Permanent deformation evaluation of Unbound Granular Materials (UGMs) layer

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ABSTRACT: This paper reports the permanent deformation evaluation of crushed rock under repeated cyclic loading triaxial tests performed at different stress levels, in order to improve permanent deformation prediction for unbound granular materials (UGMs). Road rutting is the main cause of damage in flexible pavements which the most explanation is crushed rock still not obviously understanding about plastic deformation under service load. The permanent deformation that accumulates under the repeated loading can normally describe and define the types of responses. Theoretical approach of the UGMs permanent deformation used to describe the behaviour of tested materials subject to repeated cyclic loading triaxial (RLT) tests by macro-mechanical observations of the UGMs response. The plastic limit is able to use predict the accumulated plastic deformation in the UGMs layer of road pavement or whether deterioration will be unacceptable. Tested material will be determined the limit of working stress level and the plastic deformation should be considered in this behaviour. The paper presents permanent deformation prediction.

1. INTRODUCTION

UGM layer with thin bituminous surfacing is extensively used in the road network. Normally, crushed rock is used as a base course material that can be determined as UGM. The important function of the UGM layer in pavements is only to distribute and reduce amount of vertical stresses and strains by vehicle wheel loads into sub layers with no unacceptable strain at the top of subgrade. Current pavement design terminated the plastic behaviour of UGM layer. Consequently, an apparent knowledge of entire characteristics of materials relevant to pavement mechanistic design is very great important to gain the efficiency of such materials. UGMs need to be investigated to improve analysis and design more precisely than in the past with respect of plastic strain during the service life. Consequently, a most economical construction and an appropriate material type for the pavement will be determined.

This paper focuses on applying the permanent deformation for crushed rock as a base course material and developing the specific evaluation of crushed rock for deflection analysis. The empirical design method is unacceptable because the test protocols to require the design parameter inputs from monotonic loading tests rather than cyclic loading tests which are more representative of real traffic loading conditions. A mechanistic design attempts to explain pavement characteristics under real pavement conditions such as load types, material properties of the structure and environments based on design parameters from sophisticated tests which can simulate real pavement conditions into the test protocol [1]. The main success of this analytical method is the experimental measurement and appropriate characterisation of the mechanical responses from the RLT test which is the basic protocol of this study.

2. BACKGROUND

UGMs are very significant pavement construction materials that are used as base, subbase and subgrade. Understanding on the characteristics and behaviour of UGM with the response of the materials when subjected to applied load is therefore necessary for practical work. Basically, UGMs are rather complicated materials to deal with and particularly natural soils and gravels show varied behaviour as a consequence of physical history that has an influence on the mineralogical composition, the particle form and particle size distribution. Moreover the actual degree of compaction and moisture content are of enormous importance. Normally, UGM consists of gravels or crushed rock aggregates which have particular grading that formulates mechanical strength, practicable and able to be compacted. Their performance is largely governed by their shear strength, stiffness and resistance to material breakdown under construction and traffic loading. The most common modes of deterioration of UGM base layers are rutting due to insufficient resistance to permanent deformation through shear and densification, and collapse during particle breakdown.

The nature of empirical pavement design procedure is based on experience and the results of simple tests such as the California Bearing Ratio (CBR), particle size distribution (PSD), moisture sensitivity, Los Angeles (LA) abrasion, shear strength and deflection. Such testing results are all static parameters and non-mechanical index parameters rather than any consideration of realistic material performance and displacement distribution during cyclic loading, stresses and strain distribution in multilayered pavement design. Consequently, the use of empirical approaches becomes sub-standard. Traditional procedure has been criticized by Wolff, who argued that it is too simplistic and does not take into account the non-linear behaviour of UGMs [2]. Hence, the pavement analysis and design are inevitable to involve additional base and subbase permanent deformation. For those reasons, there are some doubts in responses relative to their performance.

The performance of a base course material depends upon its stiffness and deformation resulting from a traffic load. A large deformation causes rutting on the bituminous surface. Basically, the conventional pavement construction is designed to provide adequate thickness cover the sub layer in such a way that no shear failures and unacceptable permanent deformation takes place in each layer. For pavement design purposes, the stress level which is related with a reversible strain response must be determined and consequently not exceeded, once unacceptable permanent strains are prevented. This has improved the possibility of a critical boundary stress between stable and unstable conditions in a pavement.

The RLT test has been used to simulate the behaviour of conventional engineering structures under repeated cyclic loading. For the theoretical approach of the UGMs' permanent deformation used to describe the behaviour of tested materials under RLT tests under macro-mechanical observations of the material response and in the distribution of the plastic strain in the tested material were investigated. They can predict progressive accumulations of plastic strains and whether the amount of the applied loads exceeds a certain limited-value.

A low stress levels, the mechanism of permanent strain has an initial post compaction or re-arrange phase, while the permanent strain rate is relatively high but this is reduced with increasing numbers of load cycles. A stable state may be maintained for a period of time unless the states change. Numerous investigations have been conducted regarding the behaviour of UGMs used in flexible pavements. Lekarp summarized the main findings regarding the effects of different material parameters on the permanent strain response of UGMs and the maximum applied stress in UGM layers is within the maximum repeated deviator stress limit [3]. The original concept of permanent strain response under a low repeated loading shows that UGMs will indicate plastic strain in a few initial cycles, although the ultimate response is elastic after Post-compaction. The strain is completely reversible and does not lead any permanent strains when it reaches a state of stability. However the material will show failure with a large number of load cycles after a stable state when subjected to relatively large of loading so that plastic strain accumulates rapidly with failure occurring in a small number of load cycles after stiffening.

An UGM is likely to show progressive accumulation of permanent strains (rutting) under repeated traffic loading if the magnitude of the applied loads exceeds the limiting value. With this understanding of material behaviour typically then determine the load carrying capacity of the structure if it is not to reach excessive permanent strain. For performance prediction, it is of great importance to know whether a given pavement will experience progressive accumulation of permanent strain leading to deterioration.

2.1 Permanent strain under a number of load cycles models

In the considering, the long-term behaviour model of pavements, it is essential to take into account the accumulation of permanent strain with the number of load cycles and stress levels that play and important role. Hence the main research purpose focusing on long-term behaviour should be to establish a constitutive model which predicts the amount of permanent strain at any number of cycles at a given stress ratio. In the past, permanent strain of UGMs for pavement applications has been modelled in several ways. Some of these are logarithmic with respect to the number of loading cycles [4; 5] whilst others are hyperbolic, tending towards an asymptotic value of deformation with increasing numbers of load cycles [2; 6]. The long-term strain behaviour was also investigated by Sweere in a series of RLT tests and suggested that for a large number of load cycles the following approach should be employed:

$$\varepsilon^p = A \cdot N^B \tag{1}$$

where:

ε^p	[10^{-3}] permanent strain
A, B	[-] regression parameters
N	[-] number of load cycles.

To implement the RLT measured permanent strain development in the computation of permanent strain development in a pavement structure, the permanent strain in the material under consideration has to be known as a function of both the number of load cycles and the stresses in the materials. In this research, the parameters A, B were also determined. Finally, it was realised that it is possible to predict the permanent deformation of crushed rock in a stress dependent way. However, it is necessary to maximum strain from triaxial tests.

3. LABORATORY PROGRAM AND TESTING

3.1 Crushed rock

Crushed rock is composed of rock fragments produced by the crushing and screening of igneous, metamorphic or sedimentary source rock. The crushed rock samples used in this study were taken from a local stockpile and kept in sealed containers. The crushed rock samples were prepared at 100% of maximum dry density (MDD) of 2.27 ton/m^3 and optimum moisture content (OMC) of that 5.5%. Material properties achieve base course specifications [7].

3.2 Specimen preparation

Sample preparations were carried out by using a standard cylinder mould 100 mm in diameter and 200 mm in height by the modified compaction method [8]. Compaction was accomplished on 8 layers with 25 blows of a 4.9 kg rammer at a 450 mm drop height each layer. Fully bonding conduction between the layers of each layer had to be scarified to a depth of 6 mm before for the next layer was compacted. After compaction, the basic properties of each specimen were determined after which it was carefully carried to the base platen set of the chamber triaxial cell. A crosshead and stone disc were placed on the specimen and it wrapped in two platens by a rubber membrane and finally sealed with o-rings at both ends.

3.3 Repeated cyclic load triaxial tests

The tests were carried out with a cyclic triaxial apparatus consisting of main set containing the load actuator and a removable chamber cell. The specimens were placed in the triaxial cell between the base platen and crosshead of the testing machine as Figure 1 shows. Controllers were used to manage the chamber, as well as the air pressure. The analogical signals detected by the transducers and load cell are received by a module where they are transformed to digital signals. A computer converts modules of the digital signals sent from the system. The system is located in the main set and facilitates the transmission of the orders to the actuator controller. User and the triaxial apparatus communication are controlled by a computer which uses convenient and precise software. This makes it possible to select the type of test to be performed as well as all the parameters, stress levels, data to be stored. The load cell, the confining pressure and the externally linear variable differential transducer (LVDT) on the top of the triaxial cell, used to measure deformations over the entire length of the specimens were measured by the control and data acquisition system (CDAS) which provided the control signals, signal conditioning, data acquisition. The CDAS was networked with the computer which provided the interfacing with the testing software and stored the raw test data. These enabled the resultant stress and strain in the sample to be determined. This apparatus however, is limited to laboratory samples with a maximum diameter of 100 mm and a height of 200 mm based on the standard method of Austroads APRG 00/33-2000 [9]. Moreover, the apparatus allows the laboratory sample to be subject to cyclic axial deviator stresses but it is not feasible to vary the confining radial stresses at the same time. Confining pressure was generated air to simulate the lateral pressure acting on the surrounding materials as occurs in a pavement layer.

3.4 Triaxial shear tests

Drained triaxial compression tests were conducted to determine the triaxial shear tests of crushed rock. Only specimens at 100%OMC were tested under unsaturated conditions based on the crushed rock standard. In these tests, the specimen response was measured at three different constant confining pressures of 40 kPa, 60 kPa, and 80 kPa using the same triaxial equipment and system for the measurement of permanent deformation.

3.5 Permanent deformation tests

The standard method of Austroads APRG 00/33-2000 [10] for Repeated Load Triaxial Test Method was followed for the permanent deformation tests. New specimens were prepared as stated in the previous section. Permanent deformation testing was performed during which, the specimens were loaded with three stress stages at the ratios of the dynamic deviator stress (σ_d) with frequency of 0.33 Hz (see the vertical force waveform in Figure 2) to the static confining stress (σ_3) as shown in Table 1, each involving 10,000 cycles for each particular stress condition.

Permanent deformation stress levels		
Stage Number	Base	
	Confining pressure, σ_3 (kPa)	Dynamic deviator stresses, σ_d (kPa)
1	50	350
2	50	450
3	50	550

Table 1: Stress levels following Austroad-APRG 00/33 standard.

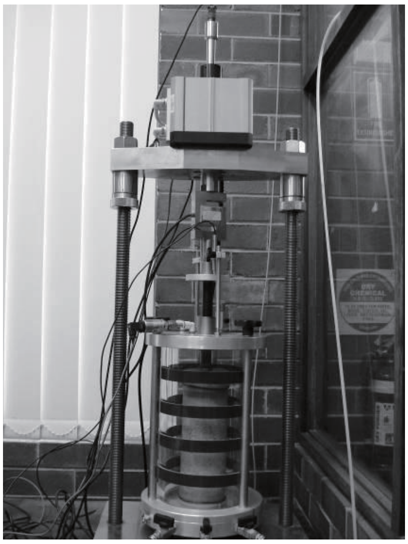

Figure 1: The repeated loads triaxial apparatus.

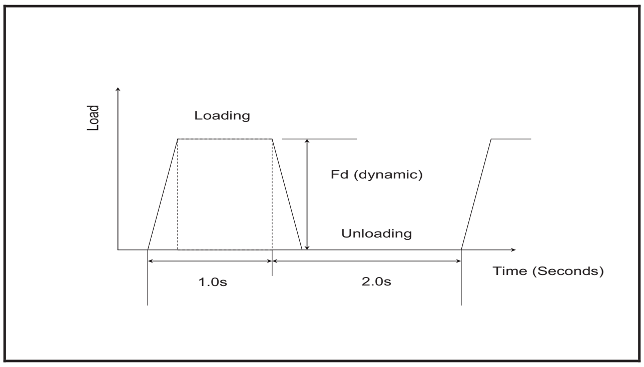

Figure 2: The vertical loading waveform.

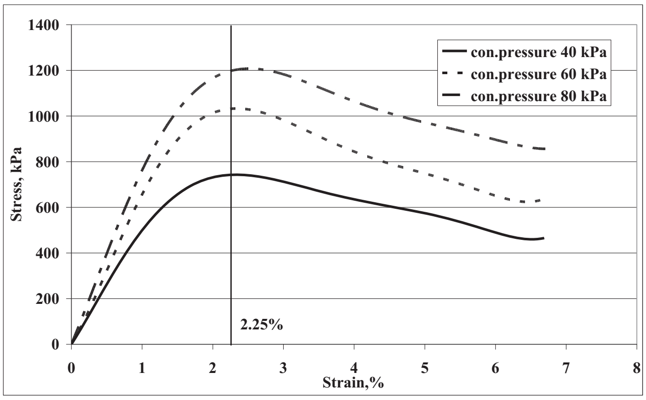

Figure 3: Permanent deformation versus number of load cycles (N).

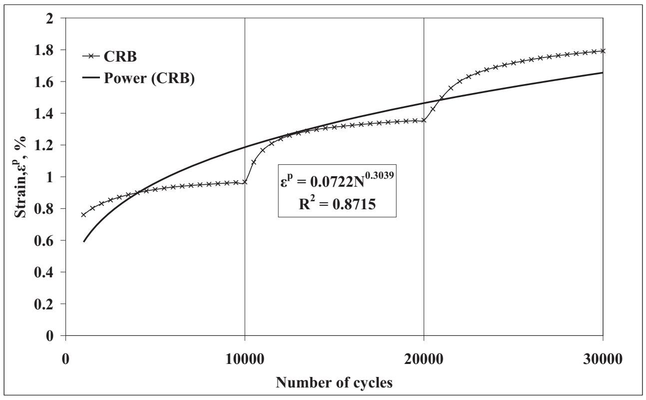

Figure 4: Range A and B permanent strain model.

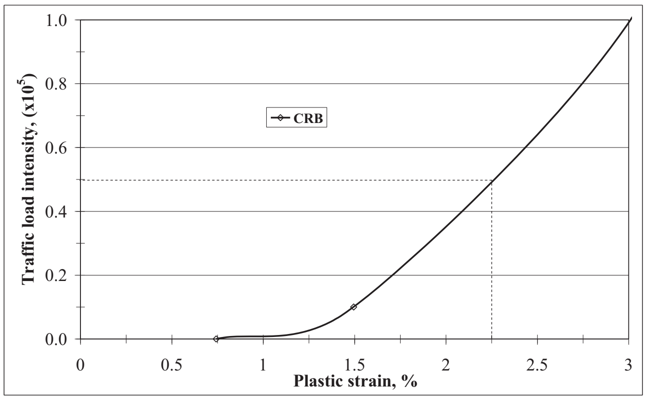

Figure 5: Number of traffic compared with plastic strain

4. RESULTS AND CONCLUSIONS

The permanent deformation accumulations were observed as shown in Figure 3. As test results present crushed rock response always produce permanent deformation during cyclic loading, hence it can describe elastoplastic behaviour under repeated cyclic loads in course base materials and the multi-layer linear elastic theory is not enough to analyse the UGM layer. Permanent deformation behaviour is described on the basis of internal friction between grains, particle shape, compaction, consolidation, distortion, etc.

The permanent deformation behaviours of crushed rock, normally used as a base course material, were investigated by RLT tests. It has been shown that the use of the application to UGMs in the permanent deformation prediction is possible. When a cyclic loading is applied, the sample responds by changing its permanent strain. At the early stage, crushed rock showed relatively high permanent deformation that means first energy input is quickly dissipated by a re-arrangement of the sliding internal contacts of material, the so-called post-compaction. Later, tested material will reaches a stable stage after post-compaction, with no large further permanent deformation developing as shown in Figure 4. In a continuous and gradual increase of the loading amplitude $\Delta\sigma$, the material will start by trying to change the mechanical behaviour. The possibility of purely elastic approach in UGM is also discarded as no purely elastic response is found in the crushed rock during repeated cyclic loading. Figure 4 shows the typical results of the permanent deformation tests in terms of the relationship between permanent deformation and loading cycles for crushed rock. Figure 4 also exhibits the comparison of the measured permanent deformation values and the predicted values for a proposed permanent deformation model of crushed rock. The permanent deformation can be modeled quite reasonably for crushed rock by using the model suggested by Sweere, G.T.H from SAMARIS [5]. Sweere suggested for the long-term deformation behaviour of UGMs under a large number of load cycles an approach should be employed as the proposed permanent deformation model of crushed rock as shown in Figure 4.

The plastic strain model should be used to predict whether or not failure occurs in the UGM layer of the road structure. It can be shown that the maximum stresses occurring in the pavement UGM are within carrying capacity. Plastic strain prediction of UGMs was also presented in order to find the number of vehicle passes on the pavement by use of RLT test results. The limit ranges defined in this study, crushed rock presented the maximum strength at strain value of 2.25% based on static shear test results. It seems crushed rock under working conditions will reach the failure after such strain. This study shows that crushed rock is able to resist only 500,000 vehicle passes based on permanent deformation test results with acceptable shear strength of 2.25 % strain as shown in Figure 6. Consequently, raw crushed rock is insufficient to use as road base for high-volume road without any deterioration with respect to the limited range of permanent deformation. Since this reason, several road bases have been improved to stabilised materials that present much better plastic strain performance. The paper exhibits that having defined the strain range and strain prediction from laboratory results, it is possible to determine whether crushed rock is sufficient or whether other thicknesses of surfacing layer are inevitable to implement satisfactory pavement performance along with pavement design should be considered permanent deformation of UGMs layers.

5. REFERENCES

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