Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 2(6):257-263
Copyright @ Chinese Society of Pavement Engineering

Characterization Analysis and Design of Hydrated Cement Treated Crushed Rock Base as a Road Base Material in Western Australia

Komsun Siripun[1+], Peerapong Jitsangiam[2], and Hamid Nikraz[3]

Abstract: The paper reports characterization of Hydrated Cement Treated (HCTCRB) that widely used as a road base material for Western Australian roads, been designed and used based on empirical approach and experience practices respectively. However, the traditional methods are not sufficient to achieve acceptable pavement performance. In the present, mechanistic approach becomes more reliable in pavement design and analysis. Consequently, the characterization of HCTCRB following the mechanistic pavement design and analysis concept is necessary. The main objective of this study is to report the results of standard and sophisticated laboratory tests to assess the mechanical characteristics of HCTCRB based on the mechanistic concept. Conventional triaxial tests and repeated load triaxial tests (RLT tests) were performed. Factors which would affect the performance of HCTCRB, hydration periods, and the amount of added water were also investigated. CIRCLY, a computer program based on the multi-layer elastic theory was used in the mechanistic approach of pavement design and analysis to determine the performance of a typical pavement model using HCTCRB as a base course layer and then the mechanistic pavement design parameters of HCTCRB for a base course material were introduced.

Key words*: Crushed rock base (CRB); Hydrated cement treated crushed rock base (HCTCRB); Mechanistic pavement design and analysis; Pavements; Repeated load triaxial (RLT) tests.*

Introduction

Crushed rock with the addition of 2% general purpose (GP) Portland cement, named hydrated cemented treated crushed rock base (HCTCRB), is commonly used as a base course material for Western Australian roads. Understanding HCTCRB with respect to shear strength, resilient modulus, and permanent characteristics is important because if these characteristics are well-understood, pavement analysis and design can be more precise than in the past.

An accurate definition of HCTCRB cannot yet be confirmed as modifications have periodically been made as a result of problems that have been encountered to date. HCTCRB is not like a modified or stabilized cement treated base as after the hydration period, it is retreated in order to maintain the properties of the unbound material (by breaking the cementitous bonds generated during the hydration time). The retreating process is aimed to prevent drying shrinkage cracks which usually occur in cement treated materials. Over the years, HCTCRB has been widely used for road construction in Western Australia (WA), with a higher modulus value (about 800-1000*MPa*) for use in heavy traffic pavements. More than 250,000 tones of HCTCRB have been used at a cost in excess of $10 million over the last eight years. For example, it has been successfully used for the Main Freeways in Perth.

In practice, a large volume of HCTCRB is usually produced daily and kept in stockpiles for an appropriate hydration period although it is difficult to control the same hydration period in use and the amount of appropriate water added. For the construction point of view, there are some doubts in its manufacturing processes regarding the effect of hydration periods and amount of added water relative to its performance. Both factors need to be investigated for its more effective use.

This study aims to analyze shear strength parameters, the resilient modulus, the permanent deformation of HCTCRB, and report on these characteristics and investigate the effect of hydration periods and added water on the performance of HCTCRB to introduce the pavement design parameters of HCTCRB based on the mechanistic pavement design so that a better understanding of the use of the material will be gained.

Experimental Programs

Materials

Crushed Rock Base (CRB)

The crushed rock used in this study was collected from a local stockpile of Gosnells Quarry and kept in sealed containers. Repeated load triaxial (RLT) tests were performed on samples complying with Western Australia Main Roads (MRWA) base course specifications [1] as shown in Table 1 and Fig. 1 illustrates the grading curve of the crushed rock with the upper and lower band of the base course specifications.

Hydrated Cemented Treated Crushed Rock Base (HCTCRB)

HCTCRB is manufactured by blending 2% cement with a standard

---

[1] PhD candidate, Department of Civil Engineering, Curtin University of Technology, Perth, WA, Australia 9845.

[2] Lecturer, Department of Civil Engineering, Curtin University of Technology, Perth, WA, Australia 9845.

[3] Professor, Department of Civil Engineering, Curtin University of Technology, Perth, WA, Australia 9845.

[+] Corresponding Author: E-mail komsun.siripun@postgrad.curtin.edu.au

Note: Submitted March 18, 2009; Revised June 29, 2009; Accepted July 10, 2009.

Table 1. Characterisation Tests (Main Roads Western Australia 2006).

Tests*	Results
Liquid Limit, LL	22.4%
Plastic Limit, PL	17.6%
Plastic Index, PI	4.8%
Linear Shrinkage, LS	1.5%
Flakiness Index, FI	22.5%
Maximum Dry Density, MDD	2.27*t/m*^{3}
Optimum Moisture Content, OMC	5.5%
Coefficient of Uniformity, Cu	22.4
Coefficient of Curvature (Cc)	1.4
% Fines	5 %
Cohesion of CRB (c)**	32*kPa*
Internal Friction Angle of CRB (ϕ) **	59°
Max. Dry Compressive. Strength, MDCS	3,528*kPa*
California Bearing Ratio, CBR	180

* Test methods in accordance with MRWA Test Method (MAIN ROADS Western Australia 2006).

** Drained triaxial compression tests at the100% OMC condition.

dry weight CRB [1]. It is mixed and stockpiled in the range of -1.0 to +2.0% of the optimum moisture content of the untreated CRB as obtained by MRWA Test Method WA 133.1[2] during the initial hydration 7-day period. Fig. 2 shows the comparison of the compaction curves between CRB and HCTCRB. In Fig. 2, MDD and OMC of HCTCRB change to 2.12*t/m*^{3} and 8%, respectively; from 2.27*t/m*^{3} and 5.5% of CRB. This figure indicates that after cement hydration occurs, the impact of cement on soil compaction was increased for optimum moisture content [3].

Cement

The cement used in this study was the bagged cement product of Cockburn Cement [4] of General Purpose Portland Cement - type GP following the standard of AS 3972-1977[5] as shown in Table 2.

Laboratory Program and Testing

The fresh crushed rock and HCTCRB (fresh crushed rock with 2% cement by dry weight) were initially tested in terms of the compaction test in accordance with MRWA Test Method WA 133.1[2] to establish the compaction curves for determining their OMC as shown in Fig. 2. HCTCRB samples for RLT tests then were made at 100, 90, and 80% OMC of HCTCRB by varying the hydration periods of 7, 14, and 30 days.

The test program consisted of both static and RLT tests. The static tests were carried out to establish the cohesion, c, and the internal friction angle, ϕ, of HCTCRB in the condition of 100% OMC at a 7-day hydration period and 28 days curing time including establishing the Mohr-Coulomb failure envelope. Repeated loading tests were performed to establish the relationships between the applied stress conditions and the resilient modulus values and the permanent deformation behavior of HCTCRB.

Specimen Preparation

All tested HCTCRB samples were prepared based upon 100, 90, and

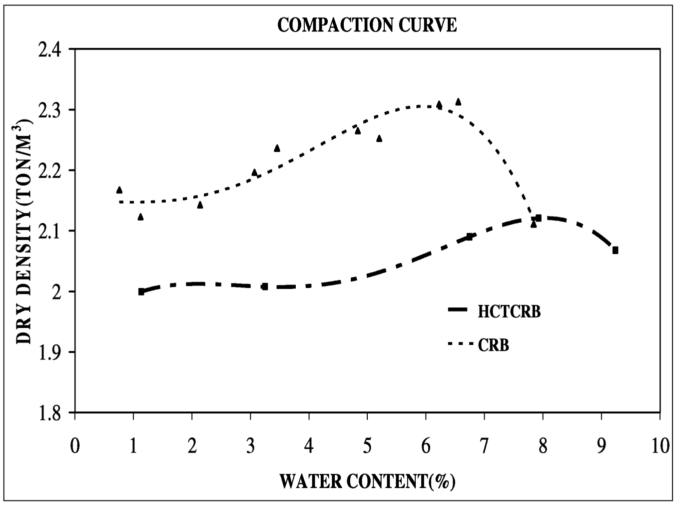


Fig. 2. Compaction Curve of CRB and HCTCRB.

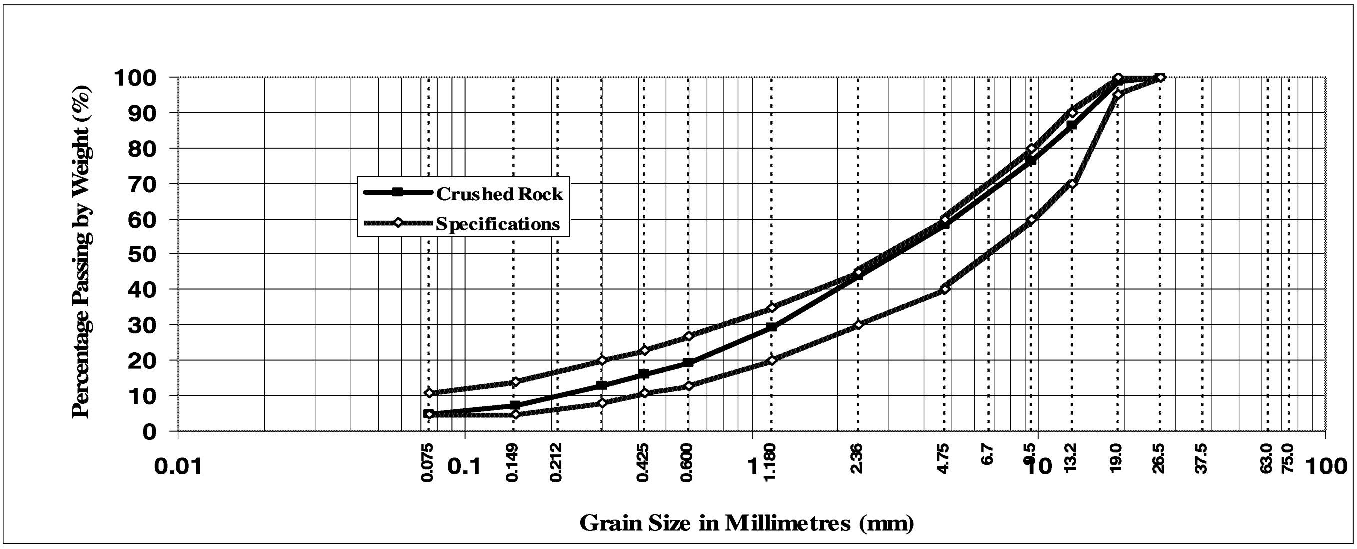


Fig. 1. Grading Curve of Crushed Rock with WA Main Roads Specifications.

Table 2. General Specifications of the Cement Used in This Study (Cockburn Cement 2006).

Parameter	Method	Units	Typical	Range	AS3972-1977 Limits
Chemical Analysis					
SiO_2					
Al_2O_3	XRF	%	20.7	19.5-21.6	-
Fe_2O_3	XRF	%	4.8	4.5-5.3	-
CaO	XRF	%	2.7	2.3-3.1	-
MgO	XRF	%	63.8	62.2-65.5	-
SO_3	XRF	%	2.1	1.5-2.8	-
LOI	XRF	%	2.5	2.0-3.2	3.5% max
Chloride	AS2350.2	%	1.8	0.5-2.7	-
Na_2O Equiv.	ASTM C114	%	0.01	0.01-0.02	-
	ASTM C114	%	0.50	0.45-0.65	-
Fineness Index	AS2350.8	m^2/kg	400	350-450	-
Normal Consistency	AS2350.3	%	29.5	28.0-30.0	-
Setting Times	AS2350.4				
Initial		mins	120	90-150	45mins min
Final		mins	190	135-210	10hrs max
Soundness	AS2350.5	*mm*	1	0-2	5*mm* max
Compressive Strength	AS2350.11				
3 Days		*MPa*	38	33-40	-
7 Days		*MPa*	48	41-52	25*MPa* min
28 Days		*MPa*	60	53-68	40*MPa* min

80% OMC of HCTCRB. The procedure entailed adding 2% GP cement (dry masses) to the wet crushed rock and each mixture was placed in the mixing machine for at least 10 minutes or until it became uniform in color and texture. The mixtures were then kept at room temperature in sealed plastic bags for periods of 7, 14, and 30 days. For a mixture of a particular OMC and hydration period, it was then re-mixed in the same machine for at least 10 minutes in accordance with MRWA specifications [6]. Compaction processes were then carried out using a modified compaction method in a standard mould 100*mm* in diameter and 200*mm* in height. Compaction was achieved with 25 blows of a 4.9*kg* rammer at 450-mm drop height in 8 layers. The specimens were kept in moulds wrapped to prevent loss of moisture for 28 days.

Static Triaxial Tests

Drained triaxial compression tests were conducted to determine the shear strength parameters (c and ϕ) of HCTCRB. Only specimens at 100% OMC of the 7-day hydration period and the 28-day curing time were tested under unsaturated conditions based on the HCTCRB standard and suctions were not measured. In these tests, the specimen response was measured at three different constant confining pressures: 50, 100, and 150*kPa* using the same triaxial equipment and system for the measurement of resilient modulus and permanent deformation.

Resilient Modulus Tests and Permanent Deformation Tests

The standard method of Austroads APRG 00/33-2000 [7] 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 in the Geomechanics Laboratory, Department of Civil Engineering, Curtin University of Technology was used.

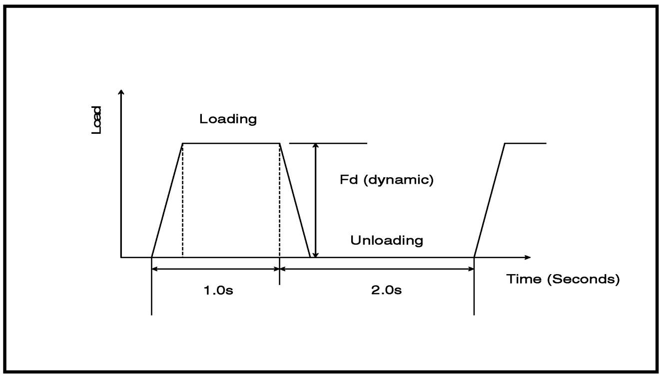


Fig. 3. Illustration of the Vertical Force Waveform.

New specimens were prepared as described 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 0.33Hz (see the vertical force waveform in Fig. 3) to the static confining stress (σ_3) as shown in Table 3, each involving 10,000 cycles for each particular stress condition.

After permanent deformation tests, in accordance with this standard [7], the same specimens were applied sequentially by the difference of the 65 stress stages straightaway to conduct the resilient modulus test to check the elastic condition of each specimen throughout the multiple loading stress stages. This process simulates complicated traffic loading acting on pavement. Two hundred loading cycles of each stress stage were applied to the specimens. Table 4 shows the stress levels for the resilient modulus.

Quality Control of All Tests

Table 3. Stress Levels for Permanent Deformation Following Austroad-APRG 00/33 Standard.

Permanent Deformation Stress Levels (Base)		
Stress Stage Number	Confining Pressure σ_3 (*kPa*)	Dynamic Deviator Stresses σ_d (*kPa*)
1	50	350
2	50	450
3	50	550

Table 4. Stress Levels for the Resilient Modulus Following Austroad-APRG 00/33 Standard.

Resilient Modulus Stress Levels								
Stress Stage Number	σ_3 (*kPa*)	σ_d (*kPa*)	Stress Stage Number	σ_3 (*kPa*)	σ_d (*kPa*)	Stress Stage Number	σ_3 (*kPa*)	σ_d (*kPa*)
0	50	100	22	30	150	44	20	185
1	75	150	23	40	200	45	30	275
2	100	200	24	50	250	46	40	370
3	125	250	25	75	375	47	50	450
4	150	300	26	100	500	48	30	275
5	100	200	27	50	250	49	20	225
6	50	150	28	30	180	50	30	335
7	75	225	29	50	300	51	40	450
8	100	300	30	75	450	52	50	550
9	125	375	31	50	300	53	20	250
10	150	450	32	30	180	54	30	375
11	75	225	33	40	250	55	40	500
12	40	125	34	30	210	56	20	300
13	30	100	35	40	280	57	30	450
14	40	150	36	50	350	58	40	600
15	50	200	37	75	525	59	30	500
16	75	300	38	40	280	60	20	350
17	100	400	39	20	150	61	30	550
18	125	500	40	30	245	62	20	375
19	75	300	41	40	325	63	30	575
20	30	125	42	50	400	64	20	400
21	20	100	43	30	245	65	20	500

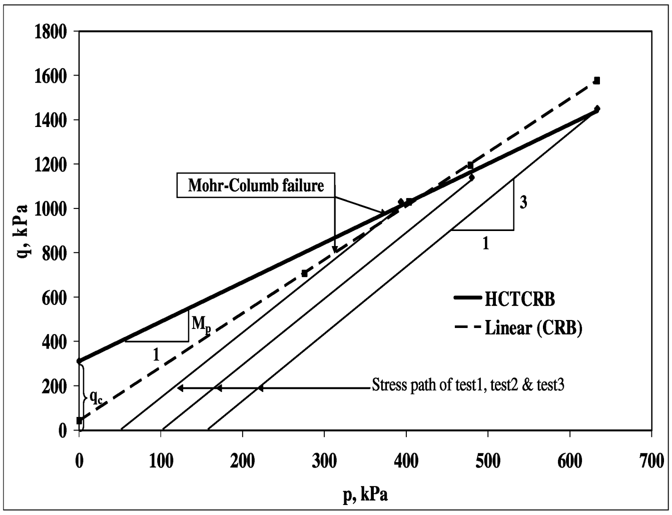


Fig. 4. Triaxial Test Results of HCTCRB Compared with CRB in p-q Stress Spaces.

Triplicate tests were performed on each sample and the averages reported as results. The coefficient of variation, CV (ratio of standard deviation to the mean) was less than 10% in all tests.

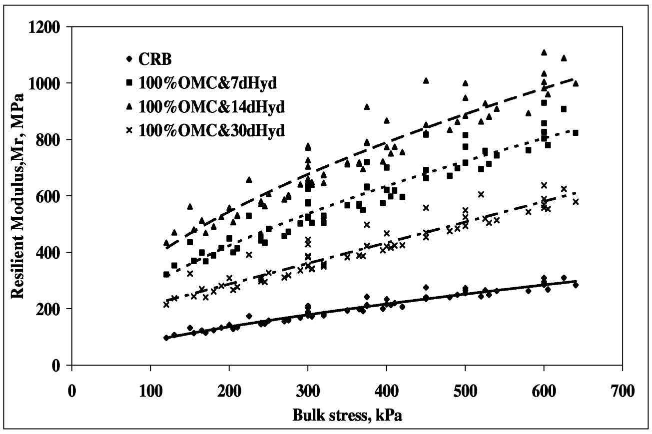


Fig. 5. The Resilient Modulus with Different Hydration Periods.

Test Results and Discussion

Static Triaxial Tests

Fig. 4 shows the static triaxial test results of HCTCRB on the p-q diagram where the Mohr-Coulomb failure was defined in terms of principle stresses (principle stresses have been written as σ_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. 4 indicate that the Mohr-Coulomb failure envelope (corresponding to the peak stresses) is linear for the stress range tested and has a characteristic in p-q stress space: $M_p = q/p = 1.723$ with a deviator stress intercept, $q_c = 339 kPa$. In the conventional Mohr-Coulomb stress space, the properties failure correspond to an internal friction angle (ϕ) at a peak strength of 43° and an apparent cohesion (c) of 168*kPa* compared to 59° and 32*kPa* respectively of CRB results.

The static triaxial test results of HCTCRB show that it improves the cohesive granular material behavior unlike the non-cohesive granular materials such as sands and gravels. The behavior of HCTCRB depends strongly upon both degrees of cohesion and the internal friction angle.

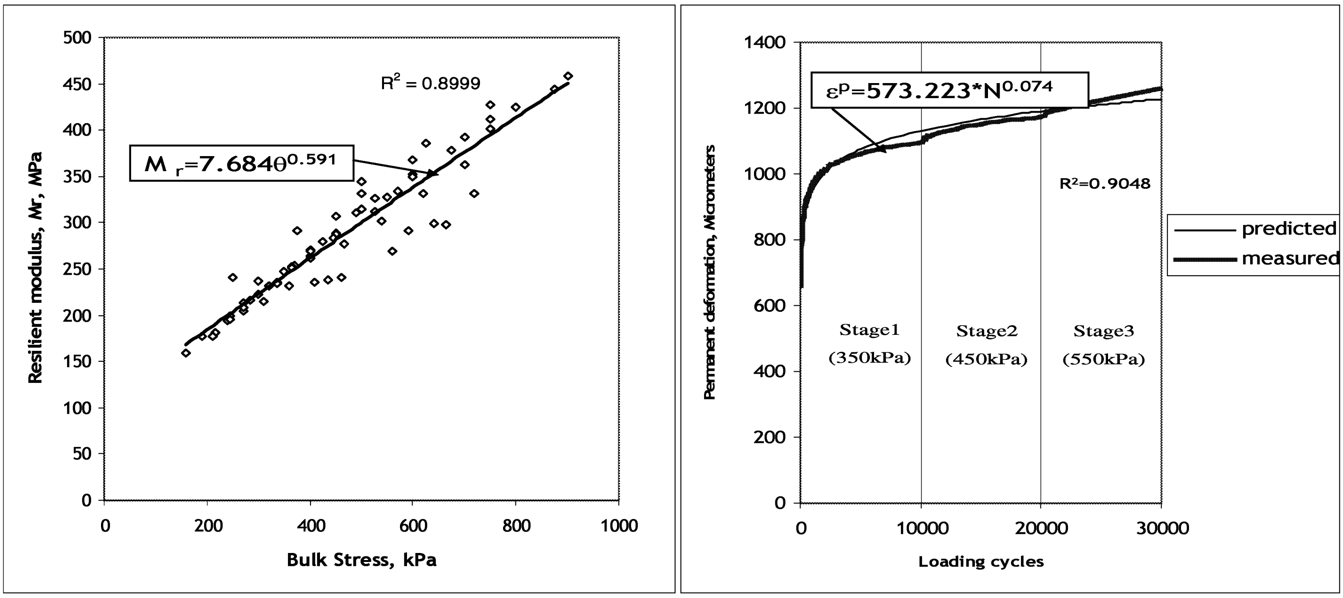
Resilient Modulus Tests and Permanent Deformation Tests

The resilient modulus determined from the repeated loading triaxial test is defined as the ratio of the repeated axial deviator stress to the recoverable or resilient axial strain:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \qquad (1)$$

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

Based on the specification of HCTCRB, the results of HCTCRB in the condition of 100% OMC at the 7-day hydration period and the 28-day curing time are represented to show its characteristics and to determine suitable mathematical models of resilient modulus and permanent deformation of HCTCRB.



(a)

(b)

Fig. 6. The Resilient Modulus and Permanent Deformation Predictions.

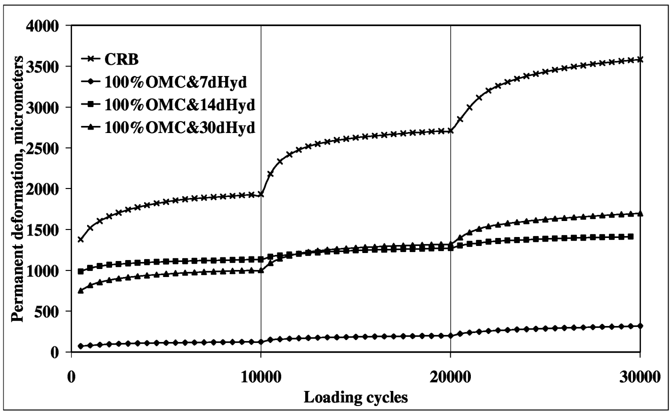


Fig. 7. Permanent Deformation with Different Hydration Periods.

Fig. 5 shows the results of the resilient modulus test which are plotted against the bulk stress ($\sigma_1+\sigma_2+\sigma_3$). Generally, they are non-linear with respect to the magnitude of applied stresses. Fig. 5 also shows the results of resilient modulus of HCTCRB can be modeled reasonably by using The K-Theta (K-θ) model [8]. The representative K-θ model of HCTCRB is exhibited in Eq. (2).

$$M_r = k_1\theta^{k_2} = 7.684\theta^{0.591} \tag{2}$$

Where M_r is resilient modulus in *MPa*; θ is bulk stress ($\sigma_1+\sigma_2+\sigma_3$) where ($\sigma_1 = \sigma_3$); σ_1 is major principal stress (axial stress); σ_3 is minor principal stress (confining stress); k_1 = 7.684 and k_2 = 0.591 are regression coefficients as shown in Fig. 6(a).

Fig. 7 shows the typical results of the permanent deformation tests in terms of the relationship between permanent deformation and loading cycles for HCTCRB at different hydration periods. Fig. 6(b) exhibits the comparison of the measured and permanent deformation values and the predicted values for a proposed permanent deformation model of HCTCRB. Fig. 6(b) also indicates that the permanent deformation can be modeled quite reasonably for HCTCRB by using the model suggested by Sweere from SAMARIS [9]. Sweere suggested for the long-term deformation behavior of unbound granular materials (UGMs) under a large number of load cycles, an approach should be employed as the proposed permanent deformation model of HCTCRB as shown in Eq. (3).

$$\varepsilon^p = A*N^B = 573.223*N^{0.074} \tag{3}$$

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

The Effects of Hydration Periods and Water Added to HCTCRB on Its Performance

Fig. 8 shows all the results of HCTCRB samples of 100, 90, and 80% OMC at 7, 14, and 30-day hydration periods. Resilient modulus values are plotted against loading sequences. All HCTCRB samples show significantly higher resilient modulus values than CRB. Indicating CRB can improve its resilient modulus characteristic by using the HCTCRB technique.

- There is a slight difference of resilient modulus characteristics of HCTCRB at all percentages of OMC over 7, 14, and 30-day periods. That means the hydration period and added water in this investigation do not affect the performance of HCTCRB in terms of the resilient modulus characteristics very much. This results from the re-treating before compaction in HCTCRB producing processes. During the hydration period, the chemical reaction between cement and water to generates the cementatious bonding. The bonding is broken up in the re-treating process. Although a

Table 5. Pavement Configurations Used in the CIRCLY Analysis.

		Design Traffic Load = 1.0 x 10^7 ESA		
Layer No.	Material ID	Isotropy	Modulus (*MPa*)	Layer Thickness (*mm*)
1	Asphalt	Isotropic	3000	40
2	HCTCRB	Anisotropic	750	150-350
3	Unbound Granular Crushed Limestone	Anisotropic	350	200
4	Subgrade CBR 15	Anisotropic	150	Infinite

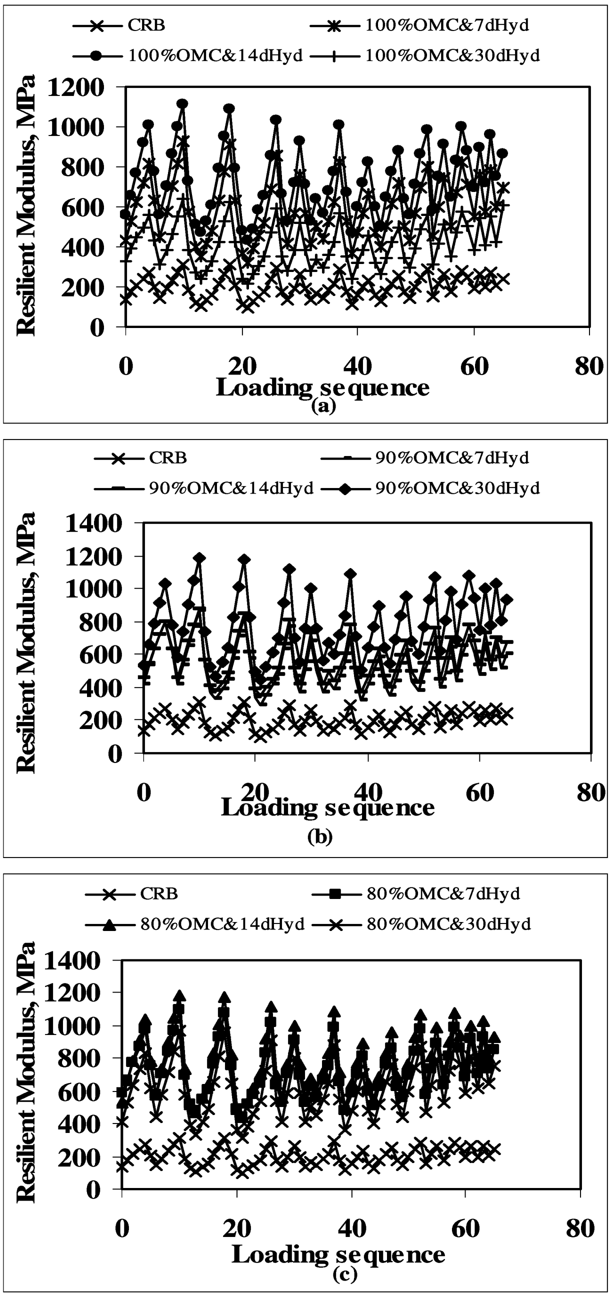


Fig. 8. The Resilient Modulus Results with Different % OMC and Hydration Periods.

compaction process is performed directly after the re-treating process, the chemical bonding, which is significant to the strength, is hard to generate further. The mixture is only compacted from the same energy effort thus the resilient modulus characteristics of all samples with different conditions of water and hydration periods are slightly different.

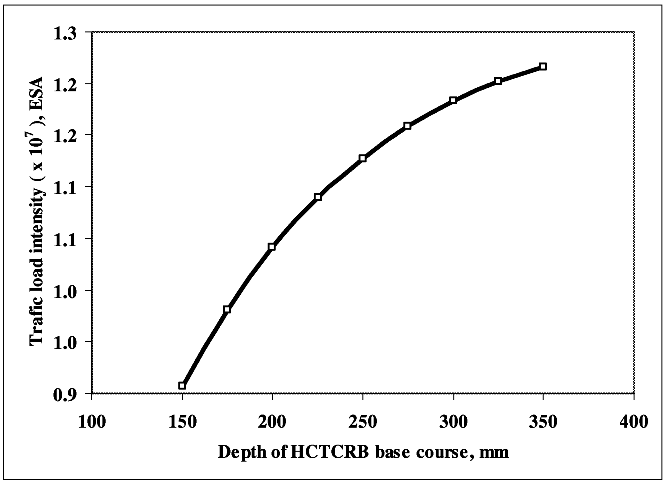


Fig. 9. CIRCLY Analysis Results.

- All HCTCRB samples exhibit the stress-dependency behavior.
- Based on 65 stress levels, the resilient modulus values of all HCTCRB samples of these conditions are between 300 and 1,100*MPa*.

General Pavement Design on HCTCRB for Road Bases

Based on the mechanistic pavement analysis and design for HCTCRB, its modulus test result is stress dependent. It was found that the stress dependency of vertical modulus can be modeled by using the elastic model CIRCLY [10] by dividing the granular layers into several sub-layers. From the mechanistic design step, the pavement structure scenario was established first from the generally used pavement cross-section in Western Australia which contains asphalt as a road surface, HCTCRB as a road base, crushed limestone as a road subbase, and Perth silty sand as a road subgrade. The pavement was analyzed to find the vertical and the horizontal stresses occurring in the HCTCRB base layer by using the MICHPAVE finite element program [11]. The suitable resilient modulus of HCTCRB for mechanistic design was determined from its resilient modulus model by relying on the laboratory results of the modulus tests. CIRCLY 5.0 was used for mechanistic pavement design to determine the traffic loading intensity of a HCTCRB base course road.

This software uses state-of-the-art material properties and performance models and is continuously being developed and extended. The first mainframe version of CIRCLY was released in 1977 and the current Windows version is CIRCLY 5.0. It is an integral component of the Austroads Pavement Design Guide widely used in Australia and New Zealand. The system calculates the cumulative damage induced by a traffic spectrum consisting of any combination of user-specified vehicle types and load configurations. As well as using the usual equivalent single wheel and axle load approximations, optionally the contribution, such as foundation engineering and settlement analysis, can also be analyzed using CIRCLY. CIRCLY is based on integral transform techniques and offers significant advantages over linear elastic analysis techniques such as the finite element method.

In this study because computer programs are relevant to pavement analysis and design, a suitable resilient modulus model is an important input parameter for the program. Generally, it is non-linear with respect to the magnitude of applied stresses. Fig. 6(a) indicates that the K-θ model [8] which is the significant model for non-linear behavior of the granular materials suitable to modeling the stress dependence quite reasonably for HCTCRB as shown in Fig. 6(a).

Table 5 shows a summary of the pavement configuration analyzed in CIRCLY 5.0 and Fig. 9 illustrates the results from CIRCLY 5.0 in terms of the graph of the traffic loading intensity of Equivalent Single Axial (ESA) of 80*kN* plotted against the varied depth of HCTCRB. CIRCLY 5.0 is capable of conducting parametric analysis with one independent parameter of HCTCRB depth from 150 to 350*mm*. This figure indicates that more than 185*mm* of HCTCRB depth could resist a traffic load higher than the design (1.0×10^7 ESA) which was the estimation of a amount of traffic in the service life of a road based on the cumulative data of current traffic conditions in target areas with some assumption of forecasting future conditions. From these results, it is suggested that the appropriate depth of HCTCRB as a base layer be at least 185*mm*.

Conclusions

The mechanical behaviors of Hydrated Cement Treated Crushed Rock Base (HCTCRB), normally used for a base course material in Western Australia, were investigated by means of static and repeated loading triaxial tests. The 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 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 a cohesion (c) of 168*kPa* and an internal friction angle (ϕ) of 43° 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-θ model. The permanent deformation characteristics could be modeled by using Sweere's model.

The hydration period and the amount of water added in this investigation do not significantly affect the performance of HCTCRB. All the samples show stress-dependency behavior. Based on the stress stage of this experiment, the resilient modulus values of HCTCRB in this study are in the range of about 300 to 1,100*MPa*.

For the design of HCTCRB for road bases following the typical model of pavement relying on the laboratory results and CIRCLY 5.0 program, it is suggested that:

- The suitable depth of HCTCRB as a base layer for WA roads can be at least 185*mm*.
- The traffic load intensity of the construction and demolition (C&D) aggregate-base course road can be about 1×10^7 ESA.

References

1. Main Roads Western Australia, (2006). Crushed Rock Base Base Course, *Main Roads Western Australia*, pp. 13-17, Australia.
2. Main Roads Western Australia, (2007), Dry Density/Moisture Content Relationship: Modified Compaction Fine and Medium Grained Soils, *Main Roads Western Australia*, pp. 1-6, Australia.
3. Zhang, Z. and Tao, M., (2008). Laboratory Testing of Cement-Treat Wet Subgrade and Design Recommendations, *International Journal of Pavement Research and Technology* 1(4), pp. 135-142.
4. COCKBURN CEMENT, (2006). Cockburn General Purpose Portland Cement Type GP, *General Specification*, Retrieved: November, 2006, from http://www.cockburncement.com.au /productinfo/range/specifications/Cockburn%20GP.pdf
5. Australian Standard, (1997). Portland and Blended Cements, *Australian Standard*, pp. 1-10, Australia.
6. Main Roads Western Australia, (2008). Pavements, *Main Roads Western Australia, Specification 501*, Australia.
7. Voung, B.T. and Brimble, R., (2000). Austroads Repeated Load Triaxial Test Method - Determination of Permanent Deformation and Resilient Modulus Characteristics of Unbound Granular Materials under Drained Conditions, in *APRG DOCUMENT APRG 00/33(MA), Austroads*, Australia.
8. Hick, R.G. and Monosmith, C.L., (1971). Factors Influencing the Resilient Response of Granular Materials, *Highway Research Record*, No. 345, pp. 15-31.
9. Sweere, G.T.H., (2004). Selection and Evaluation of Models for Prediction of Permanent Deformations of Unbound Granular Materials in Road Pavement, *Sustainable and Advanced Materials for Road Infrastructure (SAMARIS), SAM-05-DE10*, pp.17-23.
10. MINCAD Systems, (2004). *CIRCLY 5 User Manual*, Australia.
11. Harichandran, R.S., Yeh, M.S., and Baladi, G.Y., (1990). MICH-PAVE: A Nonlinear Finite Element Program for the Analysis of Flexible Pavement, *Transportation Research Record*, No. 1286, pp. 123-131.