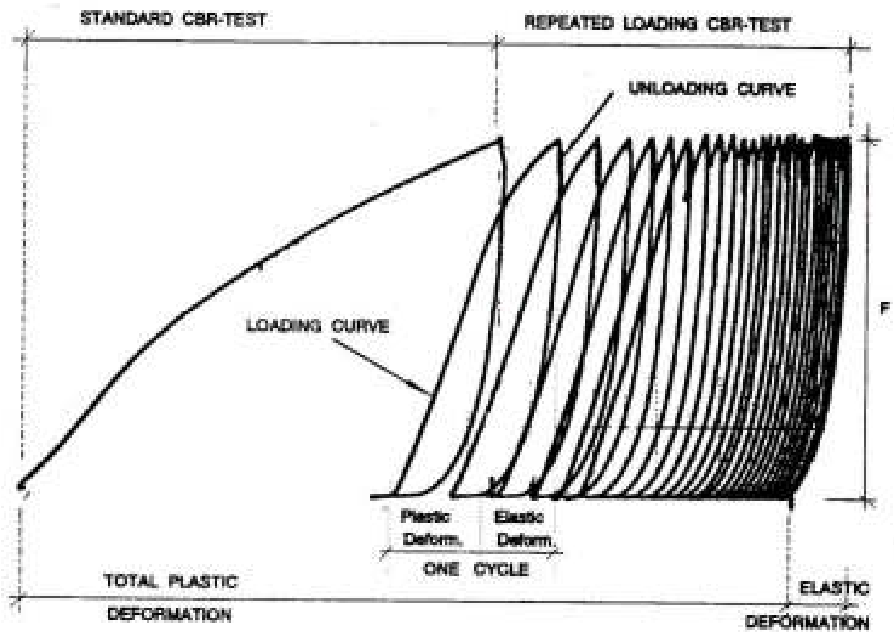

Figure 7. Example of the load – displacement curves obtained during a repeated load CBR test.

As shown in Figure 5 the grading of all the coarse grained 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. This mould size is selected because it is specified in the European specifications for use in compaction tests. Proportionally a bigger penetration plunger of 81.5 mm dia. is used instead of the standard 49.64 mm dia. plunger.

4 CALCULATION OF THE EQUIVALENT ELASTIC MODULUS

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 total 240 combinations were analyzed. 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.

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

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

When using this equation one has to make an estimate for the Poisson's ratio υ. 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) by replacing the two extreme conditions of full friction and full slip as used by him with a better contact behavior between the granular material and the mould.

5 RESILIENT DEFORMATION TRIAXIAL (RDT) TESTS

Cyclic load triaxial tests were performed on both the fine grained as well as the coarse grained materials. For the fine grained materials samples with a diameter of 100 mm and a height of 200 mm were tested. A large scale triaxial setup with specimens having 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. Both triaxial apparatus are equipped with a hydraulic loading system actuator and a controller capable of generating a cyclic axial stress at a constant confining pressure (CCP). The triaxial cell is equipped with transducers measuring the axial and radial strains on the middle third of the specimen (see Figure 8 for the large triaxial specimens. The resilient modulus is then expressed as:

$$M_r = \frac{\Delta\sigma_1}{\Delta\varepsilon_1} \qquad (1)$$

Both the RL CBR and RDT testing were carried out on all materials at varying the moisture contents (MC) and degree of compaction (DOC as % MPDD) conditions.

Figure 8. RL CBR specimen during compaction (left), RL CBR during testing (middle) and instrumented triaxial specimen ready for testing (right). All pictures relate to the coarse grained unbound aggregate specimens.

6 RESULTS AND DISCUSSION.

In this section results obtained from the various tests will be shown and some discussion on these results will be presented as well.

6.1 Fine grained materials

An example of how the resilient and cumulative permanent deformation developed during the test is given in figure 9. The effective modulus was calculated from the resilient deformation after 50 load cycles using equation (3).

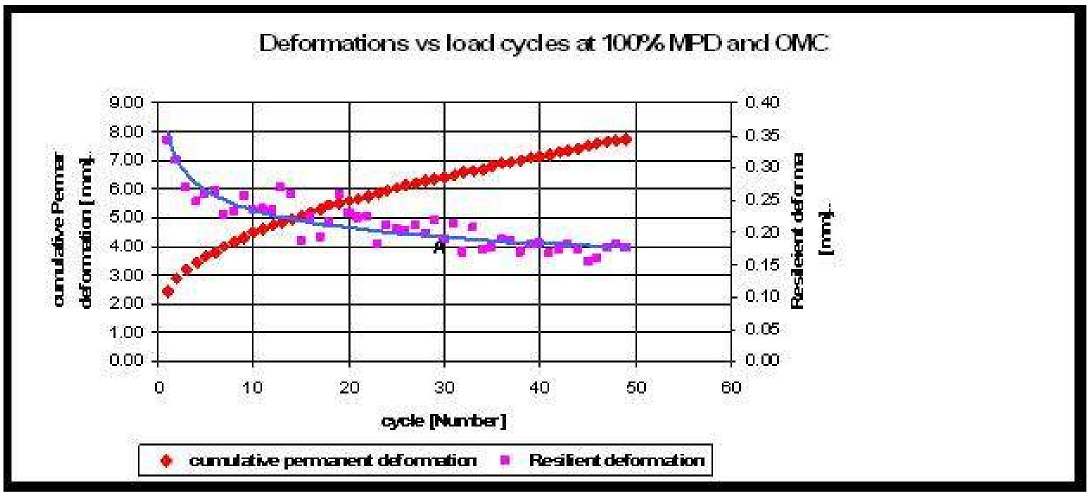

Figure 9. Development of the resilient and accumulative permanent deformation during a repeated load CBR test.

Also repeated load triaxial tests were performed and some of the test results are shown in figure 10. The stress dependency of the resilient modulus was described using the Uzan equation (equation 3).

$$M_r = k_6 (\theta / p_0)^{k7} (\sigma_d / p_0)^{k8} \quad \text{(Eq. 3)}$$

Where:
- M_r = resilient modulus [MPa],
- θ = sum of principal stresses [kPa],
- p_0 = reference stress = 1 kPa,
- σ_d = deviator stress [kPa],
- k_6 to k_8 = constants.

When analyzing the data it appeared that the effective modulus as determined by means of the repeated load CBR test was the same as the modulus as determined by means of repeated load triaxial tests if those tests were done at a confining stress level of 20 kPa. This implies that the effective modulus determined by means of the repeated load CBR should be adjusted if M_r values at other confinement levels need to be predicted. This adjustment can be made using equation 4.

$$M_{r,\ triaxial} = 0.211\ \sigma_{conf}^{0.563} * E_{eff,CBR} \quad \text{(Eq. 4)}$$

Where: M_r = resilient modulus from the repeated load triaxial test [MPa],

σ_{conf} = confining pressure as used in the triaxial test [kPa] (> 20 kPa),
$E_{eff,CBR}$ = effective modulus obtained from the repeated load CBR test [MPa].

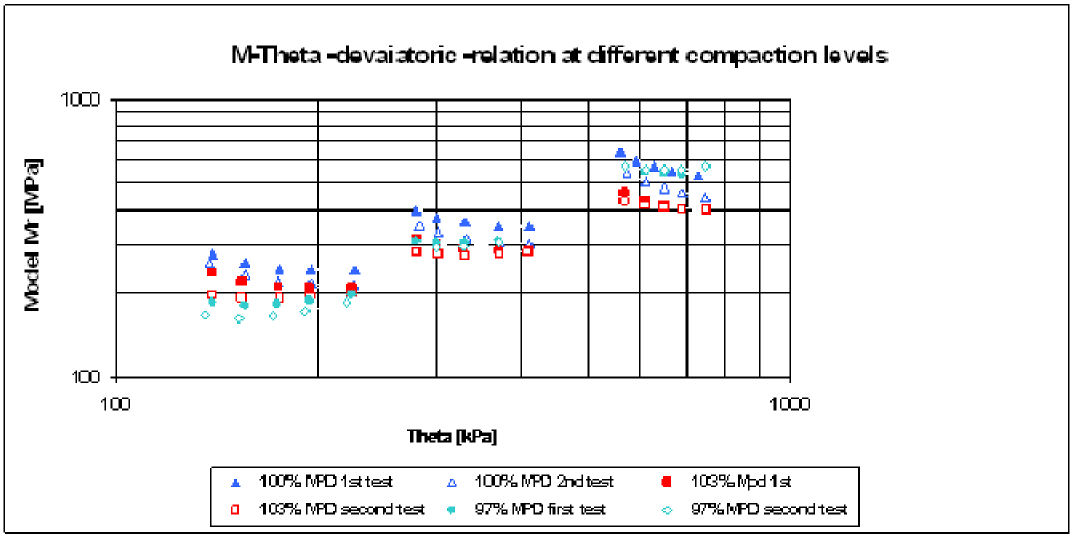

Figure 10. Stress dependency of the resilient modulus of the sand as determined by means of repeated load triaxial testing.

Figure 11 shows the stress dependency of the resilient modulus of the expansive clay. As was the case with the sand, a correction on the E_{eq} obtained from the repeated load CBR tests should be applied in order to cater for the effect of the confining pressure. This correction can be calculated using:

$$M_{r,\,triaxial} = (0.04 * w + 0.006 * \sigma_{conf} - 0.05) * E_{eff,CBR} \qquad \text{(Eq. 5)}$$

Where: w = molding moisture content [%],
σ_{conf} = confining pressure as used in the triaxial test [kPa].

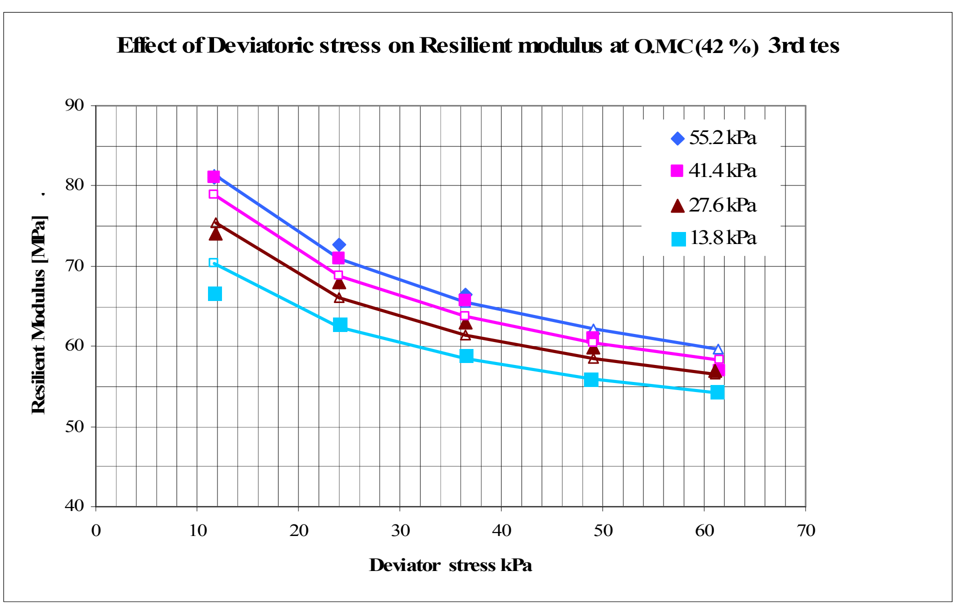

Figure 11: Example of repeated load triaxial test results obtained on the black cotton clay at

optimum moisture content.

6.2 Coarse grained materials

Figure 12 shows as an example the resilient deformation of six Ethiopian weathered basalt (WB) specimens as measured by means of the repeated load CBR test using the large mould. 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.

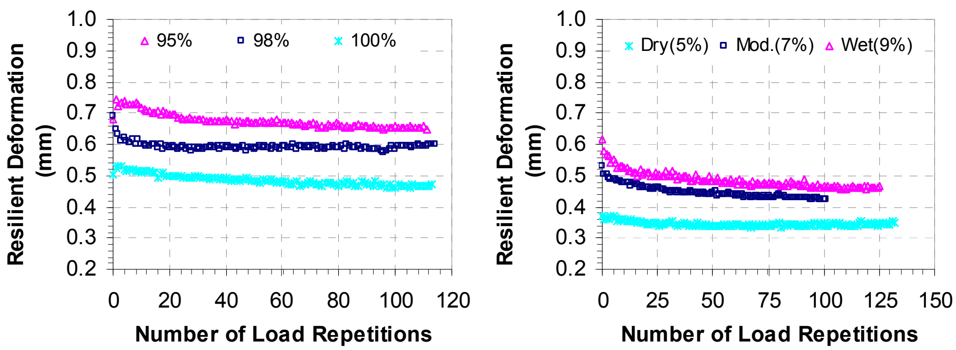

Figure 12. Effect of DOC at moderate MC and effect of MC at 95% DOC for WB.

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. Figure 13 shows stress dependent equivalent modulus as determined for the G1 material and the ferricrete 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 increases with an increase in DOC and decrease in MC. However the FC results show more scatter and are 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 which results in weakening of 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.

The resilient modulus triaxial testing has been carried out for the three materials at varying moisture and compaction conditions. The stress dependency of the resilient modulus was analyzed using different models, but the simple and well known isotropic non-linear $M_r - \theta$ model provided the best results. Some results are presented in Figure 14.

$$M_r = k_1\, \theta^{k2} \qquad \text{(Eq. 6)}$$

Where: M_r = resilient modulus [MPa],
θ = sum of principal stresses [kPa],
k_1 & k_2 = model parameters.

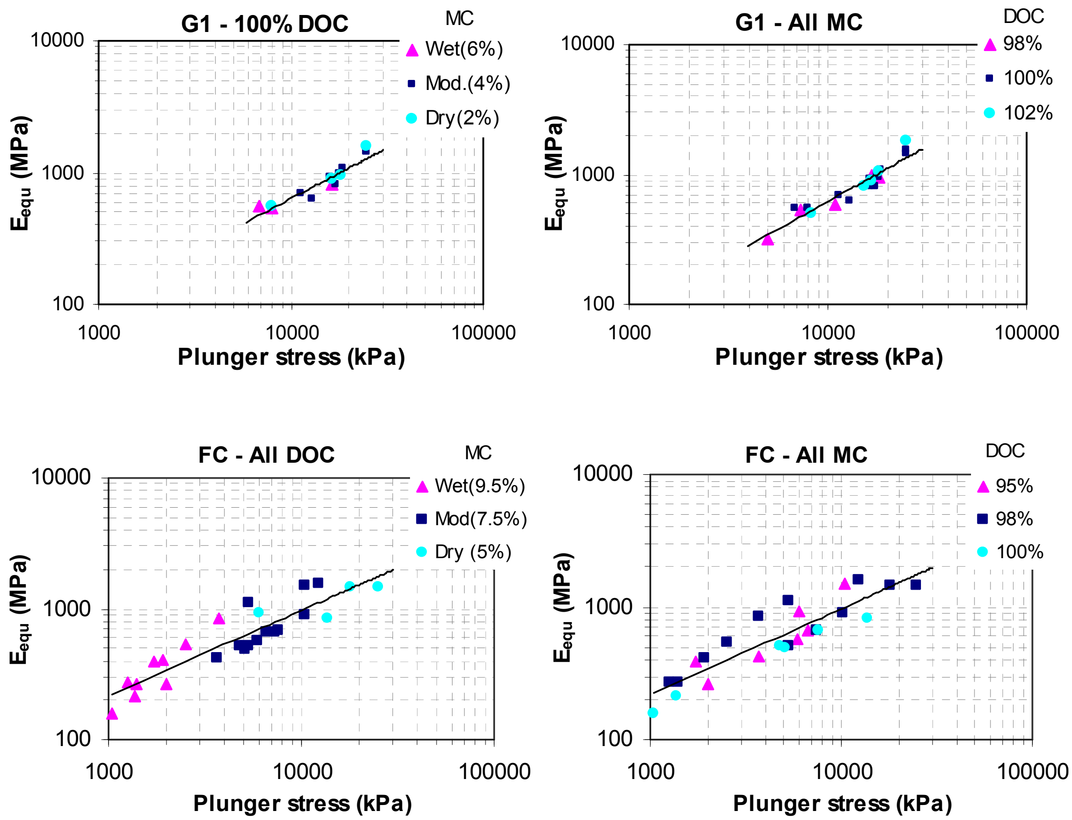

Figure 13. Stress dependent equivalent modulus for G1 and FC at various MC & DOC.

7 CORRELATING RL CBR EQUIVALENT MODULUS OF COARSE GRAINED (SUB)BASE MATERIALS WITH TRIAXIAL RESILIENT MODULUS

For the coarse unbound granular (sub)base materials, the equivalent modulus obtained from the RL CBR test can't be used directly for analysis and design of pavements as the load levels that had to be used during the tests and consequently the stresses in the specimen are quite high compared to the triaxial test loadings and practical traffic loading. Figure 15 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 correction of the RL CBR values to stress levels that occur in the triaxial test and the pavement structures 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 pavement design and analysis.

By combining equations 1 and equation 6, the plunger stress σ_p can be calculated at which the modulus determined from the repeated load CBR test is the same as the resilient modulus obtained from a cyclic triaxial test at a certain stress level. In addition the effect of the MC and DOC has to be taken into account. Using a non linear multidimensional least square regression technique, equation 7 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.

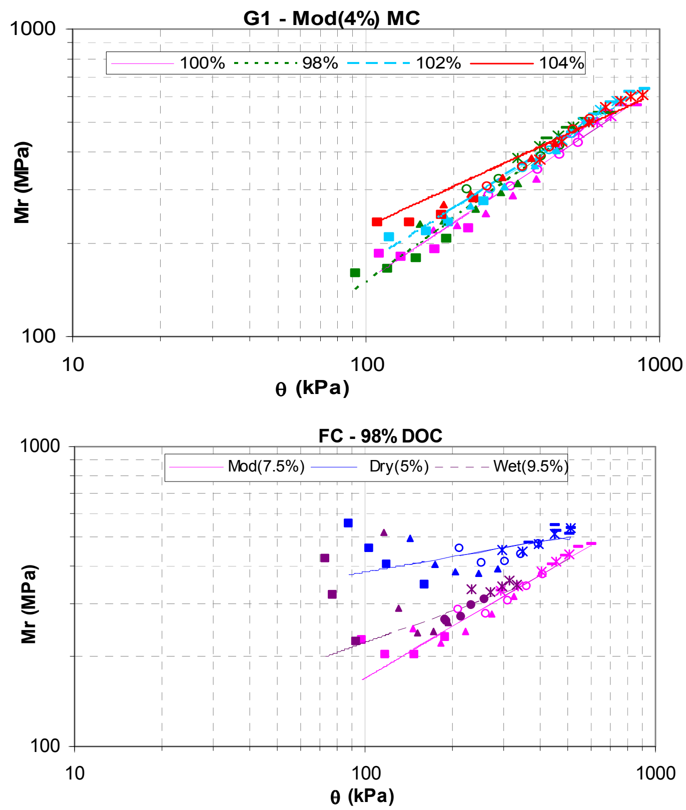

Figure 14. Examples of variation of M_r with bulk stress θ DOC and MC.

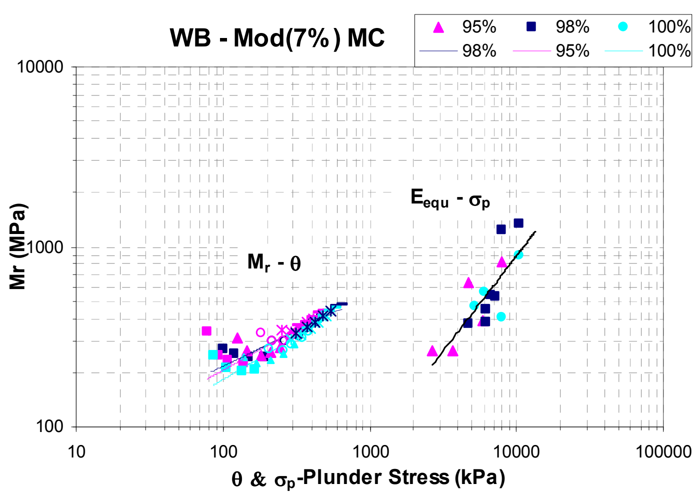

Figure 15. Comparison of resilient modulus vs. equivalent modulus typical example

$$\log(\sigma_p) = a_1 + a_2 S + a_3 e + a_4 \log(\theta) \quad \text{(Eq. 7)}$$

Where: σ_p = corrected plunger stress [MPa],
S = degree of saturation [-],
e = void ratio [-],
θ = bulk stress [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 tests.

Table 1. Model parameters for equation 7.

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

8 CONCLUSIONS

Based on the research results presented in this paper, the following conclusions have been drawn.

- The RL CBR test is a realistic and affordable technique and gives a reasonably good estimate of the resilient modulus both for fine grained as well as coarse grained materials. This makes the test extremely useful in cases repeated load triaxial tests cannot be performed because of lack of equipment, lack of required skills to do such tests and shortage of the required budget.
- The resilient modulus measured from the RL CBR testing needs to be corrected in order to take into account the stress conditions that occur in triaxial tests as well as the stress conditions that occur in the unbound base and subbase layer as well as the subgrade of pavements.
- Although not discussed here, the RL CBR test is a useful technique to evaluate the effect of moisture, compaction and stress level not only on the modulus but also on the development of permanent deformation.

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KEY WORDS

Cement stabilization, recycling, repeated load CBR test, triaxial testing, granular materials.