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# Low cement/fly ash blends for modification of Crushed Rock Base material

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## Abstract

Crushed Rock Base (CRB) material sometimes needs to be modified typically due to the moisture susceptibility. Resilient modulus is the dominant design parameter of unbound materials and should be high enough to avoid distress or failure of a pavement. In Western Australia (WA), some modification methods such as dry-back or Hydrated Cement Treated Crushed Rock Base (HCTCRB) have been implemented in trial sections of pavements. But they could not provide the desired performances by poor drainability or widely-spaced open cracks in surface of thin bituminous pavements. As such, this paper attempts to review the challenges of each method and show how design requirements can be provided by another option so-called low cement/fly ash blends even in saturated conditions. This method covers the deficiencies of two previous methods in terms of cracking or moisture susceptibility as observed in limited field tests. Series of laboratory tests including uniaxial compression strength, resilient modulus, tube suction and shrinkage tests are undertaken to explore the key features of this modification method. Typical results indicated that resilient modulus improved two times while strength, shrinkage and capillary rise of this material are in the acceptable level.

*Keywords:* Cement; Fly ash; Modification; Crushed rock; UCS; Resilient modulus; TST; ICC and shrinkage

## 1. Introduction

At construction, Crushed Rock Base (CRB) material is often compacted near optimum moisture content to get the highest density. This moisture content can vary due to different seasonal, environmental or drainage conditions. Any increase in moisture content, however, adversely affects the design modulus or strength of base course layer in pavement [29,34]. Typically in fine grain soils, stiffness or resilient modulus drops nearly 50% from optimum to saturation moisture condition [8].

For CRB material, a section of the Kwinana Freeway in Western Australia (WA) showed high curvatures and deflections in Benkelman beam surveys [14]. They were due to unexpected saturations after three years of being in service [37]. Loss of resilient modulus (MR) in this type of base course material led to premature fatigue cracking of asphalt [20].

Thus, Main Roads of Western Australia (MRWA) called for some advanced laboratory tests to investigate CRB material in 1994. As such, Repeated Load Triaxial (RLT) test results were undertaken to understand modulus changes versus moisture contents. Results revealed that MR values decrease about 20–25% for every 1% increase

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in moisture content [9]. These changes were so significant and some modification methods were required to control this situation.

### 1.1. Dry back

The first method considered was to dry back CRB material and cover it with an impermeable thin bituminous layer on top. Likewise, CRB material should be sun or air dried after compaction to 60 to 85% of optimum moisture content. The main presumption of dry-back method is to keep the moisture content low throughout the life of a pavement. In theory, this method relies on developed matric suctions in unsaturated soils that exhibit high strength and resilient modulus (MR) values [46]. As noted earlier, the persistence of the low-moisture condition highly depends on environmental, drainage condition. This method could give high modulus material during service life while there are some rooms for moisture increase during short-term inundation without serious compromise of performance. However, this method had risk of water infiltration through surface seal or failure of subsurface drainage which could bring about flooding or saturation condition. Alternative approaches in design guidelines are either application of the free-drain material with no sensitivity to moisture, or application of saturated MR [1,42,48]. For instance, clean or free-drain material concept is important for base course material as drainage in Europe [41]. As such, the roles of fine content and especially plasticity indexes of base course material will be crucial. These points will be discussed more in the next sections.

### 1.2. Hydrated Cement Treated Crushed Rock Base

The second method was to incorporate 2% cement into CRB material as cement modification [16]. The challenges of this method were generation of shrinkage cracking due to hydration reactions and likely fatigue cracking in thin bituminous layer [10]. Both types of cracking could induce additional issues. Consequently, this method was revised by introduction of Hydrated Cement Treated Crushed Rock Base (HCTCRB) material. It includes 2% General Purpose (GP) cement mixed with CRB in a pug mill [27,47]. But the mixes should be stockpiled for at least seven days allowing development of hydration reactions. Then, the hydration bounds were broken by processes of in-place disturbing, loading onto the trucks and carting to the workplace. In this manner, the hydration products or subsequent cracking is supposed to be eliminated [14].

In 1996, nine trial sections with a total length of 860 m were built in Reid highway in WA, for field investigation of HCTCRB material. However, later monitoring showed cement disappearance or cracking due to shrinkage or fatigue in HCTCRB sections [36,39,51]. During this investigation low-cement content sections showed similar performances without any issue [20].

Small quantity of binders can reduce the moisture susceptibility of soils without significantly increasing the tensile strength. Thus modified material unlike some bound material does not develop a network of widely-spaced open cracks [50]. Similar observation was observed in Orrong Rd where the section with 0.75% cement had minor distresses whereas HCTCRB section significantly failed and needed patching [35]. The process of HCTCRB production was so tedious and it was so hard to control the cement reactions in desired levels. Nonetheless HCTCTRB material provided high resilient modulus but was not successful enough due to cracking in the surface of trial test sections. Cracking of cemented soils is hard to be studied in the laboratory as will be explained in the following sections.

Above efforts encouraged authors to examine low-cement CRB material (i.e. less than 1%), where it had better performance than HCTCRB in field trials in WA. In this case, cement content is not so high to induce extensive hydration bounds and subsequently fatigue or shrinkage in CRB material. High resilient modulus and low cracks are mutually exclusive objectives, so cement content should be balanced to address both requirements. This aim can be achieved by implementation of siliceous products to increase stiffness by slow hydration reactions.

Therefore this effort tried to include fly ash as a waste by-product, which could improve the characteristics of low-cement modified CRB material. Fly ash is often used as replacement or supplement for cement that can significantly improve strength while reducing the cracking potentials [7,49]. Similar benefits are provided by use of Low Hydrate (LH) cement in WA [15]. Furthermore, non-plastic and filling features of fly ash can reduce the porosity or permeability of material as well. These benefits might be effective for moisture susceptibly of CRB material. Thus, laboratory experiments are inevitable to investigate these characteristics in more details.

## 2. Laboratory works

In this research, blend of cement and fly ash was considered as binder. Total sum of them was set to 2% as maximum binder content for modified material according to Austroad part 4L guideline [24]. This limit is to ensure that final mixes will behave like modified or lightly bound materials with trivial brittleness or rigidity [25]. As such, six different batches of modified CRB material were considered in such a way that cement content increment was 0.2%. Table 1 shows the proportions of binder in different batches.

### 2.1. Material characteristics

#### 2.1.1. CRb

CRB material is one of the common base course materials in WA, which includes granite and dolerite type aggre-

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Table 1
Binder compositions in batches.

| Batch | Cement content (%) | Fly ash content (%) |
|---|---|---|
| S1 | 0.5 | 1.5 |
| S2 | 0.7 | 1.3 |
| S3 | 0.9 | 1.1 |
| S4 | 1.1 | 0.9 |
| S5 | 1.3 | 0.7 |
| S6 | 1.5 | 0.5 |

gates. Some general features of that can be summarised as below.

*2.1.1.1. Grading & plasticity indexes.* The result of three grading and plasticity index tests on CRB material is shown in Tables 2 and 3. They are obtained according to standard test methods AS 1289.3.6.1-2009 and AS 1289.3.3.1. Samples A to C all have less than 5% finer than of 0.075 mm.

MRWA specification allows the fine content up to 11%, which might not be desired, if free drain materials are expected. The other important factor is plasticity parameters of material that are listed in Table 3.

As shown in Table 3, there is no clear limit for PI of CRB material. However, PI would be about 1.5–6%, provided that linear shrinkage is typically half to one-third of PI in different soils [31].

### 2.1.2. Cement

The cement used was General Purpose (GP) cement procured from Cockburn Cement Ltd in WA. Its chemical and physical properties are mentioned in Tables 4 and 5.

### 2.1.3. Fly ash

Fly ash was from Collie power station in WA. Table 6 lists the outcome of quantitative X-ray diffraction (XRD) and X-ray fluorescence (XRF) observations. Fly ash has reactive amorphous content ($SiO_2$) of 51.8%, but calcium oxide (CaO) content is highly less than 20%, thus this type of fly ash had no self-cementing capability and required an activator like cement.

Table 2
Grading test results on three CRB samples.

| Sieve | Percent passing % | | | | |
|---|---|---|---|---|---|
| Aperture | Sample | | | MRWA limits | |
| mm | A | B | C | | |
| 19 | 99.0 | 97.0 | 95.0 | 95 | 100 |
| 13.2 | 74.5 | 78.0 | 84.0 | 70 | 90 |
| 9.5 | 57.0 | 62.0 | 68.0 | 60 | 80 |
| 4.75 | 41.0 | 45.0 | 52.0 | 40 | 60 |
| 2.36 | 31.0 | 34.0 | 38.0 | 30 | 45 |
| 1.18 | 22.0 | 25.0 | 28.0 | 20 | 35 |
| 0.6 | 16.1 | 19.0 | 21.0 | 13 | 27 |
| 0.425 | 13.2 | 16.0 | 17.8 | 11 | 23 |
| 0.3 | 10.8 | 13.0 | 15.0 | 8 | 20 |
| 0.15 | 7.3 | 9.0 | 10.0 | 5 | 14 |
| 0.075 | 2.4 | 5.0 | 4.0 | 5 | 11 |

Table 3
Index limits of CRB material.

| Test type | Results | Specification limits | Test method |
|---|---|---|---|
| Liquid Limit (LL) | 20.2% | 25% | AS 1289.3.1.2 |
| Plastic Limit (PL) | 18.3% | – | AS 1289.3.2.1 |
| Plasticity Index (PI) | 1.9% | – | AS 1289.3.3.1 |
| Linear Shrinkage (LS) | 1.7% | 0.4–2% | AS 1289.3.4.1 |

Fig. 1 displays the comparison of fly ash and cement in their distribution of particle size. Both are virtually similar in sizes.

## 2.2. Initial Consumption of Cement (ICC)

The ICC test according to BS 1924: part 2 (BSI, 1990) was to find the lowest binder content required in a soil mixture to obtain an elevated pH of 12.4 after 1 h. Samples of CRB material with 200 g weight were mixed with cement in 150 ml plastic beakers. Water also was introduced to have mixes slightly over-saturated. Then mixes were left for a period of one hour prior to insertion of pH electrode (Fig. 2).

The results of this test are displayed in Table 7 whereas all mixes have pH greater than the minimum value of 12.4 for continuous hydration reactions.

## 2.3. Compaction

The compaction tests of mixtures in Table 1 were undertaken according to standard AS 1289.5.1.1. They were in standard Proctor compaction condition according to the requirement of Austroad, Part 4D [3]. The tests results indicated the maximum unit weight of 23.4 $KN/m^3$ corresponding to the optimum moisture content of 6% for nearly all batches.

## 2.4. Unconfined Compression Strength (UCS)

Prior to advanced RLT tests, it was essential to check the UCS of mixtures according to structural requirements for unbound or modified material [4]. To do so, standard test method AS 1141.51-1996 were used for UCS tests. Each sample was compacted using standard proctor effort in three equal thickness layers [26]. After 7 and 28 days wet curing, they were soaked in water bath for 5 h prior to UCS tests. Axial loading rate was 1 mm/min to capture the elastic modulus as well. The average results of duplicated cylindrical samples in saturated condition are presented in Table 8.

In Table 8, the compressive strengths of batches are increasing with cement content. A similar trend exists for the uniaxial elasticity modulus, but failure strains vary little from 3.0% to 4.5%. The correlations of these results are represented in Fig. 3.

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Table 4
Chemical properties of GP cement [13].

| Parameter | Units | Minimum | Typical | Maximum | AS 3972 limit | Test method |
|---|---|---|---|---|---|---|
| CaO | % | 63.1 | 63.7 | 64.4 | | AS 2350.2 |
| $SiO_2$ | % | 20.0 | 20.4 | 20.8 | | AS 2350.2 |
| $Al_2O_3$ | % | 5.1 | 5.4 | 5.8 | | AS 2350.2 |
| $Fe_2O_3$ | % | 2.6 | 2.8 | 3.0 | | AS 2350.2 |
| MgO | % | 1.1 | 1.3 | 1.5 | | AS 2350.2 |
| $SO_3$ | % | 2.3 | 2.7 | 3.0 | <3.5 | AS 2350.2 |
| $Na_2O$ equivalent | % | 0.4 | 0.5 | 0.6 | | AS 2350.2 |
| Chloride | % | 0.00 | 0.01 | 0.04 | <0.10 | AS 2350.2 |
| Loss on ignition | % | 1.5 | 2.2 | 2.7 | | AS 2350.2 |

Table 5
Physical properties of GP cement [13].

| Parameter | Units | Minimum | Typical | Maximum | AS 3972 limit | Test method |
|---|---|---|---|---|---|---|
| *Setting time* | | | | | | |
| Initial | min | 105 | 135 | 150 | >45 | AS 2350.4 |
| Final | min | 165 | 195 | 225 | <360 | AS 2350.4 |
| Soundness | mm | 0 | 1 | 3 | <5 | AS 2350.5 |
| *Compressive strength* | | | | | | |
| 3 day | MPa | 35 | 38 | 41 | | AS 2350.11 |
| 7 day | MPa | 44 | 48 | 52 | >35 | AS 2350.11 |
| 28 day | MPa | 56 | 60 | 64 | >45 | AS 2350.11 |
| Fineness | $m^2/kg$ | 350 | 370 | 390 | | AS 2350.8 |

Table 6
Chemical composition of fly ash.

| Parameter | Content (%) |
|---|---|
| $SiO_2$ | 51.8 |
| $Al_2O_3$ | 26.4 |
| $Fe_2O_3$ | 13.2 |
| CaO | 1.61 |
| $TiO_2$ | 1.4 |
| $P_2O_5$ | 1.39 |
| MgO | 1.17 |
| $K_2O$ | 0.68 |
| $Na_2O$ | 0.31 |
| MnO | 0.1 |

According to this Fig. 3, there is a linear relation between uniaxial elasticity and strength of low cement modified CRB material. It should be noted that the ratio of E over UCS in this graph is lower than 1.0–1.25 as suggested for flexural modulus in Austroad for bound material [23]. However, two batches of S2 and S3 both comply with the design requirements of UCS ≤1.0 MPa for 7-days [32] and 1.5 MPa for 28-days age [5].

### 2.5. Modulus of resilient ($M_R$)

Modulus of resilient parameter is to characterise the load-deformation behaviour of material under dynamic loads for mechanistic-empirical design procedure. It is defined as

$$M_R = \sigma_d/\varepsilon_r \tag{1}$$

where $\sigma_d$ is the deviatory stress and $\varepsilon_r$ is elastic strain in a dynamic triaxial compression test. It is based on elastic response of soil against repeated loads in pavements [43]. There are various testing methods for resilient modulus such as AG: PT/053 recommended by Austroads [6] for Australia. The samples for this test were compacted under standard energy level within metalic cylindrical moulds with 100 mm diameter and 200 mm height. Five layers were hammered for 25 blows using a 2.54 kg rammer with a drop height of 305 mm. Testing equipment used here was Universal Testing Machine UTM-14P (14 kN Pneumatic) equipped with IPC’s IMACS digital controller with UTS software. Dry and saturated specimens of each batch with 28-days age were subjected to repeated loadings. The first stress stage consists of 1000 cycles for pre-conditioning and in the next stage 200 repeated loading/unloading including 66 cycles of different stress levels. The repeated vertical loading pattern was rectangular waveform which is different from AASHTO as shown in Fig. 4.

Results of this test can be represented by K–Θ model [21] as described in Eq. (2).

$$M_R = k_1\theta^{k_2} \tag{2}$$

The resilient modulus of untreated or raw CRB material is between 160 and 240 MPa at a moisture equal to 50% of the optimum moisture level [45]. At optimum moisture content, modulus drops to a range of 120–170 MPa which imply 25–30% reduction. Although semi-saturated condition of a soil material improves stiffness or strength of material, this status is unstable. Thus, authors decided to focus only on saturated and dry conditions in this study, excluding complexity of unsaturated condition. Saturated conditions are considered for design of pavements in South

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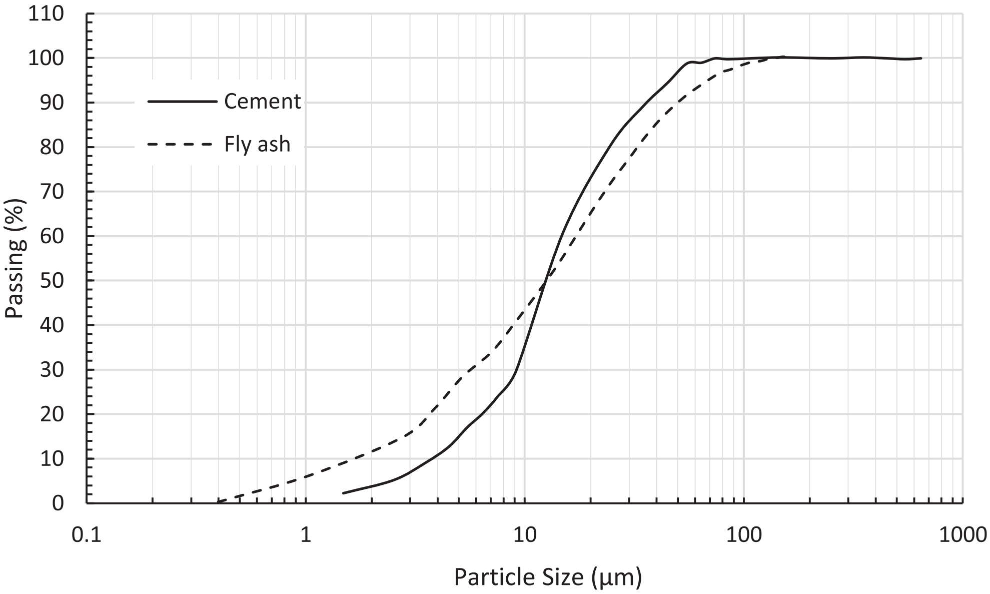

Fig. 1. Particle size of fly ash and cement (Laser diffraction method).

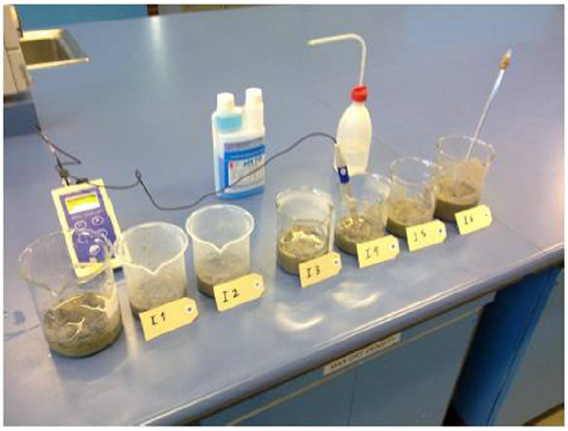

Fig. 2. Initial Cement Consumption (ICC) tests.

Table 7
pH versus cement content in CRB material.

| Cement (%) | pH |
|---|---|
| 0.5 | 12.54 |
| 0.7 | 12.70 |
| 0.9 | 12.74 |
| 1.1 | 12.82 |
| 1.3 | 12.84 |
| 1.5 | 12.88 |

Africa with similar environmental or geological conditions with WA [18]. Accordingly, the influence of low cement/fly ash modification could be better revealed in extreme cases of moisture level.

Variation of modulus in different loading stages and summary of these tests for S2 and S3 batches are illustrated in Figs. 5–8, whereas MR values go up with an increase in bulk stress $\theta$ (kPa) during 66 loading conditions. The K–Θ model seems to be a good fit for this material as *R*-squared values in both figures are close to one which implies well agreement of K–Θ model with experimental outcomes here.

In addition, moisture reduction from saturated to dry conditions increases MR values for 25–35% corresponding to bulk stresses from 300 to 500 kPa. The bulk stress is assumed 400 kPa for a base course layer in WA.

Averages results of duplicated samples for each batch S2 and S3 are shown in Table 9. Low cement/fly ash modifications have enhanced the resilient modulus to a range between 330 and 400 MPa at saturated condition which is approximately two to three times more than raw CRB material at optimum moisture. This is significant improvement of material even in saturated condition which in turn means no moisture susceptibility for this material. However further tests can clarify other characteristics of this material.

### 2.6. Shrinkage

Drying or dissipation of moisture in cemented materials is associated with cracking. Shrinkage cracks are induced by drying tension stresses that might be reflected in the surface layer of pavement. Standard practice in Australia is avoidance of cracks by limiting 7 days of UCS for less than 2.0 MPa. This is based on criteria for cracking acceptance and management [30].

Although the mechanism of shrinkage has been well-studied in concrete, this is not the case in soil stabilised material. For instance, there is no standard test method for stabilised soils [11]. Thus, the standard test method of AS 1012.13-1992 for concrete was used here to evaluate the shrinkage of S2 and S2 samples. As such, beam specimens with the size of 75x75x280 mm were prepared. The ratio of minimum specimen size to maximum aggregate size

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Table 8
UCS tests results.

| Batch | 7 days | | | 28 days | | |
|---|---|---|---|---|---|---|
| | Elasticity modulus (MPa) | Failure strain (%) | UCS (kPa) | Elasticity modulus (MPa) | Failure strain (%) | UCS (kPa) |
| S1 | 174 | 3.2 | 606 | 220 | 3.2 | 746 |
| S2 | 191 | 3.6 | 628 | 230 | 3.6 | 874 |
| S3 | 200 | 3.8 | 711 | 240 | 4.6 | 1009 |
| S4 | 266 | 4.5 | 1002 | 350 | 4 | 1419 |
| S5 | 316 | 3.2 | 1059 | 400 | 4 | 1465 |
| S6 | 406 | 3.6 | 1349 | 404 | 4.2 | 1759 |

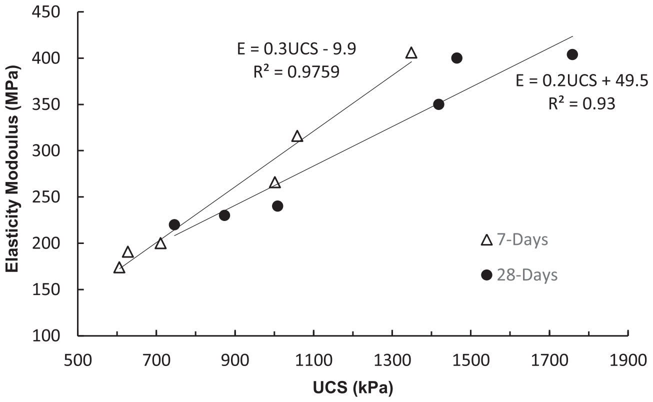

Fig. 3. Correlation of elasticity modulus versus UCS results.

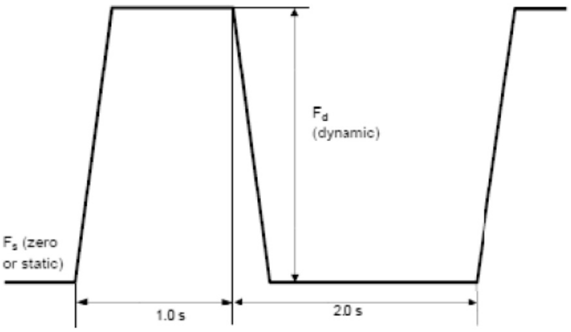

Fig. 4. Loading waveform in AG:PT/053 [6].

was greater than five by scalping the aggregates coarser than 9.7 mm. After compaction in the mould, specimens cured in a humidity cabinet having a controlled temperature of 23 °C and a relative humidity of 50%. The longitudinal changes and readings were recorded by a horizontal comparator as shown in Fig. 9. Therefore, deformations could replicate horizontal strains in practice.

Results of samples for both batches are shown in Fig. 10. In this figure, the shrinkage strains are much less than 310 microstrain as allowed for coarse soils by Portland Cement Association (PCA) [19]. The underlying idea is to have multiple minor cracks rather than limited wide cracks. Water infiltration through narrow cracks is hard enough to inhibit degradation of cement treated layers [2].

In literature, CRB material with 2–6% cement have had shrinkage in the range of 350 microstrain to 400 microstrain [12] or 150–690 microstrain [18]. Hence it can be inferred that traditional cement mixtures have shrinkages two times more than S2 and S3 batches.

This subject again highlights the benefits of low cement/fly ash blends for modification of CRB over other options. All of the above results ascertain the satisfactory field observations as noted before.

### 2.7. Tube Suction Test (TST)

Tube suction test employs electromagnetic wave or radar concept to study the moisture changes or capillary rises of in a porous material. The guidelines prepared by Saarenketo [40] were used in this investigation to monitor water movement in dry samples placed in water. Similar technique called (Ground penetration radar) GPR is used for field investigations as exercised by Shon and Estakhri [44] to examine waste materials as base course layer. However, after preparation of samples, similar to $M_R$ test, they were longitudinally sealed and place in water tray with 20 mm depth as displayed in Fig. 11.

Adek percometer used to record the Dielectric Value (DV) of samples. Waves of 50 MHz frequency were applied through a probe of 50 mm diameter.

Changes were repaid to be recorded at start, but got nearly constant after 10 min. DV readings were less than 10.0, indicating that quality is good as illustrated in Fig. 12. Poor quality mixtures have DV values more than 16.

## 3. Discussion

Particle size distribution of CRB material in WA, is in agreement of AASHTO requirements for free drainage material [22,32,32]. Fine content (≤0.075 mm) is between 5% and 11% as shown in Table 2. However there is no clear limit for Plasticity Index (PI), whereas AASHTO suggests PI less than 6% and Liquid Limit (LL) less than 25%. Thus, relying on free drainage capacity of CRB material in WA would be unreliable. Any saturation of this material cannot easily revert back to desired moisture condition. This subject has been discussed in more details by authors reviewing drainability theories [38]. The time required for moisture equilibrium has been found between 8 and 28 weeks after saturation [28]. All these points imply that dry back

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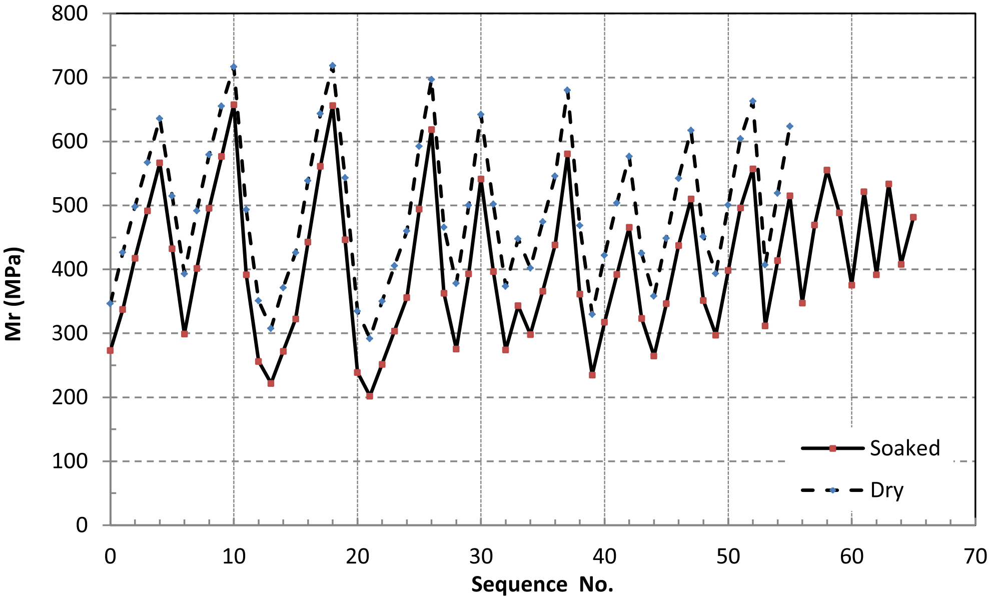

Fig. 5. Variation of resilient modulus at different stages for batch S2.

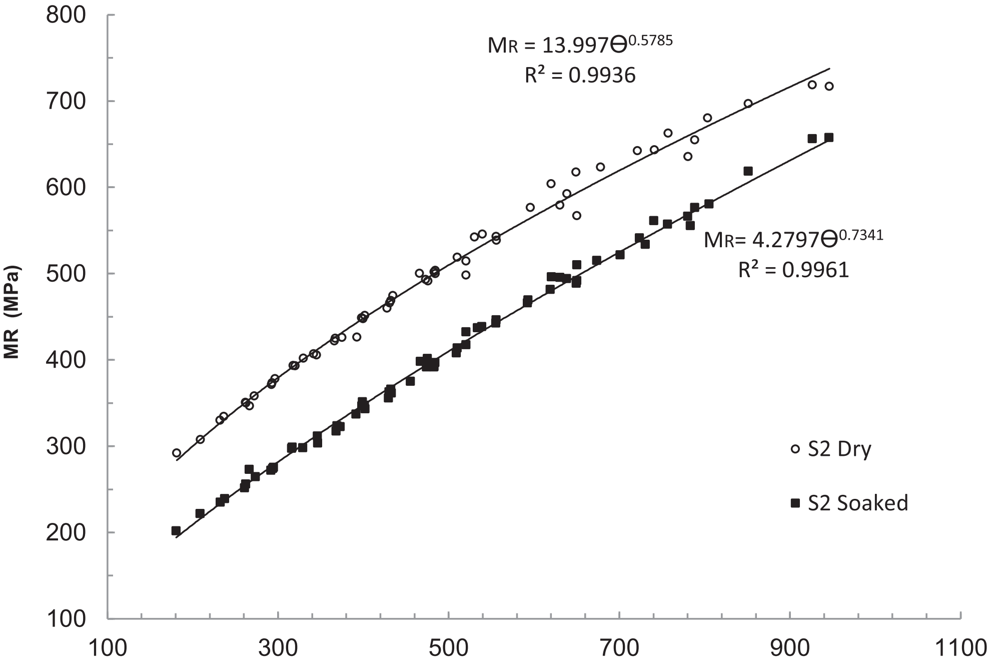

Fig. 6. Variation of resilient modulus versus bulk stress for batch S2.

method is not a reliable or long-lasting choice for modification of CRB material. It also needs vigorous impermeable wearing course protecting base layer as well.

As a result, cementitious binders are inevitable for CRB modification. Cement content should not be high (more than 2%) as it could lead to unnecessary tensile strength, flexural stiffness or fatigue. On the other hand, 2% cement could have wide crackings even from shrinkage, thus distribution of hydration products thought to be an option. HCTCRB or reworking of mixtures after initial hydration was not a satisfactory as observed in field trials as well. Slow hydration reactions by time still induce shrinkage or will generate bound material prone to fatigue.

Low cement content CRB had satisfactory performance in the field, but there has been little attention to that. As explained, low cement and inclusion of fly ash in binder illustrated promising strength and resilient modulus with limited shrinkage. Cement content around 0.7–0.9% with sufficient pH have doubled the resilient modulus in saturated condition. This was the main objective here that

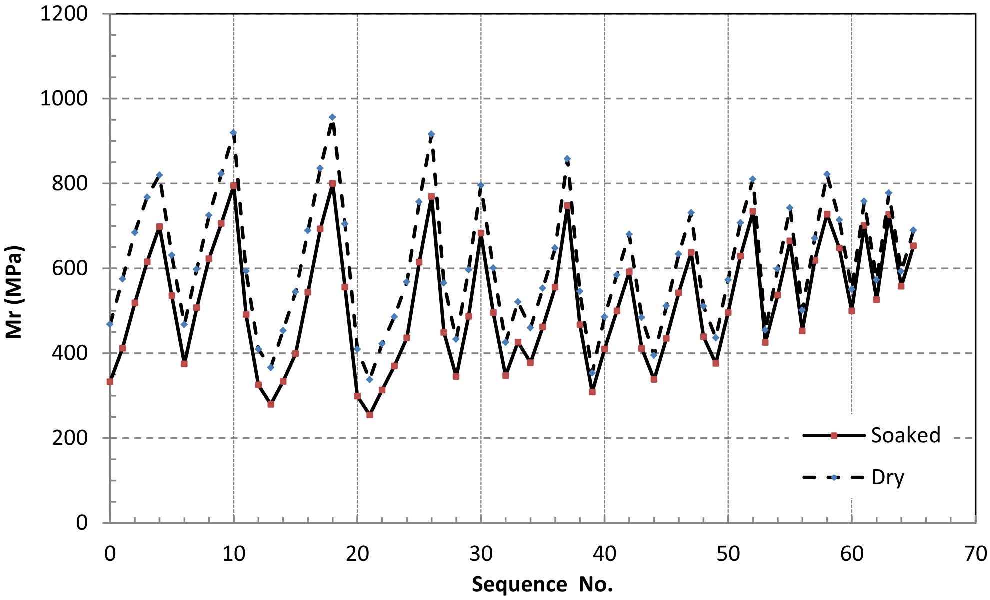

Fig. 7. Variation of resilient modulus at different stages for batch S3.

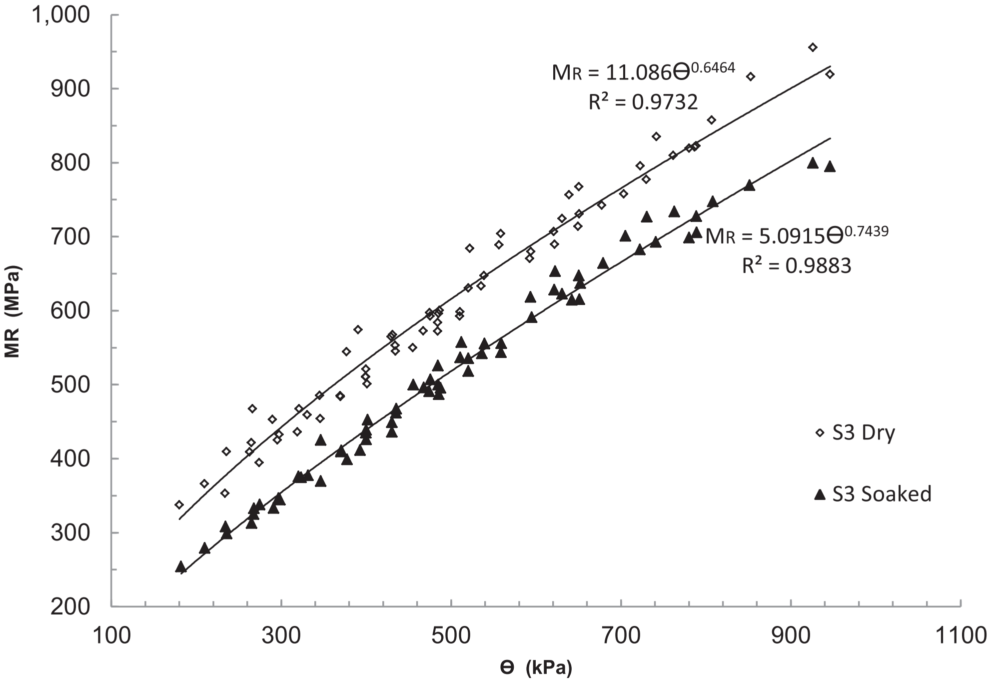

Fig. 8. Variation of resilient modulus versus bulk stress for batch S3.

Table 9
Summary of resilient modulus test results ($\theta = 400$ kPa).

| Batch | Dry | | | Soaked | | |
|---|---|---|---|---|---|---|
| | Mr (MPa) | K1 | K2 | Mr (MPa) | K1 | K2 |
| S2 | 448 | 13.996 | 0.5785 | 349 | 4.297 | 0.7341 |
| S3 | 533 | 11.086 | 0.6464 | 439 | 5.091 | 0.7439 |

achieved with meticulous laboratory tests. As such, moisture susceptibly issue of CRB material can be mitigated to great extent. Shrinkage was also more or less 50% of

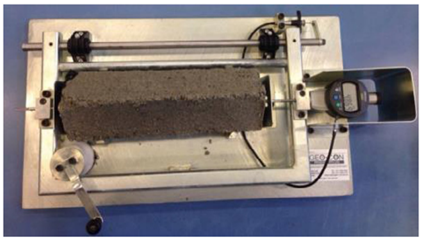

Fig. 9. Horizontal comparator (Cat. No. 55-C0115/9.Con).

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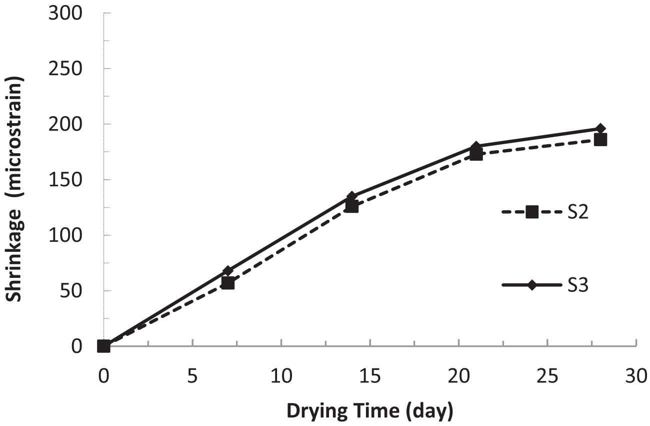

Fig. 10. Shrinkage test results.

Fig. 11. TST samples.

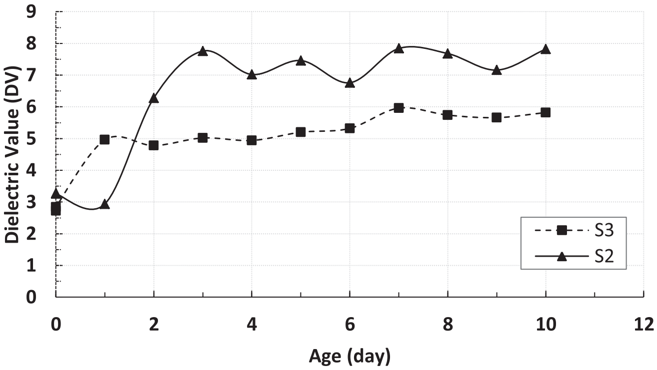

Fig. 12. TST test results.

cement treated mixtures and far below 310 microstrain as advised by PCA. Together, these findings indicate that low cement binders can be implemented successfully in situations where modification of base course material is required.

## 4. Conclusion

This research assessed and reviewed briefly the different options for modification of CRB material against moisture susceptibility issues. They are critically evaluated before extensive sets of laboratory test for suggested option as low cement option here. Dry-back method does not seem to be a reliable option due to poor drainability of material and also inherent risks exist in the performance of top sealing layers. HCTCRB also could not restrain the likely fatigue or shrinkage cracks. Thus, low-cement/fly ash blends were focused here for modification of CRB material.

Series of strength, resilient modulus and shrinkage tests were undertaken to explore characteristics of this material. Resilient modulus as main design parameter of unbound material had key role here. Extreme moisture conditions as soaked (saturated) and dry conditions assumed for test samples. At a worst case like saturated condition, it is found that the 7 days' UCS is less than 1.0 as desired. Resilient modulus is also between 330 and 400 MPa while shrinkage cracks are below the limit of 310 microstrain. This attempt gives confidence to suitability of low-cement/fly ash blends for modification of CRB material. It this case, this material will have two to three time more design modulus that raw CRB, even in case of any unexpected and long-term flooding of pavements. This is while pH of this material is more than a minimum value of 12.4 required for continuous hydration reactions. Capillary rise in samples also could not adversely impact this material as Dielectric Values (DV) were lower than 10 as a sign of good material for pavements.

## References

[1] M.Y. Abu-Farsakh, K. Alshibli, M. Nazzal, E. Seyman, Assessment of in-situ test technology for construction control of base courses and embankments, Report No: FHWA/LA, 4, 2004, p. 385.
[2] W.S. Adaska, D.R. Luhr, Control of reflective cracking in cement stabilized pavements, Proceedings of 5th International RILEM Conference on Cracking in Pavements, 2004, pp. 309–316.
[3] B. Andrews, Part 4D: Stabilised Materials, Guide to Pavement Technology, Austroads Incorporated, 2006.
[4] G. Arnold, Engineered Pavements. Roading Geotechnics 98: New Zealand Geotechnical Society 1998, Auckland, July 1998, p. 31.
[5] Austroads, A Guide to the Structural Design of Road Pavements. Austroads Publication No. APGP17/04, Austroads, Sydney, 1992.
[6] Austroads, Determination of Permanent Deformation and Resilient Modulus Characteristics of Unbound Granular Materials under Drained Conditions, 2007.
[7] R.M. Brooks, Soil stabilization with fly ash and rice husk ash, Int. J. Res. Rev. Appl. Sci. 1 (3) (2009) 209–217.
[8] T.S. Butalia, J. Huang, D.-G. Kim, F. Croft, Effect of moisture content and pore water pressure buildup on resilient modulus of cohesive soils in Ohio, Resilient Modulus Testing for Pavement Components, ASTM International, 2003.
[9] F. Butkus, A. Lee Goh, Pavement Moduli Project, A Review of Repeated Load Triaxial Test Results, MRWA, Western Australia, 1997.
[10] F. Butkus, A. Lee Goh, A Review of Repeated Load Triaxial Test Results. 97/4 M, MRWA, Western Australia, 1997.
[11] S. Chakrabarti, Kodikara, Jayantha, Laboratory method for assessing shrinkage cracking potential in stabilised pavements, Fifth International RILEM Conference on Reflective Cracking in Pavements, RILEM Publications SARL, 2004, pp. 605–612.
[12] S. Chummuneerat, P. Jitsangiam, H. Nikraz, Mechanical behaviours of a base course material in Western Australia, ARRB Conference, 25th, Perth, Western Australia, Australia, 2012.

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[13] Cockburn Cement, General Purpose Cement, Product Information, 2007

[14] G. Cocks, M. Hillman, Pavement materials and surfacing aggregates used in road construction in Perth, Aust. Gomech. J. 38 (3) (2003) (this volume).

[15] G. Cocks, R. Keeley, C. Leek, P. Foley, T. Bond, A. Cray, P. Paige-Green, S. Emery, R. Clayton, D. Mclnnes, L. Marchant, The use of naturally occurring materials for pavements in Western Australia, Aust. Gomech. J. 50 (1) (2015) 43–106.

[16] A.R. Cray, G.C. Cocks, D.B. Mcinnes, Design of stabilised pavements. 97–54 M, MRWA, Western Australia, 1997.

[17] S.J. Emery, The prediction of moisture content in untreated pavement layers and an application to design in Southern Africa, 1988. <https://trid.trb.org/view/1155808>.

[18] W. Fedrigo, W.P. Núñez, T.R. Kleinert, M.F. Matuella, J.A.P. Ceratti, Strength, shrinkage, erodibility and capillary flow characteristics of cement-treated recycled pavement materials, Int. J. Pavement Res. Technol. 10 (5) (2017) 393–402.

[19] K.P. George, Minimizing Cracking in Cement-treated Materials for Improved Performance, Portland Cement Association, Skokie, Ill, 2002.

[20] D. Harris, N. Lockwood, Reid Highway Basecourse Test Sections Construction Details and Performance to December 2008 (94/15 M). 94/15 M, MRWA, Western Australia, 2009.

[21] R.G. Hicks, C.L. Monismith, Factors influencing the resilient response of granular materials, Highway Res. Rec. 345 (1971).

[22] A.A.o.S. Highway, T. Officials, AASHTO Guide for Design of Pavement Structures 1. AASHTO, 1993.

[23] G. Jameson, Part 2: Pavement Structural Design, Guide to Pavement Technology, Austroads Incorporated, 2008, p. 263.

[24] G. Jameson, Review of Definition of Modified Granular Materials and Bound Materials, Austroads, 2013.

[25] G. Jameson, M. Shackleton, Part 4L: Stabilising Binders, Guide to Pavement Technology, 978-1-921551-37-6, Austroads Incorporated, 2009.

[26] G. Jameson, M. Shackleton, Part 4L: Stabilising Binders, Guide to Pavement Technology, 2009.

[27] P. Jitsangiam, H. Nikraz, K. Siripun, Characterization of hydrated cement treated crushed rock base (HCTCRB) as a road base material in Western Australia, Road Pavement Material Characterization and Rehabilitation: Selected Papers from the 2009 GeoHunan International Conference, 2009, pp. 1–8.

[28] J. Kodikara, S. Chakrabarti, Modeling of moisture diffusion in crushed basaltic rock stabilized with cementitious binders, J. Mater. Civil Eng. 17 (6) (2005) 703–710.

[29] R.B. Malla, S. Joshi, Subgrade resilient modulus prediction models for coarse and fine-grained soils based on long-term pavement performance data, Int. J. Pavement Eng. 9 (6) (2008) 431–444.

[30] S.C. Matthews, Control of Reflective Cracking, Cement Stabilised Pavements Course, Melbourne, Australia, 1991.

[31] MRWA, Selection and use of naturally occurring materials as base and subbase, 2003.

[32] MRWA, Engineering Road Note 9, 2012.

[33] MRWA, Specification 501 pavements, 2012.

[34] S. Nazarian, D. Yuan, Variation in moduli of base and subgrade with moisture, GeoCongress, Geosustainability and Geohazard Mitigation, 2008, pp. 570–577.

[35] A. Rezagholilou, Effect of nanoparticles on the durability of cement stabilised base course materials (Doctoral dissertation), Curtin University, 2015.

[36] A. Rezagholilou, H. Nikraz, Analytical method in carbonation of cement treated base material, 25th ARRB Conference, Perth, Western Australia, Australia, 2012.

[37] A. Rezagholilou, H. Nikraz, Theoretical challenges of cement modified crushed rock base material in pavements, Int. J. Res. Eng. Adv. Technol. 3 (1) (2015) 38–55.

[38] A. Rezagholilou, H. Nikraz, C. Leek, Estimation of drainability and its effect on the design moisture content of base course material, Aust. Geomech. J. 48 (2013) 121–128.

[39] A. Rezagholilou, V.G. Papadakis, H. Nikraz, Rate of carbonation in cement modified base course material, Constr. Build. Mater. 150 (2017) 646–652.

[40] T. Saarenketo, Tube suction test – results of round robin tests on unbound aggregates, Finnish National Road Administration, 2000.

[41] M. Scholz, in: Permeable Pavements and Storm Water Management, Climate Change, Energy, Sustainability and Pavements, Springer, 2014, pp. 247–260.

[42] M. Scholz, P. Grabowiecki, Review of permeable pavement systems, Build. Environ. 42 (11) (2007) 3830–3836.

[43] H.B. Seed, C. Chan, C.E. Lee, Resilience characteristics of subgrade soils and their relation to fatigue failures in asphalt pavements, International Conference on the Structural Design of Asphalt Pavements. Supplement, 1962.

[44] C.-S. Shon, C.K. Estakhri, In-situ and laboratory investigation of modified drilling waste materials applied on base-course construction, Int. J. Pavement Res. Technol. 11 (3) (2018) 225–235.

[45] K. Siripun, Characterisations of base course materials in Western Australia pavements (Doctoral dissertation), Curtin University, 2010.

[46] K. Siripun, P. Jitsangiam, H. Nikraz, The effects of moisture characteristics of Crushed Rock Base (CRB), Geo-Frontiers, Advances in Geotechnical Engineering, 2011, pp. 4458–4467.

[47] K. Siripun, H. Nikraz, P. Jitsangiam, Mechanical behaviour of hydrated cement treated crushed rock base (HCTCRB) under repeated cyclic loads, Aust. Geomech. 44 (4) (2009) 53.

[48] B.I. Siswosoebrotho, P. Widodo, E. Augusta, The influence of fines content and plasticity on the strength and permeability of aggregate for base course material, Proceedings of the Eastern Asia Society for Transportation Studies, Citeseer, 2005, pp. 853–856.

[49] P. Solanki, M. Zaman, Design of semi-rigid type of flexible pavements, Int. J. Pavement Res. Technol. (2016)

[50] G. White, Pavement recycling and stabilisation guide, 2015. <https://trid.trb.org/view/1366729>.

[51] Y. Yeo, H. Nikraz, Cement stabilisation of road base course: a chronological development in Western Australia, Aust. Geomech 46 (3) (2011) 53–62.

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