Failure Criteria Evaluation and Shear Strength of Granular Base Course for Thin Flexible Pavement

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Synopsis: This study aims to report theoretically the possible approach of confinement evaluation of unbound granular base course using the finite element method and the permanent deformation evaluation of crushed rock under repeated cyclic loading triaxial tests performed at different stress levels in order to implement current pavement material test algorithm. 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 unbound granular materials (UGMs) permanent deformation used to describe the behaviour of tested materials subject to repeated 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 determine the limit of working stress level and the plastic deformation should be considered in this behaviour. As is well known, triaxial and California bearing ratio (CBR) test are used to simulate the real condition of pavement materials under traffic loads by using static confinement and actuator loads. However static confining conditions in pavement structure occur only when no vehicle travels. As the effects of traffic loads and material attributes are generated when vehicles travel, horizontal stress and confinement behaviours of pavement structure were determined. CBR sample of crushed rock base was modelled using finite element in order to study the confining pressure behaviour of such material subjected to applied stress. During the load application procedure, a single wheel with a standard pressure of 750 kPa was selected to compare with the analysed strength of crushed rock base (CRB) based on laboratory test results. The results showed that horizontal stress of base course layer consists of overburdened soil and passive force from applied stress. When vehicle travels pass observed point, horizontal pressures of base course layer increase from overburdened weight and complete with passive force effect depend on applied stress and its internal friction. Seemingly, the conventional triaxial test results with finite element back calculation are able to describe the confining behaviour of unbound granular base course. In this study, triaxial tests and the confinement evaluation using finite element approach on an unbound granular base course were introduced to explain and define its limited use in order to implement the current performance test of unbound granular base course material.

Keywords: shear strength, failure criteria, thin flexible pavement, granular base course.

1. Introduction

An unbound granular material (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.

The current 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 [1]. 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, conventional pavement construction is designed to provide an adequate thickness cover over the sub layer in such a way that the pavement structure does not experience shear failures and that unacceptable permanent deformation does not take place in each layer. For pavement design purposes, the stress level which is related to 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

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 [2]. 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. This paper also focuses on the confinement evaluation of CRB using finite element and laboratory test results for Western Australia pavement. The design method will be more improved if the performance of unbound granular bases can be predicted accurately more than using as load transferring layers.

2. Laboratory Program and Testing

2.1 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 [3].

2.2 Specimen Preparation

Sample preparations were carried out using a standard cylinder mould 100 mm in diameter and 200 mm in height by the modified compaction method [3] at 100% MDD and 100% OMC. Compaction was accomplished on 8 layers with 25 blows of a 4.9 kg rammer at a 450 mm drop height on 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 was wrapped in two platens by a rubber membrane and finally sealed with o-rings at both ends.

2.3 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.

2.4 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. 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 [1]. 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.

2.4.1 Permanent Deformation Tests

The standard method of Austroads APRG 00/33-2000 [4] 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 1) to the static confining stress (σ_3) as shown in Table 1, each involving 10,000 cycles for each particular stress condition.

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

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

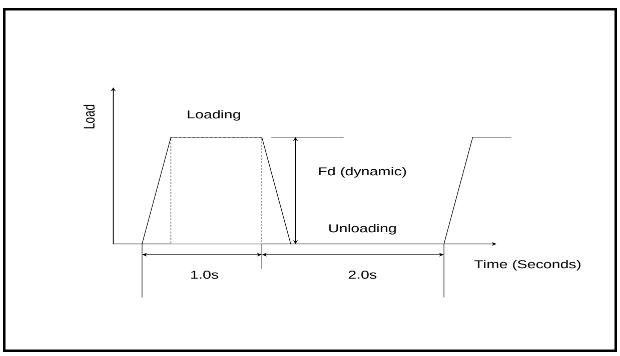

Figure 1: The vertical loading waveform

2.4.2 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 an 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 [5, 6] whilst others are hyperbolic, tending towards an asymptotic value of deformation with increasing numbers of load cycles [7, 8]. 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. Finite Element Modelling

This study was undertaken to incorporate realistic material properties of CRB layers in the analysis of flexible pavements using the finite element theory. As a preliminary step, pavement materials within Western Australia were, subjected to a static loading, selected and modelled as a finite element model. An analysis was carried out using the finite element computer package ABAQUS/STANDARD [9], when this pavement model was subjected to static loading while considering the linear material properties of the pavement layers. The results of triaxial tests under loading were considered in pavement analysis.

In the modelling of the problem, the finite element program used eight nodes of isometric elements as a solid continuum. The problems were simplified under the plain strain condition and material properties (modulus and ultimate strain) from triaxial tests on the pavement were used. Dimensional parameters used in the modelling are illustrated in Figure 2 show the finite elements mesh of the problem and type of boundary conditions of the particular structure. The pavement structure was modelled as a single layer of base course using 152 mm height, 117 mm width and piston diameter of 49.6 mm based on the California bearing ratio (CBR) test as shown in Figure 2. Finite elements were unified by nodes at their common edges. The interfaces between layers are considered as fully bonded and rough. Boundary conditions were considered in the finite element modelling and rotation was allowed at all supports. The following conditions are applied with reference to Figure 2, when defining the boundary conditions. The vertical displacements of the bottom plane of the model are pinned. The side planes were fixed horizontally and vertically. FE analysis provided an approximate solution for an engineering structure with various types of boundary conditions and under various types of loading using a stiffness or energy formulation. In the derivation of the stiffness matrix for elements, three factors such as the geometry of elements, the degrees of freedom allowed for the nodes to displace and the material properties of elements are considered. This solution provides displacements at the nodal periods and stresses and strains at integration points.

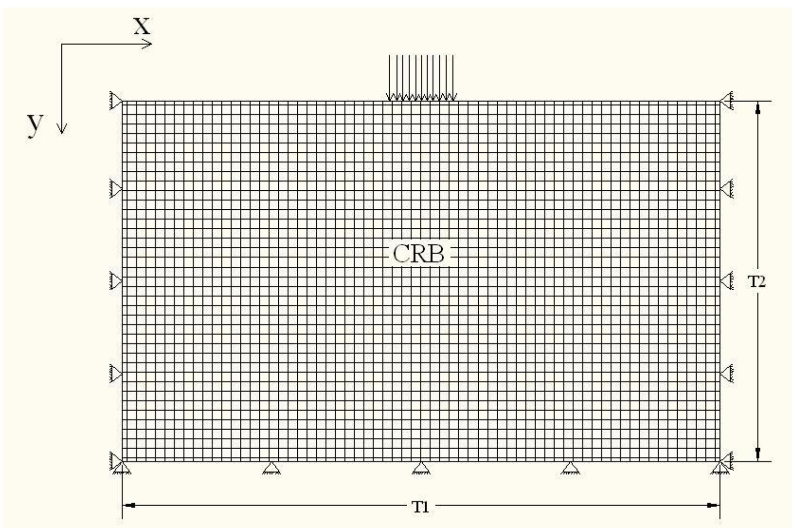

Figure 2 : Finite element diagram of pavement

4. Test Results and Conclusions

4.1 Static Triaxial Tests

This section presents the results and discusses the static triaxial shear tests operated on CRB at the compaction of 100% MDD and 100% OMC derived from the compaction curve. The purpose of the tests was to examine the strength characteristic and to determine the ultimate shear strength parameters of test materials under the triaxial shear test. These tests also established the ultimate strain of CRB to determine the maximum stress level of this material so that the limited uses of testing material could be indicated. Various confining pressures were applied on the test specimens in each test.

The peak deviator stresses from the stress-strain curves can be seen in Figure 3. Figure 3 also depicts the relationship between the deviator stress and the axial strain of the three selected confining pressures. For the stress-strain curves, it also can be observed that the static deviator stress initially increases with greater axial strain until it reaches peak strength. For a higher confining pressure, apparently, the peak strength becomes higher and the strain corresponding to the peak strength also becomes higher. All three curves in Figure 3 exhibit that after the peak strength, there is the post peak regime which the stress reduces with increasing strain. This characteristic is similar to that of dense granular materials and is normally described as strain softening. The strain-softening process is concomitant with the generation of large deformations, which cause geometrically non-linear effects to become important [10]. Based on these test results, all curves reach the peak at the strain level of 2.25% or 5 mm in each curve and always meet the failure after that. Subsequently, elastic modulus was determined at 31 MPa and was used to validate the test results in finite element analysis.

4.2 Confinement Evaluation

Modulus of 31 MPa from triaxial test results was employed in this section to study stress-strain distribution of the triaxial test using finite element analysis. Stress distribution of a triaxial sample presents an asymmetric maximum stress at the both ends of testing sample even if the sample subjected to the applied load only on the top end. From this point, the ultimate strain of CRB in the tested condition could be estimated at 50% of the measured value from triaxial test results. Consequently, the ultimate strain of CRB was defined at the value of 2.5 mm which was used in next analysis to evaluate its strength and confinement. The finite element model of CBR which was analysed at modulus of 31 MPa and deformation of 2.5 mm and it found the peak stress level of 1300 kPa as the ultimate strength of CRB.

The ultimate stress of 1300 kPa from finite element analysis was applied on the selected model of CRB in order to study confining behaviour. The confining pressure starts around 210 kPa at the surface and increases relatively high at 2.5 mm below the surface around 420 kPa after that reduce gradually then reach the stable state at depth of 60 mm as shown in Figure 4. At the depth of 60 mm can be determined as influencing boundary (passive area) of the applied stress which was no more affect the confining pressure. The minimum confining pressure could be defined at the value of 75 kPa at depth of 60 mm.

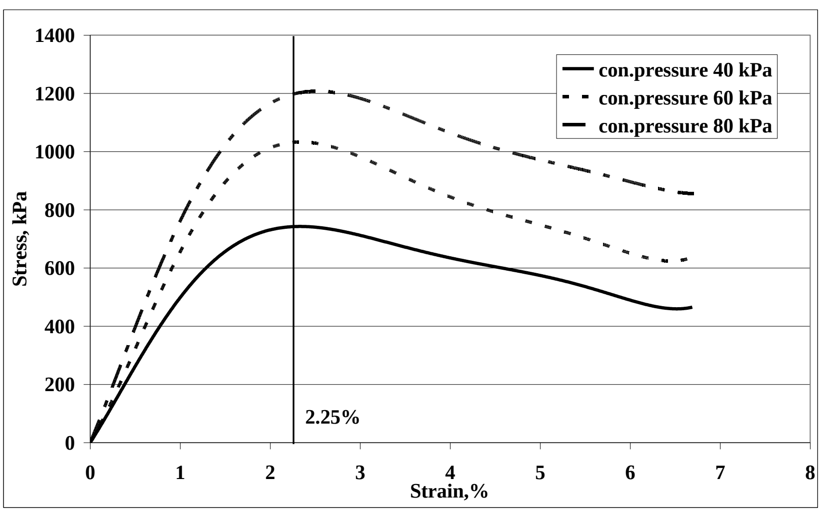

Figure 3: Triaxial test results

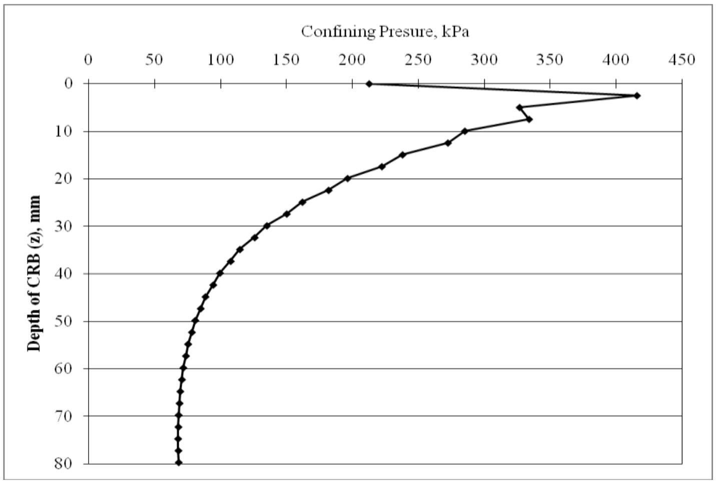

Figure 4: Confining pressure diagram

The confining behaviours of Crushed Rock Base (CRB), normally used for a base course material in Western Australia, were investigated by means of static triaxial tests using finite element approach. The three confining pressures, namely 40, 60 and 80 kPa, of triaxial tests were carried out in order to provide an ultimate strain of CRB at the peak strength then input in finite element to study the confining pressure along the depth of CBR sample size modelling. The results can be drawn that:

- All triaxial test results of CRB always present the ultimate strain at 2.25% strain or 5 mm derived from the sample height at the peak load.
- The deformation behaviours of triaxial test completely differ to CBR test and pavement condition that the 50% strain results therefore can be used properly as the ultimate strain in CBR test and modelling.
- Based on this experiment, the confining pressure values of CRB under the ultimate strain of 2.5 mm are in the range of about 75 kPa to 420 kPa. It seems the applied load could influence the confining pressure underneath only twice of the contacting area of the applied stress and the confining pressure of 75 kPa was determined as the minimum value.
- The peak strength of CBR at 2.5 mm as ultimate strain is 1300 kPa which is higher around 2 times of current pavement design load of 750 kPa.
- A 3D finite element approach will improve the accuracy of the evaluation because it seems that the plain strain analysis for this study presents the conservative strength of CBR compared with the CBR test results.

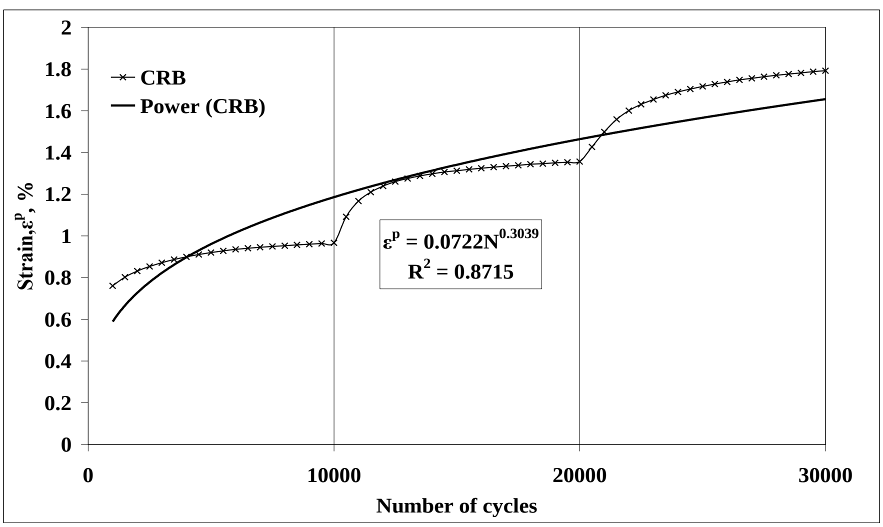

Figure 5: Range A and B permanent strain model

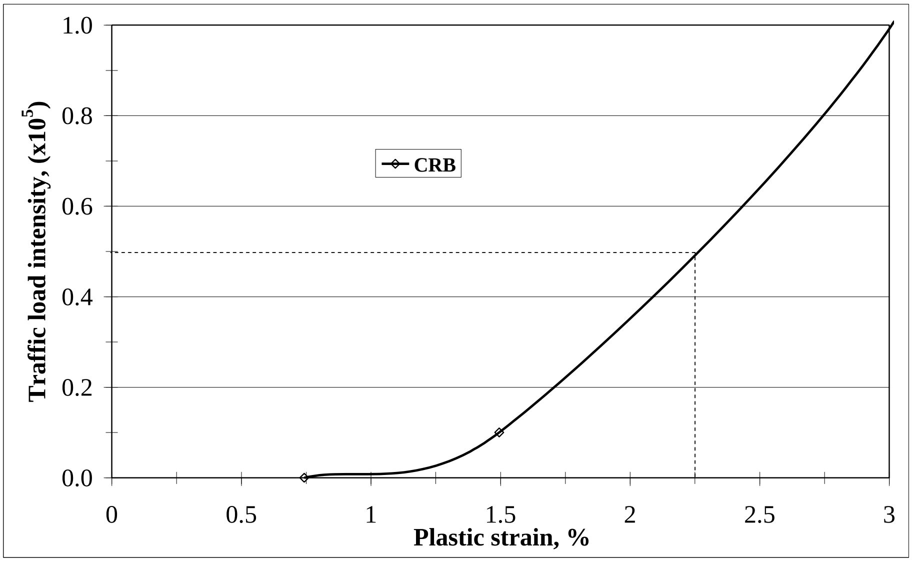

Figure 6: Number of traffic compared with plastic strain

4.3 Permanent Deformation

The permanent deformation accumulations were observed as shown in Figure 5. 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 5. In a continuous and gradual increase of the loading amplitude Δσ, 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 5 shows the typical results of the permanent deformation tests in terms of the relationship between permanent deformation and loading cycles for crushed rock. Figure 5 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 [6]. 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 6.

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.

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