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Performances of hydrated cement treated crushed rock base for Western Australian roads

Suphat Chummuneerat*, Peerapong Jitsangiam, Hamid Nikraz

Department of Civil Engineering, Curtin University, Perth, Western Australia, Australia

Abstract: The resilient modulus (RM) of hydrated cement treated crushed rock base (HCTCRB) affected by amount of hydration periods, compaction and dryback processes was presented using repeated load triaxial tests. The related trends of RM corresponding to the different hydration periods still cannot be concluded. Instead, It is found that the moisture content plays more major influence on the RM performance. Higher additional water during compaction of HCTCRB, even at its optimum moisture content and induced higher dry density, led to the inferior RM performance compared to the sample without water addition. The RM of damper samples can be improved through dryback process and superior to that of the sample without water addition at the same moisture content. However, the samples without water addition during compaction deliver the comparable RM values even its dry density is lower than the other two types. These results indicate the significant influence of moisture content to the performances of HCTCRB with regardless of the dry density. Finally, the experimental results of HCTCRB and parent material are evaluated with the *K*-*θ* model and the model recommended by Austroads. These two models provide the excellent fit of the tested results with high degree of determination.

Key words: base course; hydrated cement treated crushed rock base; cement modified material; repeated load triaxial test; resilient modulus; pavement

1 Introduction

The flexible pavements in Western Australia (WA) have a surface of approximately 30 mm in thickness. Thus, traffic loads on the road surface result in high stress levels on underlying layer. Crushed rock base (CRB) was the traditional base course material used in WA. CRB is an unbound granular material that has the insufficient capability to resist the increasing traffic loads and volumes. Moreover, CRB is susceptible to moisture which accelerates pavement deterioration. High quality aggregates are therefore required for the base course layer. These requirements led to the improvement of base course material in WA.

Cement is usually used to improve the engineering properties of the unbound granular materials such as

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* **Corresponding author**: Suphat Chummuneerat, PhD candidate.
E-mail: sch_cv32@hotmail.com.

crushed rock, aggregates and soils. Cement treated base (CTB) is a mixture of the original base course material, cement and water used for pavement structure. Cement content for CTB varies from 3% to 8% by mass of the aggregate which depends on the required strength (Garber et al. 2011). CTB mixture can be placed and compacted in the field immediately after mixing and hauling to the site. The strength of the base course is greatly improved using CTB. For example, a typical modulus of crushed rock base can be developed from 500 MPa to 5000 MPa by blending it with 4%-5% cement to construct CTB (Austroads 2010).

The cement stabilisation technique has been employed in WA by blending small amounts of cement with standard CRB. However, it is believed that even 1% of cement can lead the base course material too stiff and prone to fatigue cracking. Thus, the approach to prevent the bound characteristics of the base course layer was investigated. The investigation outcome was unique base course material used in WA called hydrated cement treated crushed rock base (HCTCRB) (Butkus 2004; Harris and Lockwood 2009; Rehman 2012). HCTCRB is made by mixing 2% of general purpose Portland cement with standard CRB at the optimum amount of water obtained by main roads Western Australia (MRWA) test method (MRWA 2007). Unlike the common CTB, the mix is stored and cured to have the specific hydration period. And then it is retreated by putting the hydrated mix to the mixer to break bonds generated during the hydration reaction. Finally, HCTCRB is transported and constructed in the field. The retreated process makes HCTCRB different from the conventional CTB. HCTCRB is expected to provide higher strength and lower moisture sensitivity than CRB while prevent the base layer becoming too stiff.

Over the years, HCTCRB has been commonly used as a base course material in WA, with a relatively high modulus value, about 800-1000 MPa, in particular for heavy traffic pavements. HCTCRB was developed during the empirical design period and has not yet been characterised following the pavement mechanistic approach. Therefore, uncertainties during manufacturing and construction procedures are still taking place. This uncertainty has contributed to the early damage of some new highways and roads. Some of highways and roads in WA are exhibiting extensive surface damage as a result of increasing traffic volume. However, explanations for the damage occurring under present conditions are difficult to determine and assess. Accordingly, an understanding of the material characteristics, in accordance with the pavement mechanistic approach, is strongly advised to maximise its use.

This paper aims to present the resilient modulus (RM) of HCTCRB affected by amount of hydration periods, compaction processes and dryback using the repeated load triaxial tests. The study is designed to further standardise HCTCRB's manufacture and construction, and overcome doubts regarding its use.

Some basic properties of base course materials used in WA were previously explored by Jitsangiam et al. (2013). Particle size distributions of CRB and HCTCRB at different hydration periods were examined at before and after compaction. The particle size distributions of CRB at before and after compaction conformed to the MRWA specification (MRWA 2008). It was found that hydration periods insignificantly differentiate the HCTCRB gradation characteristics. The gradation of HCTCRB for all hydration periods which varied from 3 to 45 days failed to meet the specification either before or after compaction. The fine contents (smaller than 4.75 mm) of HCTCRB samples before compaction were below the lower limit of the specification. After compaction, HCTCRB grains were broken resulting in smaller grain size. The gradation curves shifted up, and the fine contents were closer to the lower limit while the coarse grain lines lay just above the upper limit. The shear strength parameters of CRB and HCTCRB were investigated using scanning electron microscopy and static triaxial test. Observation of the scanning electron microscope pictures of CRB and HCTCRB conformed well to the static triaxial tests which revealed that CRB showed higher internal friction angles but less cohesion than HCTCRB. From static triaxial tests, the cohesion and angle of internal friction parameters of CRB were 38 kPa and 59°, for HCTCRB these two parameters were 169 kPa and 46°, respectively.

2 Laboratory works

2.1 Materials and basic characteristics

The crushed rock samples were collected from a local Gosnells quarry to produce HCTCRB. The basic properties of CRB were checked in accordance with MRWA specifications (MRWA 2008). The cement used in this study was general purpose Portland cement, conforming to the standard AS 3972-1997 (Standards Australia 1997).

The moisture-dry density relationships of materials were evaluated using modified compaction method through the standard test WA 133.1 (MRWA 2007). The compaction curves for CRB and CRB-cement mix were conducted initially to determine the appropriated water for HCTCRB preparation. In this study, HCTCRB samples were prepared based on the CRB-cement compaction test result of 2%-cement and 6.26%-water. CRB and cement were blended and kept in sealed plastic bags for 14, 28, 45 and 60 days hydration periods. Each mix was retreated to finish manufacturing process of HCTCRB once the individual hydration time was due. The modified compaction tests were then performed for all these sorts of HCTCRB. All compaction curves, the OMC and MDD of abovementioned materials are presented in Fig. 1 and Tab. 1.

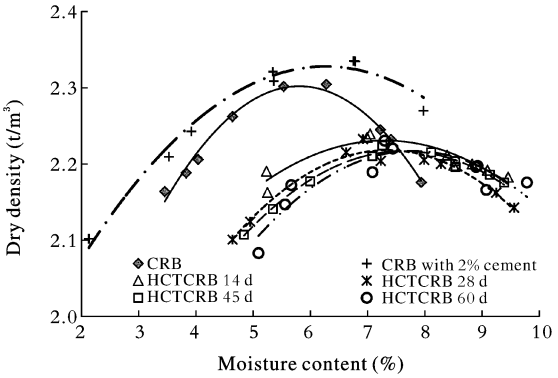


Fig. 1 Modified compaction curves for test materials

There were slight increases in OMC but minor decreases in MDD for longer hydration periods amongst these four types of HCTCRB. Compared to the CRB, the OMC of HCTCRB increased dramatically by 25.9% to 34.5%, while the corresponding MDD decreased by 3.1% to 3.7%. Reduction of MDD in HCTCRB samples is caused by its poorer gradation compared to that of CRB. The gradation curves of HCTCRB shifted rightward to that of CRB and did not comply with the specification limit. This occurrence is due to lower fine content as a result of cement and fine particles of CRB forming the larger grains (Jitsangaim et al. 2013).

Tab. 1 OMC and MDD of test materials

Material	OMC (%)	MDD (t/m³)
CRB	5.80	2.301
CRB with 2% cement	6.26	2.327
HCTCRB 14 d	7.30	2.230
HCTCRB 28 d	7.34	2.217
HCTCRB 45 d	7.62	2.216
HCTCRB 60 d	7.80	2.217

2.2 Specimen preparation

All tested specimens were prepared according to modified compaction method in mould size of 200 mm in height and 100 mm in diameter. Material for each specimen was divided and compacted in evenly eight layers. Each layer was subjected to 25 blows of 4.9 kg hammer and 450 mm drop height which provided 21.6 J per blow. The top of each layer was scarified about 6 mm in depth prior addition of material for next layer. HCTCRB samples were compacted instantly after completion of retreated processes. Then, all HCTCRB specimens were cured for 28 days at 25 ℃ prior to the tests, while CRB samples were tested immediately once finishing compaction.

This study investigated the effect of hydration periods, water addition during compaction and dryback on the RM of HCTCRB. Hydration periods varied from 14, 28, 45 and 60 days. For longer hydration period, the moisture content of CRB-cement mixes will be lower and the samples may be too dry to compact. Thus, additional water may be required for compaction. Consequently, the influence of water addition during compaction on the material performances was also examined. There were three different levels of the water addition, types A, B and C which represented no additional water, adding water to OMC of

CRB-cement mixture and adding water to OMC of individual hydration period. After 28 days of curing, the specimens had been dried during dryback process prior to the tests (ARRB 2003; MRWA 2008; Midgley 2009). Three degrees of dryback were used, including no dryback, dryback to 80% of OMC and dryback to 60% of OMC.

2.3 Testing protocol

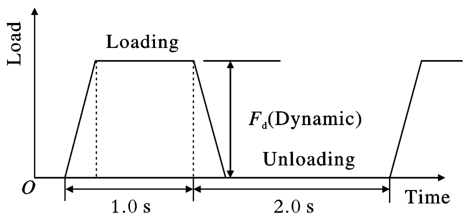
The resilient moduli of the materials were investigated by repeated load triaxial tests, following the Austroads standard test method AG: PT/T053 (Austroads 2007) based on the study by Vuong and Brimble (2000). The tests were conducted under drained condition and the suctions were not measured. The repeated vertical load waveform has a period of 3 s consisting of 1 s load pulse, with rise and fall times of up to 0.3 s.

The resilient modulus tests involved 66 stress stages of different deviator and confining stresses to simulate the complicated traffic loadings. The applied deviator and confining stresses ranged from 100-600 kPa and 20-150 kPa, respectively. The stress ratios of deviator stress to confining stress varied from 2 at the first stage to 25 at the final stage. The applied stresses and vertical load waveform are illustrated in Fig. 2. During the test, each specimen was subjected to minimum one thousand cycles of preconditioning and then followed by minimum fifty cycle-loadings at each stress stage. The resilient moduli were calculated from the last six cycles in which the results varied less than 5% of the mean of those six results.

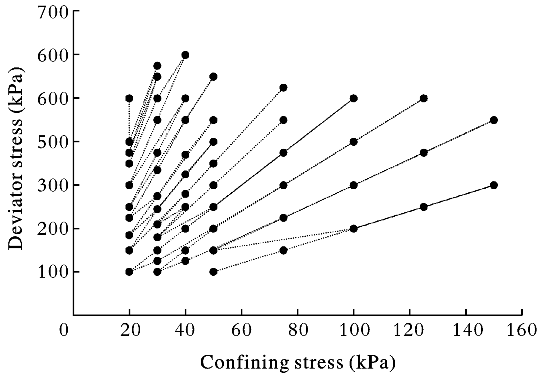
3 Experimental results

3.1 Effect of hydration periods on the resilient modulus

The tested results proved that the HCTCRB impressively improved the RM of the original material about treble even though the CRB-cement blends were disturbed after hydration. There were differences in resilient modulus characteristics of the HCTCRB at different hydration periods. The HCTCRB sample of 45-day hydration period showed the highest RM values while the sample of 28-day hydration period provided the lowest RM values among these four samples. The distinction of results between the hydration not longer and longer than 28 days can be observed. The RM ranges for 14, 28, 45, and 60 days hydration period samples, as plotted in Fig. 3, were 400-1070, 400-1040, 550-1360 and 530-1290 MPa, respectively. Other factors such as density and moisture content of the tested specimens as shown in Tab. 2 were also considered together with the hydration period. There were similar RM and moisture content between samples of 14 and 28 days as well as between those of 45 and 60 days. Thus, it is expected that the moisture content plays the major influence on the material performance. However, the related trends corresponding to the different hydration periods still cannot be concluded. Consequently, more experimental data are still needed.



(a) Vertical load waveform



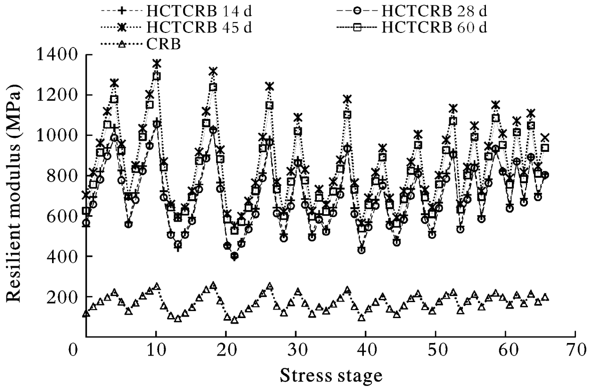
(b) Magnitude of deviator and confining stresses

Fig. 2 Illustrations of applied loads for resilient modulus test

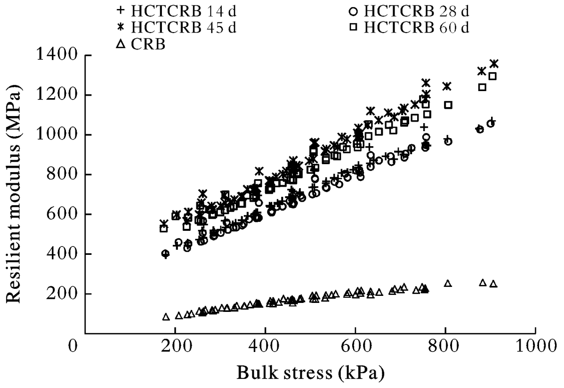
Tab. 2 Density and moisture content of HCTCRB specimens

Hydration period (d)	Moisture content (%)	Wet density (t/m^3)	Dry density (t/m^3)	MDD* (%)
14	5.26	2.219	2.110	94.6
28	5.20	2.190	2.081	93.9
45	4.96	2.160	2.058	92.8
60	4.90	2.217	2.113	95.3

Note: * Calculated according to individual HCTCRB shown in Fig. 1.



(a) MR over 66 stages



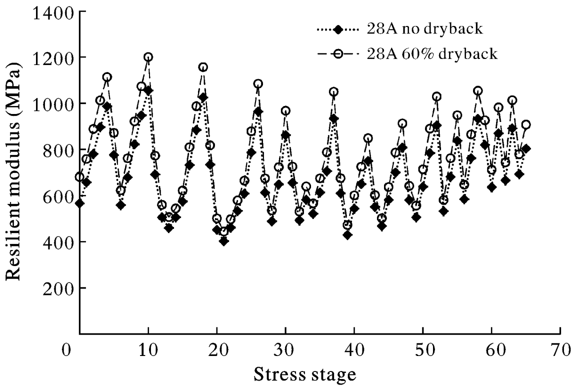
(b) MR-bulk stress relationships

Fig. 3 RM test results for CRB and HCTCRB

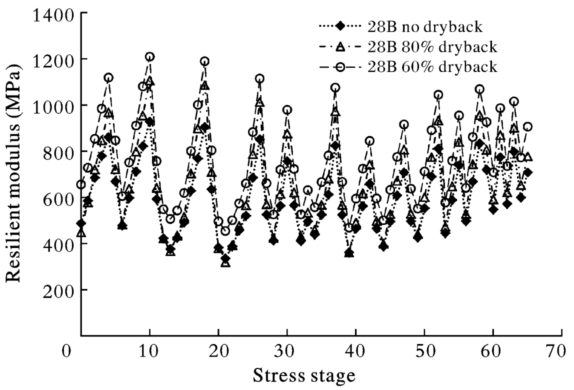
3.2 Effect of compaction and dryback process on the resilient modulus

The 28-day hydration samples with three types of water addition (A, B and C) were tested to examine the effect of dryback process at three different levels, no dryback, dryback to 80% of OMC and dryback to 60% of OMC. The moisture content of the HCTCRB at 28-day hydration dropped to 80% of OMC as a result of water consumption through hydration and curing processes. Therefore, sample 28A that was not subjected to dryback and sample 28A that was dried to 80% of OMC was the same specimen. The average moisture content after curing were 97.9% of OMC for type B sample and 97.2% of OMC for type C sample. The average dry density with respect to MDD of sample types A, B and C were 93.4%, 97.6% and 98.7%, respectively. Addition of water to the OMC of HCTCRB, type C, provided the worst RM performances although the samples achieved more than 98% of MDD.

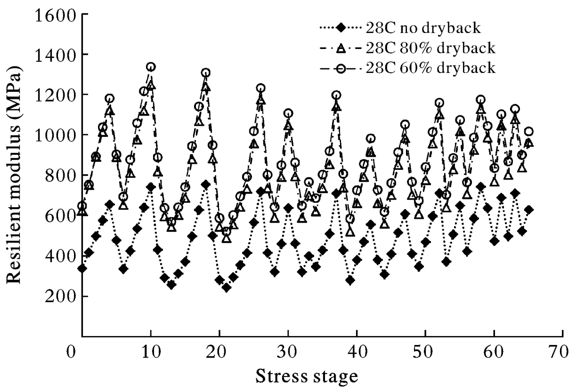
Figure 4 illustrates the tested results of HCTCRB of 28-day hydration with variation of additional water and degree of dryback. Two samples of 28A provided quite similar RM, which varied from 400-1040 MPa and 440-1200 MPa for no dryback and dryback samples, respectively. For samples 28B, RM increased



(a) No added water



(b) Water added to OMC of CRB-cement mix



(c) Water added to OMC of HCTCRB

Fig. 4 RM results for HCTCRB samples of 28-day hydration period from the range of 330-930 MPa to 320-1100 MPa and 450-1210 MPa as the moisture dropped from 97.6% to 80% and 60% of OMC. The RM values of samples 28C were 240-750 MPa for no dryback sample, 490-1250 MPa for the sample dryback to 80% of OMC and 520-1340 MPa for the sample dryback to 60% of OMC.

Higher additional water during compaction led to inferior RM performance, compared to the sample without additional water during compaction, although the specimens became denser. The RM of samples 28B and 28C could be improved during dryback process and superior to that of 28A at the same level of moisture content. The results stated that dryback process could improve the material performances caused by reduction of the moisture content of the specimens. The drier the sample, the bigger the resilient modulus. All these results indicate the significant influence of moisture content to the performances of HCTCRB.

3.3 Modelling of resilient modulus test results

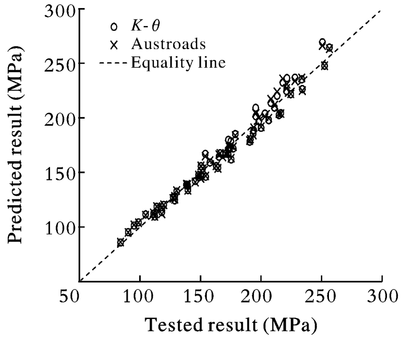
The resilient modulus is the key input for current pavement analysis and design. Analyses of experimental results using the constitutive models are demonstrated in this section. The *K*-*θ* model (Hick and Monismith 1971) and the model recommended by Austroads (Witcsak and Uzan 1988; Austroads 2010) were examined with the RM results of CRB and HCTCRB sample of 28-day hydration period with no dryback (sample 28A). The *K*-*θ* model and the model recommended by Austroads are expressed in Eqs. (1) and (2), respectively.

$$M = k_1 \theta^{k_2} \tag{1}$$

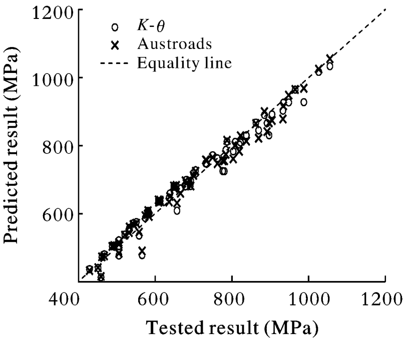
$$M = k_1 P \left(\frac{\theta}{P}\right)^{k_2} \left(\frac{\tau}{P} + 1\right)^{k_3} \tag{2}$$

where M is resilient modulus (MPa); P is atmospheric pressure (100 kPa); θ is bulk stress (kPa), $\theta = \sigma_1 + \sigma_2 + \sigma_3$; τ is octahedral shear stress for cylindrical specimens in triaxial tests, $\tau = \frac{\sqrt{2}}{3}\sigma_d$; σ_1 is major principal stress; σ_2 is intermediate principle stress; σ_3 is minor principal stress or confining stress; σ_d is deviator stress, $\sigma_d = \sigma_1 - \sigma_3$; k_1, k_2 and k_3 are regression parameters.

The model parameters for CRB and HCTCRB of 28-day hydration period are summarized in Tabs. 3 and 4 respectively. These evaluations provided that the *K*-*θ* model fit well with the tested results and provided high degree of determination (R^2) no less than 96%. Another model is associated with more factors and complicated forms, but delivers a little higher R^2. Thus the *K*-*θ* model is useful for preliminary evaluation of granular material due to its simplicity and high reliability. However, more complex models are required for better explanation of the influences of individual factor. Fig. 5 presents comparison between the RM tested results and predicted results using the *K*-*θ* model and the model recommended by Austroads for CRB and HCTCRB.



(a) MR of CRB



(b) MR of HCTCRB

Comparison between RM tested and predicted results for CRB and HCTCRB

Tab. 3 Model parameters for CRB

Model	k_1	k_2	k_3	R^2
K-*θ* model	2.235	0.704	—	0.978
Austroads	0.572	0.656	0.082	0.980

Tab. 4 Model parameters for HCTCRB

Model	k_1	k_2	k_3	R^2
K-θ model	14.637	6.626	—	0.967
Austroads	2.610	0.712	−0.148	0.973

4 Conclusions

This study has examined the resilient modulus (RM) of HCTCRB conducted under various scenarios of hydration periods, water addition during compaction and dryback. The hydration periods of 14, 28, 45 and 60 days were evaluated. There were three different levels of the water addition during compaction, no water added, water added to OMC in CRB-cement mixture and water added to OMC in individual hydration period. Eventually, the specimens involved dryback process prior to the tests. Three degrees of dryback, no dryback, dryback to 80% of OMC and dryback to 60% of OMC, were examined. The important results obtained from the tests are concluded as follows.

There were slight increases in OMC but minor decreases in MDD for longer hydration periods amongst these four types of HCTCRB. The related trends of resilient modulus corresponding to the different hydration periods cannot be concluded. Instead, It was assumed that the moisture content played the major influence on the RM performance.

Higher additional water during compaction of HCTCRB, even at its OMC and inducing higher dry density, led to inferior RM performance compared to the sample without water addition. The dryback process has potential to improve the material performances. The RM of damper samples could be improved through dryback process and superior to that of the dried sample at the same moisture content. However, the samples without water addition during compaction provided the comparable RM values even its dry density was lower than the other two types. These results indicated the significant influence of moisture content on the performances of HCTCRB with regardless of the dry density.

Finally, the experimental results of CRB and HCTCRB were evaluated with the K-θ model and the model recommended by Austroads. These two models provided the excellent fit of the experimental results with high degree of determination.

Acknowledgments

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