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Cover Photograph: The 190-m-high concrete-faced rockfill dam (CFRD) of Nam Ngum 2 Hydropower Project in Lao PDR, at its completion during the first impoundment. Construction of the project involved a variety of challenging geotechnical works that were executed under constraints of environment (Courtesy of Ch. Karnchang (Lao), Co., Ltd.)
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NOTES FOR GUIDANCE TO AUTHORS

SEAGS encourages the submission of scholarly and practice-oriented articles to its journal. Starting from 2008, the journal will be published quarterly. Before you submit an article, please review the guidelines stated herein for the manuscript preparation and submission procedures.

Geotechnical Engineering Journal accepts submissions via electronic or postal mail (by sending a CD). The manuscript file (text, tables and figures) in PDF format together with the submission letter should be submitted to the Editor, Geotechnical Engineering Journal, c/o School of Engineering and Technology, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand. E-mail noppadol@ait.ac.th or seags@ait.ac.th. Papers under review, accepted for publication, or published elsewhere are not accepted. The review and publication procedures will be faster if the basic requirements listed below are followed.

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2. The length of titles must not exceed 70 characters and spaces.
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4. Figures: Line art should be submitted in black ink or laser printed; halftones and color should be original glossy art. Figures should be submitted at final width i.e. 90 mm for one column and 185 mm for two columns. The font of the legends should be in Times New Roman and should use capital letters for the first letter of the first word only and use lower case for the rest of the words. Background screening and grids are not acceptable.
5. Each table must be typed on one side of a single sheet of paper.
6. All mathematics must be typewritten and special symbols identified. Letter symbols should be defined when they first appear.
7. The paper must end with a set of conclusions.
8. Practical applications should be included, if appropriate.
9. If experimental data and/or relations fitted to measurements are presented, the uncertainty of the results must be stated. The uncertainty must include both systematic (bias) errors and imprecisions.
10. Authors need not be Society members. Each author’s full name, Society membership grade (if applicable), present title and affiliation, and complete mailing address must appear as a footnote at the bottom of the first page of the paper.
11. Each author must use SI (International System) units and units acceptable in SI. Other units may be given in parentheses or in an appendix.
12. Maximum of five keywords should be given.
13. References should appear in the text as the author name(s) followed by the year of publication in parentheses. A list of references must be given at the end of the text in alphabetical order in capitals and double spacing must be used between references. An example of the format to be used in reference list are given below:


CHARACTERIZATION OF CEMENT-MODIFIED BASE COURSE MATERIALS FOR WESTERN AUSTRALIA ROADS

P. Jitsangiam, 1 H. R. Nikraz2, K. Siripun3

ABSTRACT: The cement-modified soil (CMS) is described as a soil that has been treated with a relatively small amount of cement in order to improve its engineering properties so that it is suitable for construction. This soil stabilization technique is employed for the typical base course material in Western Australia named “Hydrated Cement Treated Crushed Rock Base (HCTCRB)”1. In present, the mechanistic approach of pavement design and analysis become more important and widely used internationally but HCTCRB has been created from the empirical approach empirical approach point of view. In order to be able to use this material effectively relating to the new pavement design method, its shear strength, resilient modulus, and permanent deformation characteristics need to be more investigated and deeply understood. This study aimed to perform the results of the laboratory testing which was carried out to assess the mechanical characteristics of HCTCRB. Our findings show that HCTCRB can be characterized as a relevant cohesive granular material with significant shear strength parameters. Based on the laboratory results, the suitable models of the resilient modulus characteristics and the permanent deformation characteristics were determined and introduced

Keywords: Cement-Modified Soil (CMS), Cement modified base course material, Pavement, Repeated Loading Triaxial (RLT) test, Resilient modulus, Permanent deformation

INTRODUCTION

The cement-modified materials as a base course aggregate for Western Australia roads is crushed rock with the addition of 2% cement, described as Hydrated Cemented Treated Crushed Rock Base (HCTCRB). The main function of the base course is to reduce the vertical compressive stress induced by traffic, in the subbase and the subgrade, to a stress level at which no unacceptable deformation will take place in these layers. Knowledge of HCTCRB shear strength, resilient modulus, and permanent deformation characteristics is important because if these characteristics are well understood, pavement analysis and design can be more reliable than in the past where design was empirically based.

Currently most road and highway agencies rely on the California Bearing Ratio (CBR) to characterize pavement materials for design of pavements. CBR, however, is a static parameter which has been corrected empirically with response of the pavement materials under dynamic loads of moving vehicles. The permanent deformation of pavement materials is manifested as rutting and shoving, the visible damage on the road coming from excess deformation of the pavement. This is caused by the pavement material having insufficient stability to cope with the prevailing loading and environmental conditions. Consequently, clearly understanding shear strength, resilient modulus and permanent deformation characteristics of HCTCRB is important for improved reliability in design.

This study reports results of tests for shear strength parameters, the resilient modulus, and the permanent deformation of HCTCRB and to report on its characteristics so that a better understanding of the beneficial uses of the material can be gained

MATERIALS

Hydrated Cemented Treated Crushed Rock Base (HCTCRB)

Hydrated cemented treated crushed rock base (HCTCRB) is manufactured by blending 2% GP or Portland cement, which shall be the General Purpose (GP) or Portland cement (Australian Standard AS 3972-1997 1997), with standard crushed rock base (MAIN ROADS Western Australia 2003). HCTCRB is mixed and stockpiled in the range of -1.0% to +2.0% of the optimum moisture content of the untreated crushed rock base as obtained by WA 133.2(MAIN ROADS Western Australia 1997).

Crushed rock

The crushed rock, used in this study, was obtained from a local Gosnells Quarry. Crushed rock samples were collected randomly from a stockpile area and kept in sealed plastic containers. Samples were re-checked, at the Department of Civil Engineering, Curtin University of Technology, in the laboratory as to their important properties in accordance with the Crushed Rock Base (CRB) specification (MAIN ROADS Western Australia 2003).

Figure 1 shows the particle size distribution of the crushed rock of this study corresponded to the average particle size of the base course specifications. Comparisons of important properties and specifications were made as shown in Table 1.

Cement

The cement used in this study was the bagged type GP cement product of Cockburn Cement (COCKBURN CEMENT 2006) complying with Australian Standard(Australian Standard 1997).
For Specimen preparation

All HCTCRB samples were prepared based upon 100% OMC of the crushed rock. The mixing procedure consisted of adding 2% GP cement (by dry masses) to the crushed rock at the 100% OMC condition and mixing then all mixtures in the mixing machine at least 10 minutes or until the mixture being uniform in color and texture. The mixture then was kept at room temperature in sealed plastic bags for a 7-day period. After that, the mixture was then re-mixed in the same mixing machine at least for 10 minutes. Compaction was then carried out in a mould 100mm in diameter and 200mm in height, using 25 blows of a 4.9 kg rammer at 450mm drop height in 8 layers. This is equivalent to 100% Modified energy in terms of total energy per unit volume compared to conventional Modified mould. After compacting, the specimen was carefully removed from the mould. Immediately, after the specimen was removed from the mould, it was reweighed and wrapped with the plastic to prevent loss of moisture and then, the wrapped specimen was left before it was transferred to the bottom plate of the triaxial cell.

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Static triaxial tests

The drained triaxial compression tests were conducted to determine Mohr-Coulomb shear strength parameters (c and φ) of HCTCRB. The specimens were tested under the unsaturated condition (at the compaction condition) and suction were not measured during triaxial testing. In these tests, the specimen response was measured at three different constant confining pressures: 50kPa, 100kPa, and 150kPa. These tests were conducted with the same triaxial equipment and system used for the measurement of resilient modulus and permanent deformation.

Resilient modulus tests

The standard method of Austroads APRG 00/33-2000 (Young and Brimble 2000) for Repeated Load Triaxial Test Method was followed for the resilient modulus tests and the permanent deformation tests. The UTM-14P digital servo control testing machine which has an ability to conduct resilient modulus tests and permanent deformation tests was used in the Geomechanics Laboratory, Department of Civil Engineering, Curtin University of Technology. Fig.2 shows the apparatus performed in the testing process.

The specimens were placed within the triaxial cell and positioned between the base plate and crosshead of the testing machine. The dynamic axial stress came from a feedback-controlled high pressure air actuator capable of accurately applying a stress pulse following the acting stress of the standard. A confining pressure was generated by a closed loop controlled actuator to simulate the lateral stress of the standard. A confining pressure was generated accurately applying a stress pulse following the acting pressure acting on the surrounding materials, as would occur in a road. The confining pressure was applied by air pressure. The machine conveyed a vertical dynamic force of rectangular waveform with a period of 3 secs and a load pulse of 1sec duration, in accordance with the standard requirements and is demonstrated in Fig.3.

The load cell, the confining pressure, and the externally linear variable differential transducer (LVDT) on the top of the triaxial cell, which was used to measure deformations over the entire length of the specimen, were measured by the control of a control and data acquisition system (CDAS).
which provided the control signals, signal conditioning, data acquisition. The CDAS was communicated 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.

Fig. 2 Triaxial test machine used in this study.

In accordance with this standard, the specimens were applied sequentially by the difference of the 65 stress stages to check the elastic condition of each specimen throughout the multiple loading stress stages as shown in Fig.4. This process simulates the complicated traffic loading acting on pavement. Before performing the resilient modulus process, a pre-conditioning stage was carried out to allow the end caps to bed into the specimen and allow the applied stresses and resilient strains to stabilise under the imposed stress condition. For these reasons, 1000 loading cycles of pre-conditioning were used and for each stress stage after pre-conditioning, 200 loading cycles were applied to the specimens.

Permanent deformation tests

New specimens were prepared following the same method as the resilient modulus specimens, described in item 3.1. Permanent deformation testing was calculated in accordance with Austroads – APRG 00/33 standard (Young and Brimble 2000). In this testing, the specimens were loaded with three stress stages, each involving 10,000 cycles at a stress condition of specific dynamic deviator stress and static confining pressure as shown in Table 2.

### RESULTS AND DISCUSSION

**Static triaxial tests**

Static triaxial tests by means of the drained triaxial compression tests were performed to obtain information on the cohesion, c, and the internal friction angle, φ, of HCTCRB. These tests also established the failure line of HCTCRB to determine the maximum stress level which could be applied on this material, so that the limited uses of HCTCRB would be known. The confining pressures of 50kPa, 100kPa, and 150kPa were applied on the tested specimens in each test. The characteristics of each test are summarized in Table 3. This should be noticed that the dry unit weight and the water content of HCTCRB were slightly less than the fresh crushed rock values (MDD= 2.27ton/m³ at OMC=5.5%) after the 7-day hydration period.

### Table 2 Stress levels for permanent deformation of base materials following Austroad-APRG 00/33 standard

<table>
<thead>
<tr>
<th>Permanent Deformation Stress Levels</th>
<th>Stress Stage Number</th>
<th>Confining pressure, σ₃ (kPa)</th>
<th>Dynamic deviator stresses, σ₄ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>1</td>
<td>50</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>50</td>
<td>450</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>50</td>
<td>550</td>
</tr>
</tbody>
</table>

* Water content of the sample after the hydration period of 7 days.
Figure 5(a) depicts the relationship of the deviator stress and the axial strain at the three selected confining pressure. It also can be observed that the static deviator stress initially increases with increasing the axial strain until it reaches the peak strength. For a higher confining pressure, apparently, the peak strength becomes higher and strain corresponding to the peak strength becomes higher, as well. All three curves in Fig. 5(a) exhibit that after the peak strength taken place, the postpeak regime, during 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 caused geometrically non-linear effects to become important (Suiker, Selig et al. 2005).

The peak strength of HCTCRB in these tests was interpreted by means of a Mohr-Coulomb failure law that the cohesion, c, and the internal friction angle, φ, are considered in a failure relationship, a straight line fitted to a Mohr envelope (Lamb and Whitman 1979).

Figure 5(b) shows the static triaxial test results of HCTCRB on the p-q diagram. On this diagram, the Mohr-Coulomb failure was defined in terms of principle stresses (principle stresses have been written as \(\sigma_1\) = the major principle stress and \(\sigma_2=\sigma_3\) = the intermediate or minor principle stress). The deviator stress, \(q=(\sigma_1-\sigma_3)\), was plotted against the mean applied stress, \(p=(\sigma_1+2\sigma_3)/3\). The results shown in Fig. 6 indicate that the Mohr-Coulomb failure envelope (corresponding to the peak stresses) is linear for the stress range tested and has the characteristic in p-q stress space: \(M_p=q/p=1.723\) with a deviator stress intercept, \(q_c=239\) kPa. In the conventional Mohr-Coulomb stress space, thus the properties failure correspond to an internal friction angle (\(\phi\)) at peak strength of 42° and apparent cohesion (c) of 177 kPa.

The results of the static triaxial test of HCTCRB show that it performs the cohesive granular material behaviors. HCTCRB is not the non-cohesive granular material like the general non-cohesive granular materials such as sands and gravels. The behaviors of HCTCRB strongly depend upon both degrees of cohesion and internal friction angle.

**Resilient modulus tests**

The resilient modulus determined from the RLT test is defined as the ratio of the repeated axial deviator stress to the recoverable or resilient axial strain as shown in Fig. 6 and equation (1):

\[
M_r = \frac{\sigma_d}{\varepsilon_r}
\]

Where \(M_r\) is the resilient modulus, \(\sigma_d\) is the repeated deviator stress (cyclic stress in excess of confining pressure), and \(\varepsilon_r\) is the resilient (recoverable) strain in the vertical direction.

Figure 7 shows the results of the resilient modulus which are plotted against with the bulk stress \((\sigma_1+\sigma_2+\sigma_3)\). Generally, the resilient modulus is non-linear with respect to the magnitude of applied stresses. Fig. 7 also shows the results of resilient modulus of HCTCRB can be modeled reasonably by using The K-Theta (K-θ) model (Hick and Monismith 1971).

The representative K-θ model of HCTCRB is exhibited in equation (2).

\[
M_r = k_1\theta^k_2 = 7.684\theta^{0.591}
\]

Where: \(M_r\) is Resilient modulus in MPa; \(\theta\) is bulk Stress \((\sigma_1+\sigma_2+\sigma_3)\) where \(\sigma_1=\sigma_3\); \(\sigma_1\) is major principal stress (axial stress); \(\sigma_3\) is minor principal stress (confining stress); \(k_1=7.684\) and \(k_2=0.591\) are regression coefficients.
Permanent deformation tests

Figure 8 (a) and (b) shows the typical results of the permanent deformation test in terms of relationship between permanent deformation and loading cycles for HCTCRB. The various test values could be extracted from Fig.8(a) for uses in assessing the potential for permanent deformation. Furthermore, from Fig.8(a), it can be noted that the permanent deformation of HCTCRB is not dominated by the applied load in the testing range because when the applied loads increase from loading stage 1 to loading stage 3, the permanent deformation of HCTCRB did not increase dramatically. In contrast, the number of loading cycles seemed to be more influential to the permanent deformation values. Fig.8(b) exhibits the comparison of the measured permanent deformation values and the predicted values for a proposed permanent deformation model of HCTCRB. Fig.8(b) indicates that the permanent deformation can be modeled quite reasonably for HCTCRB by using the model suggested by Sweere, G.T.H from SAMARIS(SAMARIS 2004). The proposed permanent deformation model of HCTCRB is shown in equation (3).

\[ \varepsilon^p = A \cdot N^B = 573.223 \cdot N^{0.074} \]  (3)

Where: \( \varepsilon^p \) is permanent deformation in Micrometers; \( A=573.223 \) and \( B=0.074 \) are regression constants; and \( N \) is the number of loading cycles.

CONCLUSIONS

The mechanical behavior of Hydrated Cement Treated Crushed Rock Base (HCTCRB) which is normally used for a base course material in Western Australia were investigated by means of static and repeated loading triaxial tests. The repeated loading triaxial tests were carried out in terms of the resilient modulus test and the permanent deformation test to provide insight into the resilient and permanent deformation characteristics of this material under the real conditions of traffic loading simulated in these tests.

It has been shown that HCTCRB can be characterized as an apparently cohesive granular material which has the cohesion (c) of 177kPa and the internal friction angle (\( \phi \)) of 42°over the stress range significant for pavement behavior. Based on the Austroads – APRG 00/33 test standard, the resilient modulus characteristics could be modeled using the K-0 model. The permanent deformation characteristics could be modeled by using the Sweere’s model.
ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Centre of Sustainable Resource Processing (CSRP) for the financial support and Western Australia Main Roads for a lot of assistance to the research group.

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