Constitutive Modelling of Hydrated Cement Treated Crush Rock Base with Cyclic-loading Behaviour

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Synopsis: Hydrated Cement Treated Crush Rock Base (HCTCRB) is a unique road base material developed and commonly used for Western Australia roads. This paper presents the application of disturbed state concept (DSC) for the constitutive modelling of HCTCRB. DSC was adopted as the modelling approach because of its simplicity and yet is powerful in capturing the elastic and inelastic responses of materials to loading and unloading-reloading history. The DSC constitutive model depends on the main assumption that the actual material deformation, at any loading state, can be determined from its assumed relative intact (RI) state. DSC equations are derived based on an idealised material model of the RI state, namely linear elastic RI state. The use of the idealised linear elastic RI state leads to a unified stress-strain equation in terms of the stress and strain values at the maximum yielding and ultimate limit states. The DSC models are found to be in good correlation with the actual HCTCRB behaviour based on the test data. The proposed constitutive model is also suitable for predicting the resilient modulus of HCTCRB, which will be presented and verified.

Keywords: HCTCRB, disturbed state, relative intact, fully adjusted, triaxial test.

1. Introduction

Crushed rock mixed with General Purpose (GP) Portland cement, named HCTCRB, can be used as a based course material of roads in Western Australia. The normal function of a base course layer is to distribute the stresses from the wearing surface to the supportive layers below. In order to improve the accuracy of structural pavement analysis, modulus characteristics of materials must be investigated and then a suitable model should be introduced for calculation.

The base course material's ability to resist external loads can be provided by the characteristics of the resilient modulus and permanent deformation. However, HCTCRB has been developed empirically and not well understood. Therefore, the constitutive model which can describe its behaviour under traffic loads is still needed. Also, modelling based on the test results is necessary for analysis and design. Nowadays, mathematical model is the most powerful tool for modelling of materials and it is familiar to engineers. Consequently, there is a great deal of modelling based on mathematics done by engineers, one of which is the Disturbed State Concept (DSC) [1]

The purpose of this paper is to apply DSC for derivation of the constitutive modelling of HCTCRB. The DSC equation for predicting the resilient modulus of HCTCRB was derived from the experimental results and the equation then was used to back predict the resilient modulus at different stress level for comparing. This equation can further be applied for analysis of structural pavement by using finite element method. The benefits of using DSC are that it is convenient for applying with numerical analysis and obtain more accurate results, because the behavioural characteristic of materials is described based on mechanistic-empirical method.

2. Materials

Materials in this study were compliant with Main Roads Western Australia, namely

2.1 Crushed Rock

Crushed rock used in this study was randomly collected from a stockpile area of a local quarry (Gosnells Quarry). The properties of crushed rock were checked in the Geomechanics laboratory at Curtin University for compliance with the specifications of CRB [2].

2.2 Cement

A bagged type GP cement, the product of Cockburn Cement [3], was selected for use in this study.

2.3 Hydrated Cemented Crushed Rock Base (HCTCRB)

HCTCRB was prepared by mixing a standard crushed rock base (CRB) [2] with 2%, by weight, of GP Portland cement following the standard of AS 3972-1997 [4]. HCTCRB was kept in the range of -1.0% to +2.0% of the optimum moisture content (OMC) of CRB as stated in MRWA Test Method WA 133.1 [5]. According to MRWA specification, 7 days is a standard hydration period for manufacturing of HCTCRB.

3. Laboratory Testing

This section uses the data from the repeated load triaxial (RLT) tests in accordance with the standard method of Austroads – APRG 00/33 – 2000 [6] for the permanent deformation and resilient modulus which were conducted by Komsun [7]. For comparing with failure criteria, the control sets of static triaxial test were carried out to establish cohesion (c) and internal friction angle ($\emptyset$) parameters of HCTCRB. However, only the results from the resilient modulus tests were used in this study.

3.1 Specimen Preparation

The HCTCRB samples were prepared at the 100% MDD with 100% OMC of CRB condition. All mixtures were mixed in the mixing machine until their texture and colour were uniform. After finishing the mixing procedure, the mixture was cured at room temperature by placing it in a sealed plastic bag for 7-days of a hydration period; after a hydration period, the mixture was re-mixed for at least 10 minutes in the same mixing machine. The modified compaction method [5] was then performed in a standard cylinder mould 100 mm in diameter and 200 mm in height. Samples were divided into 8 layers and energy was applied to the specimen by the use of a 4.9 kg rammer with drop height of 450 mm, 25 blows for each layer. To increase bonding between the layers, the surface of each layer was scarified to a depth of 6-mm before starting the compaction of the next layer. After compaction, the specimen was moved to the base platen set of the chamber triaxial cell. Then a stone disc and crosshead were put on the specimen and a rubber membrane was used to wrap it with the top and bottom platens, and it was eventually sealed by the o-rings at both ends. Both the permanent deformation and the resilient modulus tests, the samples were tested immediately after the compaction was finished.

3.2 Static Triaxial Test

Firstly, the controlled static tests were conducted for comparing with failure criteria. Three specimens, which were the specimen at 100% OMC of the 7-day hydration period, were prepared and tested under the unsaturated condition (at the compaction condition) by neglecting to measure the suctions. The static confining stress was applied at three different stages namely 50, 100, and 150 kPa then the stress-strain curves were plotted. Also, the Mohr-Coulomb failure envelope was constructed.

3.3 Resilient Modulus Test

The HCTCRB samples were tested to determine the resilient modulus according to the standard method of Austroads – APRG 00/33 – 2000 [6]. The tests were performed in the Geomechanics laboratory, Department of Civil Engineering, Curtin University by the use of UTM-14P digital servo control testing machine, which is able to conduct static triaxial, resilient modulus, and permanent deformation tests.

For the resilient modulus test, 66 different stress stages were applied to the specimens. The specimens were subjected to 1000 cycles for the pre-conditioning process and followed by a 200-cycle in each stress stage for 66 stages. Also, a 0.33 Hz of loading frequency was used for all stages of stress. To simulate the complicated traffic loading acting on pavement structure, for each stress stage, the specimens were firstly applied and held the static confining stress, and then the loading and unloading cycles of the respective deviator stress were applied.

4. Disturbed State Concept

The DSC was introduced by Professor Chandrakant S. Desai of the University of Arizona, USA since 1974 [8]. The main idea of the DSC is that the responsibility of the loading of mixtures in material can be represented as the interaction between its components. The self-adjustment of the material's microstructure, which can involve decay (damage) or growth (healing), are considered to be material parts in the relatively intact (RI) or "continuum" state and the fully adjusted (FA) state. The behaviour of materials exhibited through the interacting mechanisms of components in a mixture can be expressed in terms of the responses of the components connected through a coupling function, called the disturbance function (D). The disturbance of material, before the loads are applied, can be zero. Or, in the case that the material has initial anisotropy, microcracking, and flaws, the initial disturbance is nonzero. The disturbance can be expressed in any term that is required by engineers, such as stress, modulus, void, area, mass, velocity, etc.

The stresses on any section of material are composed by the stress at a point on the entire the sectional area. The point can be stayed in the RI or the FA state and the observed stress of the section comes from the summation of stress in the RI part and in the FA part.

4.1 Relative Intact State

The RI state is the response of the material, which excludes the effects of the factors that make the observed behaviour of the material deviate from the given RI state, and it is relative in this sense. An elasticity or plasticity model with an associative response, or any other suitable continuum model (viscoplastic, thermoviscoplastic, etc.), can be characterized as the RI behaviour. In the present case, the RI state response is idealised as a linear elastic model.

4.2 Fully Adjusted State

For the DSC, it is considered that the FA material does possess strength properties and certain deformation, and the material can also stiffen or gain strength during loading. Therefore, the DSC allows for the characterization of both stiffening (healing) and degradation (damage or decay) in material responses. Usually, the FA state can be determined based on the ultimate disturbance, D_u (Figure 1), because the FA state cannot be measured in the laboratory. The FA state is supposed to occur in the ultimate range and, because the measurement system would stop to operate when the material specimen "collapsed" from an engineering viewpoint, an approximation procedure must be used for determining the material response at the FA state.

Figure 1, for instance, shows the schematic of stress-strain behaviour. In this study, the linear elastic RI states were used for derivation of DSC equation. The disturbed state is the difference between the RI stress and the observed stress. The disturbed state is a function of stress and strain, D = $f(\sigma, \varepsilon)$, and its value is gradually increased from zero at the origin to D_u at fully adjusted state. In the same way, we can use this concept for defining any mechanical property of materials such as resilient modulus or permanent deformation of HCTCRB.

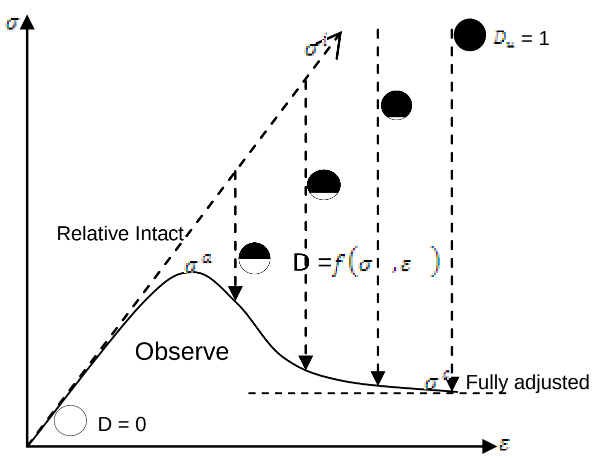


Figure 1. Representations of DSC [1]

4.3 The Formulation of Disturbed State Concept

Consider the material element which is based on the equilibrium of forces; the element is composed of the clusters of particles in the RI and FA parts (Figure 1). We obtain

$$F^a = F^i + F^c \tag{1}$$

Where F^a is the observed force, F^i is the force in relative intact part, and F^c is the force in fully adjusted part.

Division of both sides by the total area (A), also the corresponding area of the RI part and the FA part, A^i and A^c respectively, are applied in an equation. We have

$$\sigma^a = \sigma^i \cdot \left(\frac{A^i}{A}\right) + \sigma^c \cdot \left(\frac{A^c}{A}\right) \tag{2}$$

Where σ^a is the observed stress, σ^i is the stress in relative intact part, σ^c is the stress in fully adjusted part, and $A = A^i + A^c$.

However, we can express the ratio of the area in terms of disturbance function, namely

$$D = \frac{A^c}{A} \tag{3}$$

And

$$\frac{A^i}{A} = \frac{(A - A^c)}{A} = 1 - \left(\frac{A^c}{A}\right) = 1 - D \tag{4}$$

By substituting Eq. (3) and (4) into Eq. (2) yields

$$\sigma^a = (1 - D) \cdot \sigma^i + (D) \cdot \sigma^c \tag{5}$$

Eq. (5) is the basic equation for the DSC and we can use this equation to predict the response of material. Also we can use it for analysis and design of structural members. Furthermore, the resilient modulus can be found by division of both sides of Eq. (5) by the resilient strain (ε_R), we obtain

$$M_R^a = (1 - D) \cdot M_R^i + (D) \cdot M_R^c \tag{6}$$

Basically, the disturbance function is the ratio of interested factors with respect to the FA state. The foregoing disturbance function can be expressed in terms of any material properties which can be measured by laboratory tests. For instance, if the DSC is used to predict the resilient modulus, the disturbance function will be calculated by

$$D = \frac{(M_R^i - M_R^a)}{(M_R^i - M_R^c)} \tag{7}$$

In this study, Eq. (7) and the linear elastic RI response were used to back predict the resilient modulus-stress relationship of HCTCRB specimens.

5. Results and Discussion

Figures 2 (a) and (b) show the results from the static triaxial tests of the controlled set of HCTCRB samples. Figure 2 (b) indicates that the Mohr-Coulomb failure envelope, which is corresponding to the peak stresses, is a straight line with inclined slope of 1.723 (= $M_p = \frac{q}{p}$) and it intercepts the deviator stress at 339 kPa (= q_c).

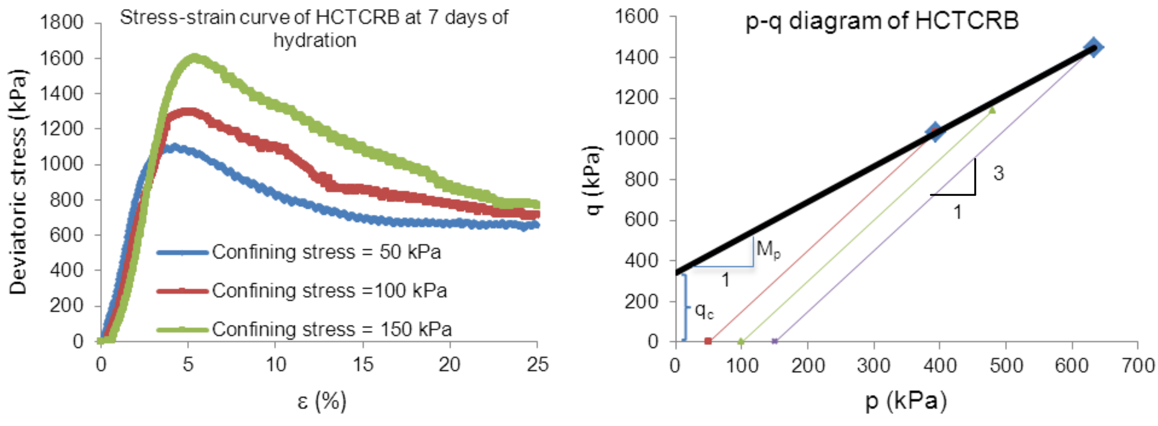
By observation on the experimental results, the resilient modulus-stress relationship of the samples are formed as a function of linearity, namely

$$M_R^a = (C_1)\left(\frac{\sigma_1}{\sigma_3}\right) + C_2 \tag{8}$$

Where C_1 and C_2 are constant.

σ_1 = Axial stress (kPa)

σ_3 = Confining stress (kPa)



(a) (b)

Figure 2. The static triaxial test results of controlled samples

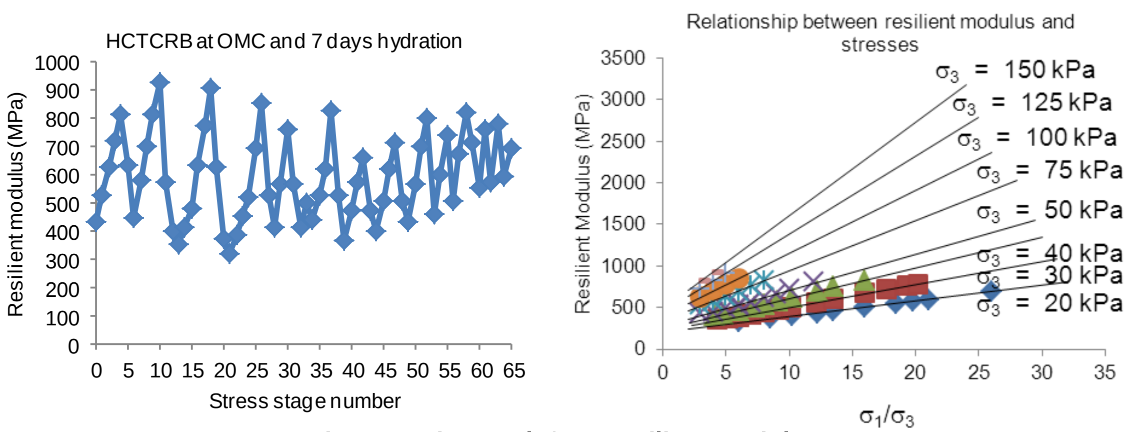


Figure 3. The result from resilient modulus test

Using the trial and error method applied with the averages procedure to determine the constants, we obtain

$$C_1 = (0.675)(\sigma_3) + 6.750$$

$$C_2 = (2.400)(\sigma_3) + 165.000$$

By applying linear elastic RI together with Eqs. (6), (7), and (8), the disturbance function (D) can be expressed as

$$D = \frac{[(2.400)(\sigma_3)+165.00]}{[(3.075)(\sigma_3)+171.750]} \quad (9)$$

Substituting Eq. (9) into Eq. (6) and rearrange the equation to conform the DSC formula, yield

$$M_R^a \text{ (MPa)} = \left\{\frac{[(0.675)(\sigma_3)+6.750]}{[(3.075)(\sigma_3)+171.750]}\right\}(M_R^i) + \left\{\frac{[(2.400)(\sigma_3)+165.000]}{[(3.075)(\sigma_3)+171.750]}\right\}(M_R^c) \quad (10)$$

Where $M_R^c = (3.075)(\sigma_3) + 171.75$ and $M_R^i = (M_R^c)\left(\frac{\sigma_1}{\sigma_3}\right)$.

Eqs. (9) and (10) show that the disturbed function is a function of confining stress (σ_3) and the relative intact resilient modulus is a function of stress ratio $\left(\frac{\sigma_1}{\sigma_3}\right)$.

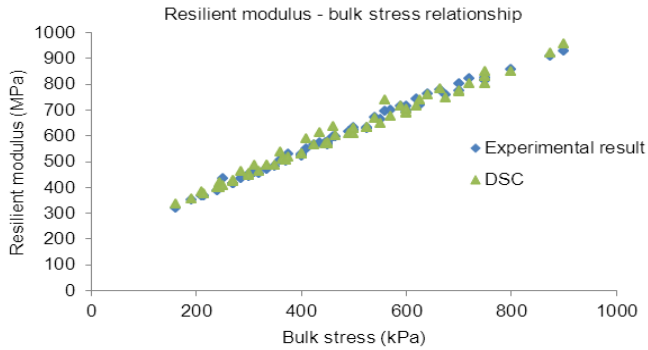


Figure 4. Comparing the resilient modulus between the use of DSC equation and the test results

Figure 4 shows the use of DSC equation to back predict the resilient modulus of HCTCRB. The results reveal that the use of the proposed DSC equation for calculating the resilient modulus gives a good prediction which is almost fitted to the value from laboratory tests.

6. Conclusions and Recommendations

According to the foregoing comparison, the resilient modulus-stress relationships which were back predicted using the DSC modelling were consistent with the experimental results. Based on the test data used, the main conclusions and recommendations are:

1. The DSC can be used for defining HCTCRB behaviour in pavement structure. For this study, emphasis was given to the prediction of the resilient modulus, which is important for analysis of structural pavement.
2. The proposed DSC equation can be used for predicting the resilient modulus-stress relation of the HCTCRB at 7-days of hydration period. Also, it could be modified to predict the resilient modulus of HCTCRB at any hydration period by using the experimental data [9].
3. The DSC model introduced in this study needs to be investigated to find whether it has the ability for prediction of the permanent deformation of HCTCRB samples, which is being used as one of the design criterion of pavement structure.

7. References

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