The background of the entire page is a close-up photograph of crushed red bricks, showing various sizes and angular shapes of the fragments.

# Crushed Brick as a Supplementary Material in Cement Treated Crushed Concrete Pavement Applications

# SWINBURNE UNIVERSITY OF TECHNOLOGY

Centre for Sustainable Infrastructure

## **Crushed Brick as a Supplementary Material in Cement Treated Crushed Concrete Pavement Applications**

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## 1 PROJECT BACKGROUND

Traditional pavement base and sub-base materials is becoming scarce in some regions. In some cases, the use of these materials is unsustainable from both an environmental and cost perspective. VicRoads manages a road network of 151,000 kilometres, from major freeways to minor local roads. Approximately 50,000 kilometres of this road network is located in metropolitan Melbourne and requires cement treatment of pavement bases/sub-bases, there are also similar requirements for municipal roads, which frequently use similar pavement compositions on local roads. Traditionally, only cement treated crushed rock and crushed concrete have been used in cement treated pavement bases/sub-bases. There is presently a state government sustainability initiative to use recycled materials where appropriate and where they are fit for purpose, particularly in roads and other infrastructures.

This project proposes to investigate the use of crushed brick as a supplementary material with recycled concrete aggregates in cement treated bound pavement applications. The development of a procedure for the evaluation of these reclaimed products as a base/sub-base material would result in an increased level of confidence within industry as to their likely in-service performance and appropriate application as well as result in a higher uptake of recycled materials in urban areas where cement treated sub-base pavements are commonly used.

Currently in Victoria approximately 2.0 million tonnes of crushed concrete and 1.4 million tonnes of crushed brick are stockpiled annually and these stockpiles are growing. The reuse of these recycled materials in applications such as road bases/sub-bases will result in a low carbon solution for future roads, considering that recycled materials have significant carbon savings compared with virgin quarried materials. The focus of this new research project is on the laboratory evaluation of crushed brick when used as supplementary material in cement treated crushed concrete pavement sub-base applications.

Swinburne University has previously been actively undertaking research with VicRoads since 2006 on the use of various recycled demolition materials as pavement sub-bases. Completed joint research projects and Victorian outcomes to date are as follows:

- 15% crushed brick in Class 3 pavement sub-bases (VicRoads Standard Specification 812 and 820).
- 50 % crushed brick in footpath bases (Municipal Association of Victoria specifications, 2011).
- 15 % crushed glass in Class 3 pavement sub-bases (VicRoads Standard Specification 812 and 820).
- 30 % crushed glass in footpath bases (Municipal Association of Victoria specifications, 2011).

## **2 INTRODUCTION**

This applied research project has been undertaken to assess the suitability of crushed brick when used as a supplementary material in cement treated crushed concrete pavement sub-base applications.

Crushed concrete and crushed brick materials are commonly obtained from construction and demolition (C&D) activities. Construction wastes are produced during different phases of construction. Demolition waste materials arise from demolition activities.

There is now a developing emphasis on environmental management which has resulted in growing pressure to investigate the viability of reuse of all categories of waste material such as C&D materials. The use of recycled C&D material would greatly reduce the demand for landfill sites and for virgin resource materials by re-using what would be normally regarded as a waste material. Guided by the principles of sound environmental management, more sophisticated models for waste management involving reuse and recycling have been developed by governments and industries.

## **3 RECYCLED MATERIAL SOURCES**

Samples of crushed concrete and crushed brick for this project were collected from Delta Recycling site at Sunshine in Victoria. Delta Recycling, at this site, produces recycled materials such as crushed concrete, crushed rock in various classes. Crushed brick from the Delta Recycling site typically comprises graded aggregates up to 20 mm in size.

## **4 LABORATORY TESTING METHODOLOGY**

This section describes the test methods used to determine the engineering properties of cement treated crushed concrete blended with crushed brick. The following geotechnical laboratory tests are described in this section to determine the engineering properties of recycled brick when blended (0%, 15%, 30%, and 50%) with cement treated (3% GP cement) crushed concrete:

- pH
- Plasticity Index
- Foreign Materials Content
- Particle Size Distribution
- Hydrometer
- Linear Shrinkage Test
- California Bearing Ratio
- Modified Compaction
- Repeated Load Triaxial Test
- Unconfined Compressive Strength Test
- Flexural Beam Test

### **4.1 pH**

pH tests were performed in accordance with AS 1289.4.3.1 “Soil chemical tests - Determination of the pH value of a soil - Electrometric method” on crushed concrete and crushed brick (Standards Australia, 1997). Both samples consisted of material passing 2.36 mm sieve.

### **4.2 Plasticity Index**

Plastic limit, liquid limit and plasticity index tests were performed in accordance with AS 1289.3.1.1 “Soil classification tests – Determination of the liquid limit of a soil – Four point Casagrande method” for liquid limit (Standards Australia, 2009a) and AS 1289.3.2.1 “Soil classification tests – Determination of the plastic limit of a soil – Standard method” for plastic limit (Standards Australia, 2009b). Some consideration was given to using the “one point method” as this method most likely provides adequate characterisation for processed

recycled materials with a Plasticity Index ranging between 0 and 2. However, it was decided in this particular instance with the method normally specified in VicRoads specifications.

### **4.3 Foreign Material Content**

To determine the percentage by mass in the fraction of a crushed concrete product retained on a 4.75 mm sieve, visual categorisation was carried out according to RC 372.04, VicRoads' manual of testing: Foreign Materials in Crushed Concrete (VicRoads, 2008).

### **4.4 Particle Size Distribution**

Particle size distribution tests were performed in accordance with AS 1141.11 "Particle size distribution by sieving" (Standards Australia, 2009d). The Australian Standard sieves used were with the aperture sizes of 19mm, 13.2mm, 9.5mm, 6.7mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 425µm, 300µm, 150µm and 75µm. The minimum amount of 3 kilograms was sieved and the particle size distribution was plotted for each blend.

### **4.5 Hydrometer**

A hydrometer was used to determine the particle size distribution for particles finer than the 75µm sieve in accordance with AS 1289.3.6.3 "standard method of fine analysis using a hydrometer" (Standards Australia, 2003a).

### **4.6 Linear Shrinkage Test**

Linear shrinkage of both crushed concrete and crushed brick were carried out according to AS 1289.3.4.1: "Determination of the linear shrinkage of a soil" (Standards Australia, 2009c).

### **4.7 California Bearing Ratio**

California Bearing Ratio tests were performed in accordance with AS 1289.6.1.1 "Soil strength and consolidation tests – Determination of the California Bearing Ratio of a soil – Standard laboratory method for a remoulded specimen" (Standards Australia, 1998b). The samples were prepared at their optimum moisture content using "modified" compactive effort (100% Maximum Dry Density) and tested upon completion of four days soaking condition.

### **4.8 Modified Compaction**

Modified compaction tests were performed in accordance with AS 1289.5.2.1 "Soil compaction and density tests – Determination of the dry density/moisture content relation of

a soil using modified compactive effort” to determine the maximum dry density and optimum moisture content (Standards Australia, 2003b). Samples were compacted in a 105mm diameter mould in 5 layers with an average height of 120mm.

#### **4.9 Repeated Load Triaxial Test**

Repeated load triaxial (RLT) tests were undertaken in accordance with the Austroads Repeated Load Triaxial Test Method AG:PT/T053 “Determination of Permanent Deformation And resilient Modulus Characteristics of Unbound Granular Materials Under Drained Conditions” (Austroads, 2007). The samples were compacted in a 105mm diameter mould with the height of 200mm in 8 layers. The samples were then dried back to approximately 70% of the Optimum Moisture Content (OMC) prior to testing.

#### **4.10 Unconfined Compressive Strength Test**

Unconfined Compressive Strength (UCS) test was conducted using AS5101.4 (Standards Australia, 2008). Samples were prepared fully in accordance with the methods of testing soils for engineering purposes as prescribed in AS 1289.1.2.1 and AS 1289.5.2.1 (Standards Australia, 1998a, Standards Australia, 2003b) using “split moulds” to ensure UCS samples were not damaged during removal and parallel end faces were maintained. The unconfined compressive strength of the samples was determined after 7 days and 28 days of curing in fog chamber. The samples were immersed in water for 4 hours prior to testing.

#### **4.11 Flexural Beam Test**

Flexural beam test consisted of 3 stages of testing to determine the following properties of the cement stabilised materials:

- Flexural Strength
- Flexural Modulus
- Fatigue Life

One pair of beams for each blend (4 pairs in total) was prepared at an external laboratory facility. Flexural strength was subsequently determined in accordance with AS 1012.11 “Determination of the modulus of rupture” (Standards Australia, 2000). Flexural modulus and fatigue life were determined in accordance with Austroads’ protocols “Flexural Beam Test Method – Modulus and Fatigue” (Yeo, 2008).

## 5 EXISTING SPECIFICATIONS FOR CONSTRUCTION & DEMOLITION MATERIALS IN VICTORIA

In Victoria, the construction of road works is generally in accordance with specifications established by VicRoads after many years of hands-on practical experience. Standard Section 820 of the VicRoads specification describes requirements for the use of recycled crushed concrete for pavement sub-base and light duty unbound base (VicRoads, 2011b). The required engineering properties for recycled crushed concrete and the limitations for foreign materials are summarised in Table 1 and Table 2 respectively.

**Table 1. Required engineering properties of crushed concrete (VicRoads, 2011b)**

Test	Test Value		
	Class CC2	Class CC3	Class CC4
Liquid Limit %(Max)	35	35	40
Plasticity Index (Max)	6	10	20
California Bearing Ratio % (Min)	100	80	15
Los Angeles Abrasion Loss(Max)	30	35	40
Flakiness Index	35	-	-

**Table 2. Maximum allowable foreign material (%) in crushed concrete (VicRoads, 2011a)**

Foreign Material Type	% retained
High density materials such as metal, glass and brick	3
Low density materials such as plastic, rubber, plaster, clay lumps and other friable material	1
Wood and other vegetable or decomposable matter	0.2

Foreign materials in crushed concrete prior to the addition of cementitious binder (GP cement used in this project) is currently specified to comply with the requirements of Class CC3 as presented in Table 2 (VicRoads, 2011a).

While the addition of crushed brick or crushed glass to Class 3 or Class 4 sub-base may be approved as a part of a VicRoads registered crushed rock mix design for “unbound” pavements.

Currently, the presence of brick and glass is still considered as a foreign material and limited thus to 3% for cement treated crushed concrete pavement sub-bases (Section 821) as

indicated in Table 2. Hence the need for this research to assess the viability of higher proportions of brick specifically focusing on Section 821.

The grading requirements for uncompacted crushed concrete (Class CC3) are tabulated in Table 3. This gradation is required ( Section 821) for the Class 3 crushed concrete product prior to the addition of any cementitious binder, for use as a pavement sub-base (VicRoads, 2011a, VicRoads, 2011b).

**Table 3. Grading requirements for 20 mm Class CC3 crushed concrete (VicRoads, 2011b)**

Sieve Size AS (mm)	Target Grading ( % Passing)	Limits of Grading Test Value before Compaction (% Passing)
26.5	100	100
19.0	100	95-100
13.2	85	75-95
9.5	75	60-90
4.75	59	42-76
2.36	44	28-60
0.425	19	10-28
0.075	6	2-10

VicRoads sets a reasonably coarse grading envelope for its recycled products to ensure that the final placed product does not degrade (excessively breakdown) significantly under compaction. VicRoads generally permits a maximum of 2-3% breakdown on the finer sieve sizes for sub-base products which allows for some reworking, if required.

## **6 ENGINEERING PROPERTIES OF CEMENT TREATED CRUSHED CONCRETE BLENDED WITH CRUSHED BRICK**

Laboratory tests were undertaken on prepared samples of cement treated crushed concrete blended with crushed brick obtained from the Delta Recycling site at Sunshine. 3% GP cement was used in the cement treated crushed concrete blends. The engineering properties of the four (4) cement treated crushed concrete blends investigated were: 100% crushed concrete (100CC), 85% crushed concrete blended with 15% crushed brick (85CC-15CB), 70% crushed concrete blended with 30% crushed brick (70CC-30CB) and 50% crushed concrete blended with 50% crushed brick (50CC-50CB).

### **6.1 pH**

The pH values of the 4 nominated blends are presented in Table 4. The range of pH value for crushed concrete is between 11.3 – 12.0 which indicates that all the blends are alkaline by nature. These values are consistent with previous works by Swinburne on C&D materials.

**Table 4. pH value of crushed concrete-crushed brick blends**

Type of Material	100CC	85CC-15CB	70CC-30CB	50CC-50CB
pH Value	12.0	11.3	11.9	11.8

### **6.2 Plasticity Index**

As the clay content in all the blends was low, the plastic limit and liquid limit could not be obtained. This is because the Atterberg limit is directly related to clay mineralogy and thus to the clay content. Lower clay contents result in lower plasticity.

### **6.3 Foreign Material Contents**

The summary of the foreign material content in the Class 3 crushed concrete sample is presented in Table 5. Low density materials include plastic, rubber, plaster, clay lumps and other friable materials. With respect to the crushed brick sample, typically this material will consist of a mixture of materials including some crushed concrete, low density materials as well as wood and vegetable matter. The crushed brick samples used were visually assessed to contain between 50 and 70% brick component.

**Table 5. Foreign material content of crushed concrete**

Composition of Samples	Crushed Concrete Sample
Crushed Concrete (%)	96.44
Crushed Brick (%)	2.62
Asphalt (%)	0.94
Low density materials (%)	0
Wood and vegetable matter (%)	0

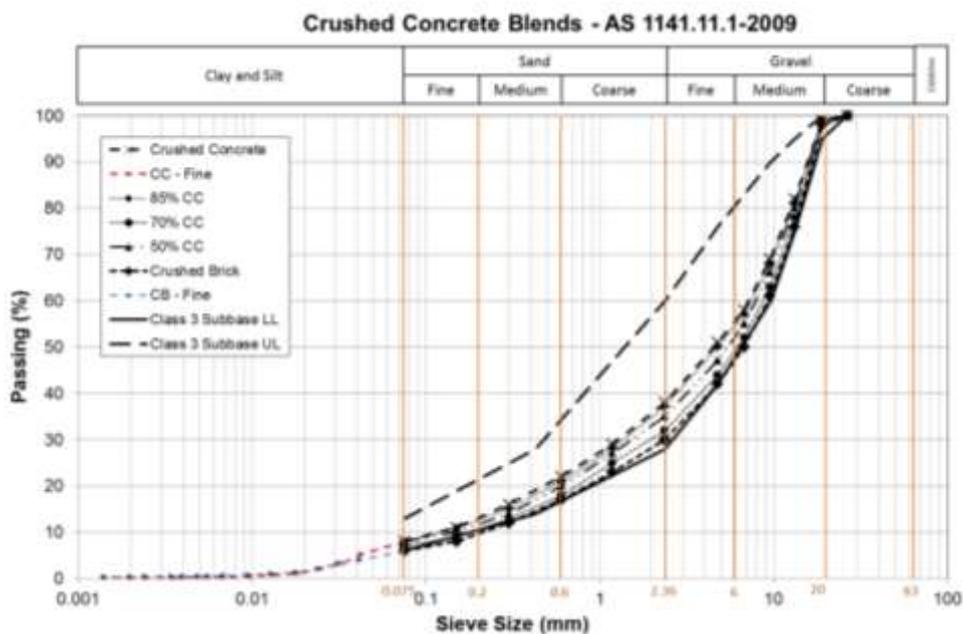
With reference to Table 2, the Class 3 crushed concrete sample is on the borderline of the allowable percentage of foreign material content. The presence of foreign materials in crushed concrete was visually identified and a photo snapshot of the materials is presented in Figure 1.



**Figure 1. Foreign material contents in crushed concrete**

## 6.4 Particle Size Distribution

The particle size distributions of cement treated crushed concrete and crushed brick are shown in Figure 2. The grading limits of all blends, except 100% crushed brick, were found to be within the VicRoads specified limit for class 3 sub-base. Although the crushed brick is slightly lower than the lower limit for class 3 sub-base but when blended with cement treated crushed concrete it complies with the acceptable gradation envelope for Class 3 sub-base materials.



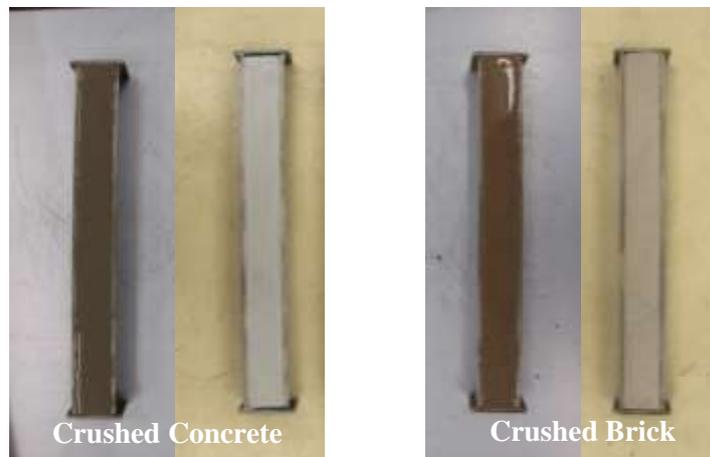
**Figure 2. Particle size distribution of cement treated crushed concrete-crushed brick blends**

The red dotted line in Figure 2 indicates the fine particle size distribution which was determined by hydrometer testing. Similarly, the fine particle size distribution of crushed brick was shown in blue dotted line.

## 6.5 Linear Shrinkage Test

Due to the low clay content of crushed concrete and the blends, it was not possible to measure the linear shrinkage of the materials. Figure 3 shows two sets of linear shrinkage tests; the left side of each set shows the beginning of the test and the right side of each set shows the linear shrinkage after 24 hours air-drying followed by transferring the samples in the oven at 105°C to 110 °C until the shrinkage ceased. As it was shown in Figure 3, a change

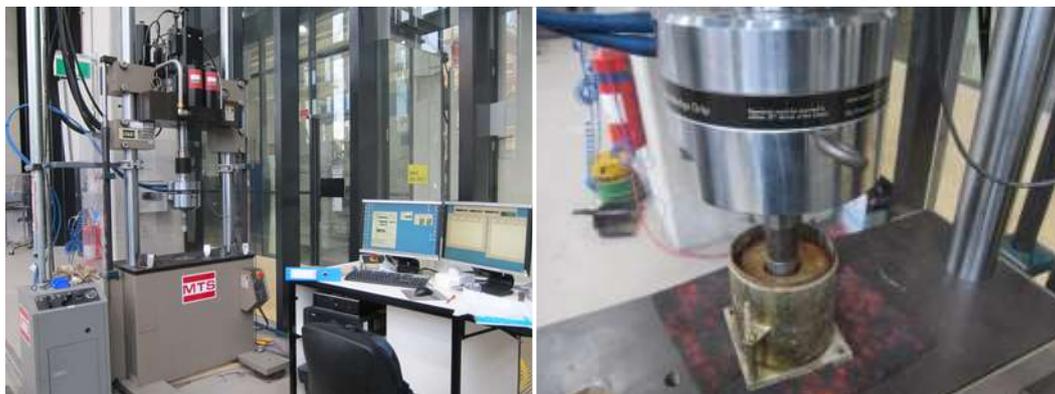
in colour was noticed in both cement treated crushed concrete and crushed brick however there was no significant change in length of the samples.



**Figure 3. Linear shrinkage of cement treated crushed concrete and crushed brick**

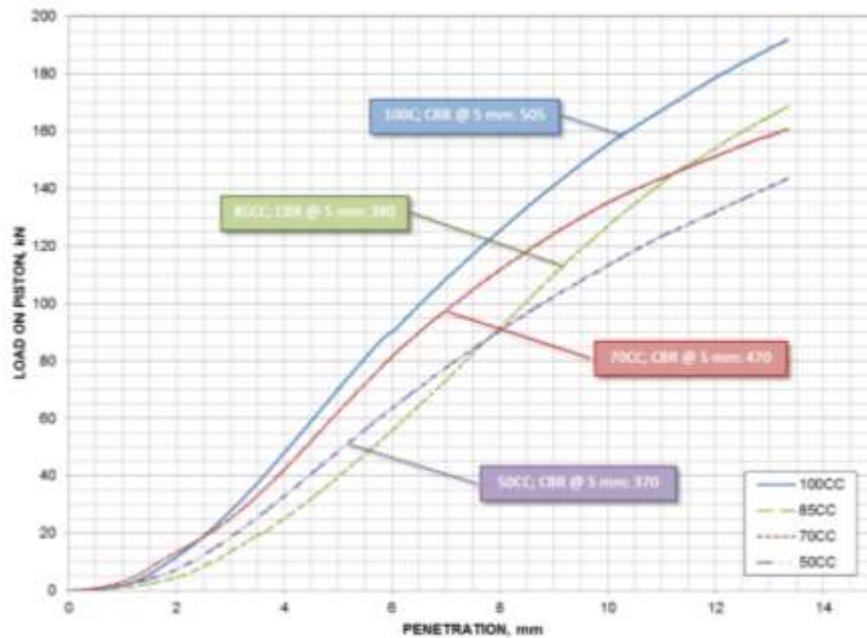
#### **6.6 California Bearing Ratio (CBR)**

The CBR value of cement treated crushed concrete blends was high and varied from 380 for 85%CC to 505 for 100%CC. Due to high strength of CBR samples, the CBR test was carried out using a MTS-250kN equipment at Swinburne (Figure 4).



**Figure 4. CBR test using MTS-250kN**

The load-penetration curves of crushed concrete and its blends are summarised in Figure 5. The high CBR values are due to cement treatment of all blends as 3% of GP cement was added as a stabiliser to crushed concrete and its blends.



**Figure 5. Load-Penetration curves of cement treated crushed concrete-crushed brick blends**

### 6.7 Modified Compaction Test

The results of optimum moisture content (OMC) and maximum dry density (MDD) of crushed concrete and its blends with crushed brick including 3% GP cement are summarised in Table 6.

**Table 6. Modified compaction results of cement treated (3% GP Cement) crushed concrete-crushed brick blends**

Type of Material	100CC	85CC-15CB	70CC-30CB	50CC-50CB
OMC, %	11.7	11.7	11.7	12
MDD, t/m <sup>3</sup>	2.039	2.007	1.991	1.996

OMC varies from 11.7% for crushed concrete to 12% for crushed concrete blended with 50% crushed brick while the MDD declines from 2.039 t/m<sup>3</sup> to 1.996 t/m<sup>3</sup> for crushed concrete blended with 50% crushed brick. The OMC and MDD values were found to be consistent, with only minor variations.

## 6.8 Repeated Load Triaxial Test

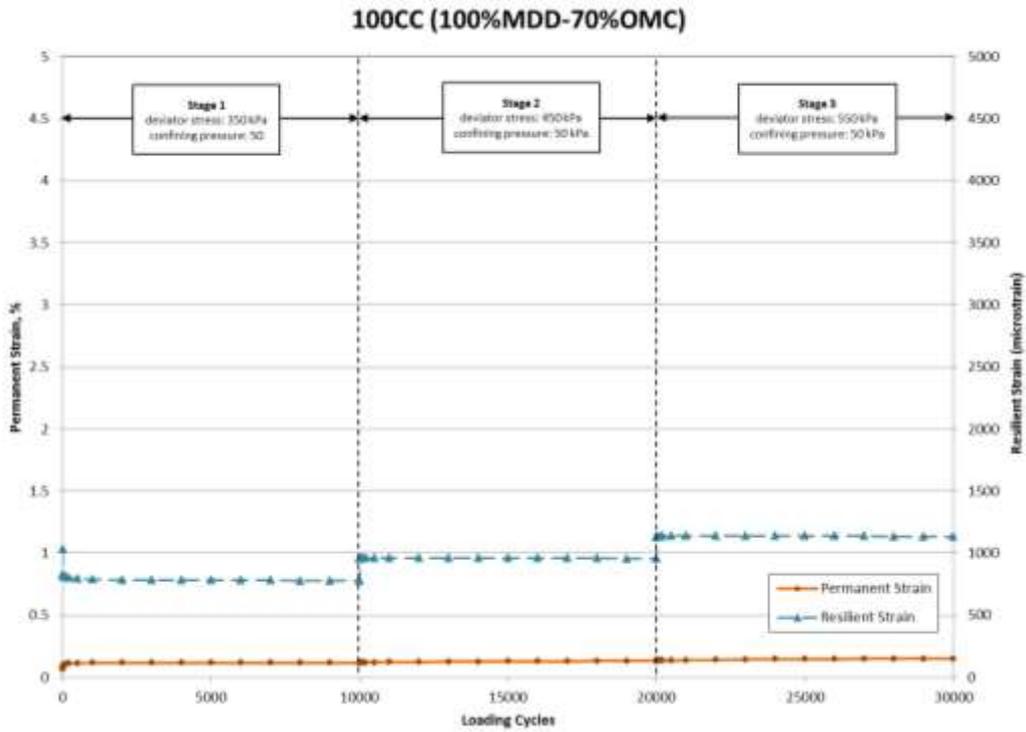
Four specimens were prepared for RLT testing with dynamic compaction effort as specified by AS 1289.5.2.1(Standards Australia, 2003b). The automatic (mechanical) compaction apparatus, which permits a continuous and even compaction mode, was used to produce uniform specimens to specified density and moisture condition. All the specimens were compacted to the target density of 100% MDD and target moisture content of 100% of the OMC. The specimens were then dried back to a target value of 70% of the OMC. Table 7 summarises the target (at compaction) and actual (after RLT testing) sample degree of compaction and moisture content values for each specimen. Generally, it was possible to prepare the specimens within the tolerance of 0.9% for density ratio using the dynamic compaction method at 100% OMC. However, it was difficult to obtain the target moisture contents using the dry-back method. This difficulty in the dry-back method was observed in previous studies (Vuong et al., 2010) and is an accepted feature of RLT testing. Swinburne's Advanced Geotechnical Laboratory RLT testing equipment was used in the laboratory testing program.

**Table 7. RLT specimens moisture contents and degree of compaction**

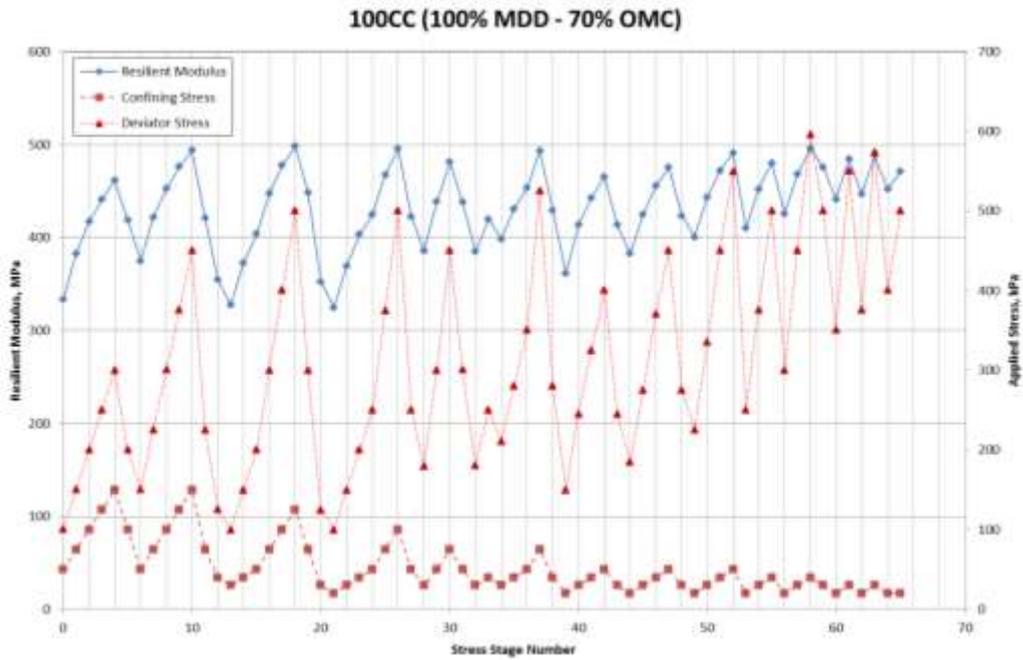
Specimen	Target MC, (% OMC)	Actual MC– after RLT test (% OMC)	Target degree of compaction, %	Actual degree of compaction, %
100CC	70	56	100	99.7
85CC-15CB	70	56	100	99.1
70CC-30CB	70	79	100	99.9
50CC-50CB	70	70	100	100

The RLT testing procedure consists of a permanent strain test followed by a resilient modulus test. The permanent deformation determination characterises the vertical permanent strain with multiple loading stages (at different stress conditions) to enable quantification of the effects of vertical stress on permanent strain in a single test. For the cement treated crushed concrete blends, 50 kPa confining stress, three different loading stages (at specified deviator stresses of 350 kPa, 450 kPa and 550 kPa respectively) were used, each loading stage involved 10,000 repetitions. A confining stress of 50 kPa was applied for all loading stages. The resilient modulus determination characterises the vertical resilient strain response over sixty stress conditions using combinations of applied dynamic vertical and static lateral stresses in the ranges of 100-500 kPa and 20-150 kPa, respectively. Each stress condition involved 200 load repetitions. The stresses and stress ratios are increased in small sizes to

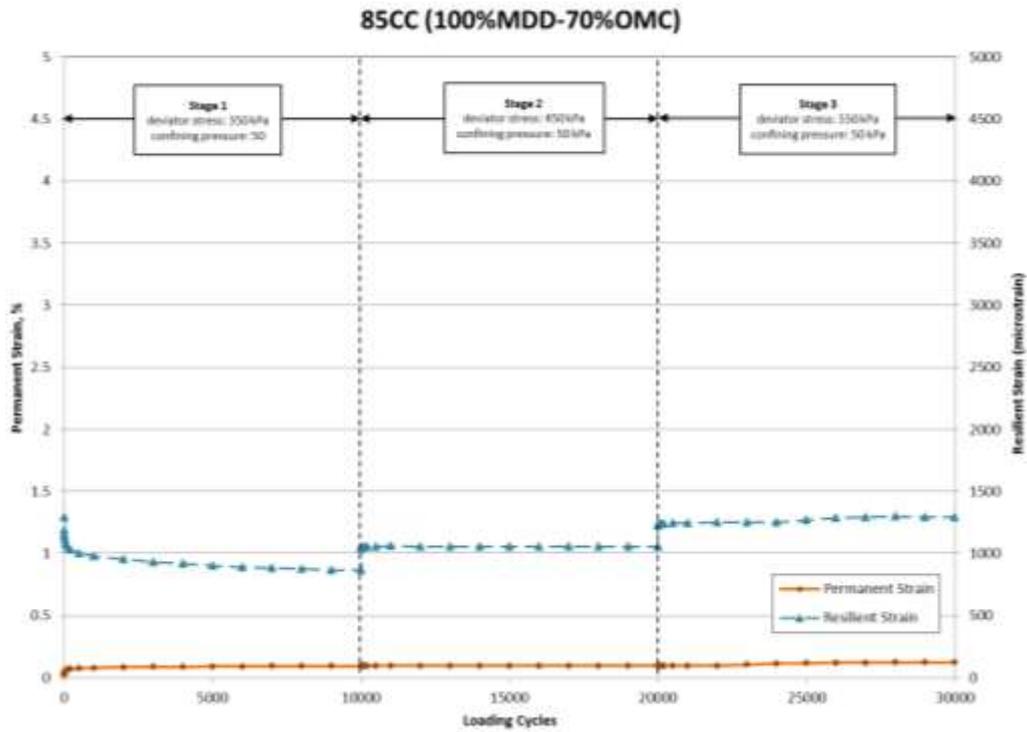
avoid early failure, which can occur at high stress ratios. The permanent deformation and resilient modulus results of cement treated crushed concrete-crushed brick blends are presented in Figure 6 to Figure 13.



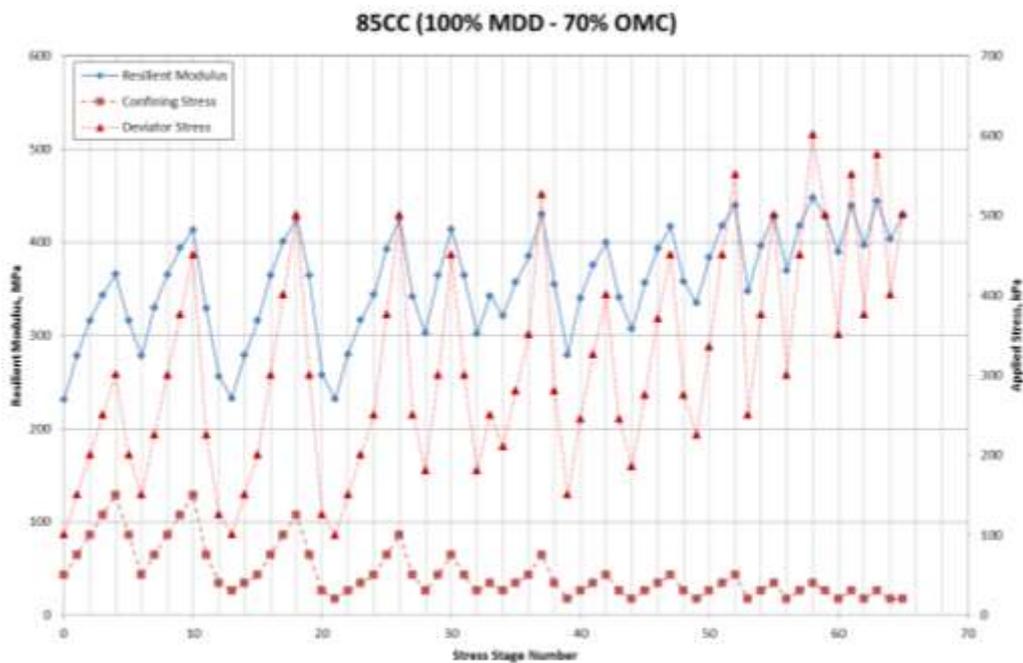
**Figure 6. Permanent deformation of cement treated crushed concrete (100CC)**



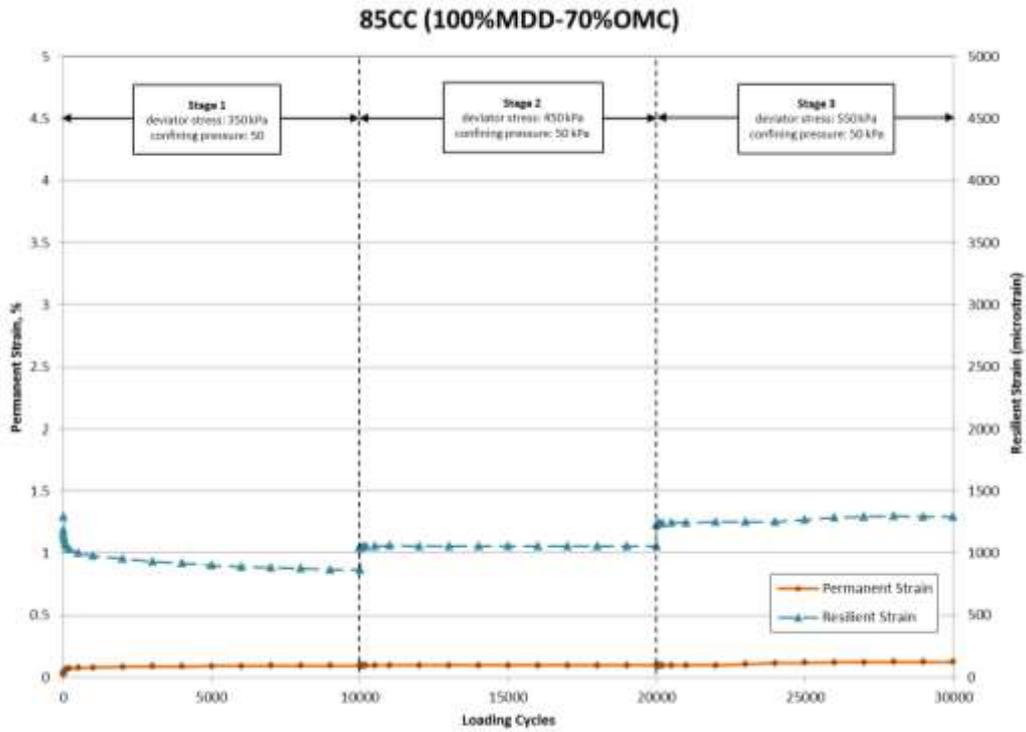
**Figure 7. Resilient modulus of cement treated crushed concrete (100CC)**



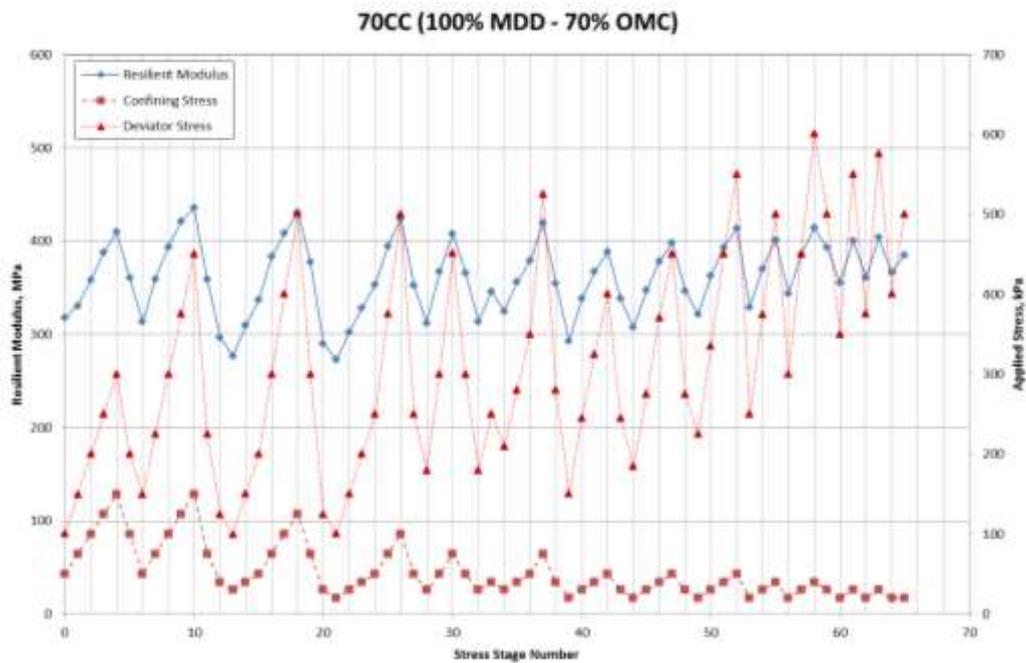
**Figure 8. Permanent deformation of 85% cement treated crushed concrete (85CC-15CB)**



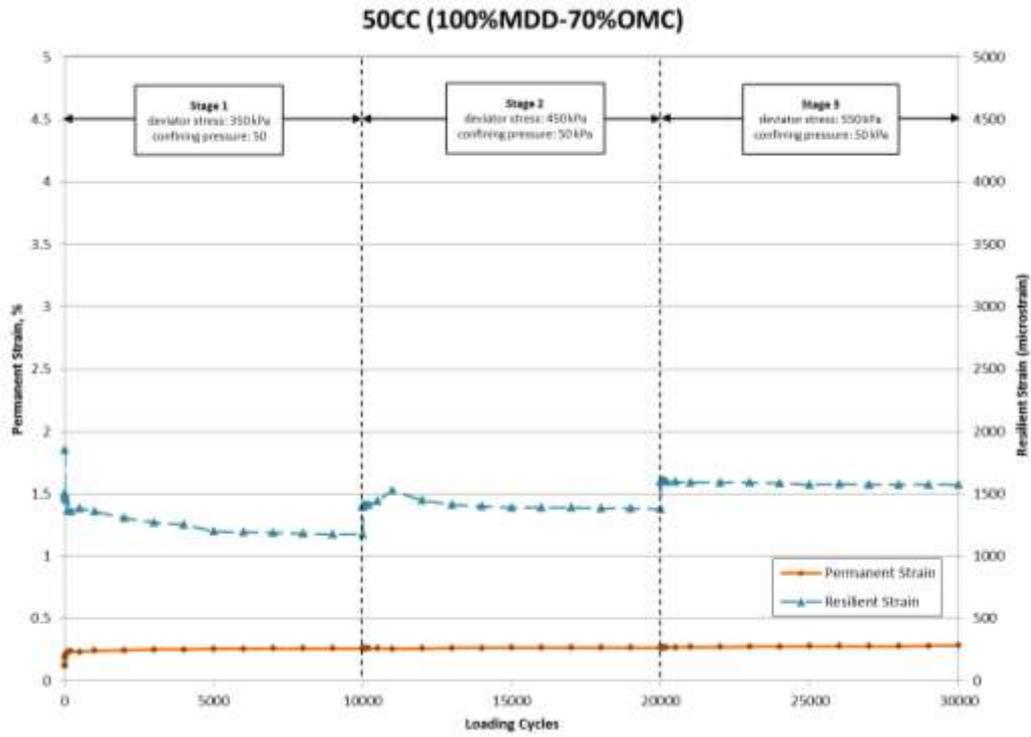
**Figure 9. Resilient modulus of 85% cement treated crushed concrete (85CC-15CB)**



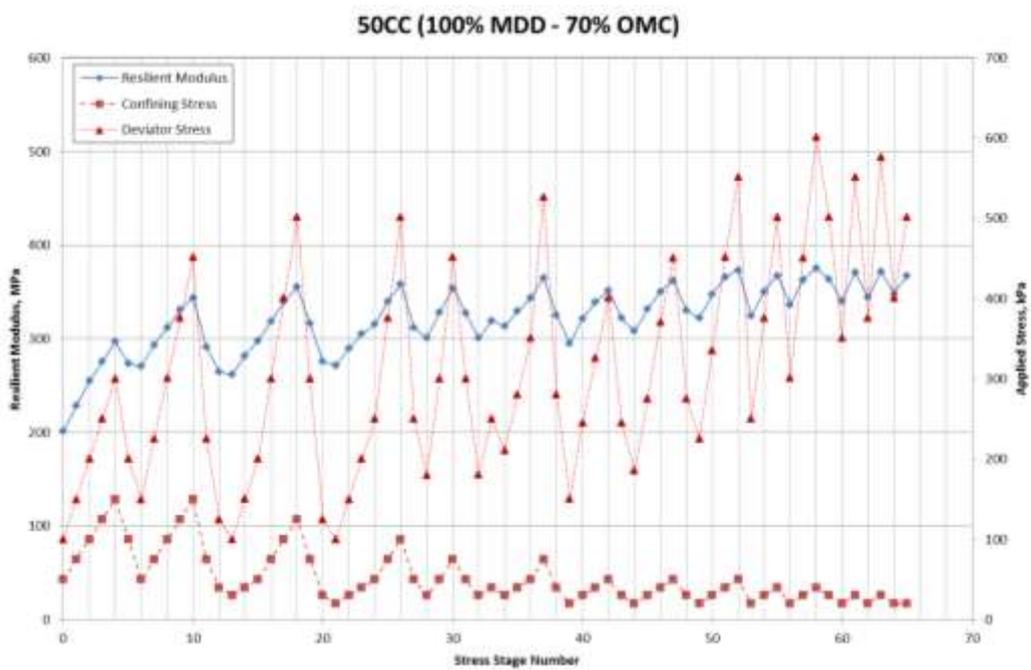
**Figure 10. Permanent deformation of 70% cement treated crushed concrete (70CC-30CB)**



**Figure 11. Resilient modulus of 70% cement treated crushed concrete (70CC-30CB)**



**Figure 12. Permanent deformation of 50% cement treated crushed concrete (50CC-50CB)**



**Figure 13. Resilient Modulus of 50% cement treated crushed concrete (50CC-50CB)**

The summary of permanent strain, achieved moisture content and degree of compaction results are presented in Table 8.

**Table 8. Results of permanent strain testing for cement treated crushed concrete-crushed brick blends**

Specimen	Actual dry density (% MDD)	Actual moisture content (% OMC)	Permanent Strain at the end of each stage, microstrain		
			Stage 1	Stage 2	Stage 3
100CC	99.7	56	1180	1340	1500
85CC-15CB	99.1	56	940	950	1230
70CC-30CB	99.9	79	1450	1450	1550
50CC-50CB	100	70	2570	2640	2820

In general, there was an increasing trend for permanent deformation with the increase of moisture content, which is expected. It was difficult to compare the effect of added crushed brick since the achieved moisture content of specimens after dry-back was not at the same level.

The Austroads test method gives no guidance on how the RLT results relate to in-service performance (Vuong et al., 2010) but a simplified method for assessing the performance of materials has been proposed by Vuong (2000) and Vuong and Arnold (2006), which is defined as follows:

- **Stable** – behaviour is defined as a decreasing permanent strain rate and/or decreasing to constant resilient strain (or constant to increasing modulus) with increasing loading cycles in the permanent strain test.
- **Unstable** – behaviour is defined as a decreasing to constant permanent strain rate and/or constant to increasing resilient strain (or constant to decreasing modulus) with increasing loading cycles in the permanent strain test.
- **Failure** – behaviour is defined as a constant to increasing rate of permanent strain and increasing resilient strain (or decreasing modulus) with increasing loading cycles in the permanent strain test or when the total permanent strain reaches a nominal failure strain observed in a static triaxial shear test (say in the range 15,000 to 20,000 microstrain).

With reference to the permanent deformation results of all cement treated crushed concrete specimens, the blends are seen to exhibit constant permanent strain rate and increasing resilient modulus. The behaviour of the materials can thus be defined as “Stable”.

Summary of resilient modulus test results of cement treated crushed concrete-crushed brick blends are presented in Table 9.

**Table 9. Resilient modulus range of cement treated crushed concrete-crushed brick blends**

Specimen (with 3%GP)	Actual dry density (% MDD)	Actual moisture content (% OMC)	Resilient Modulus Range MPa
100CC	99.7	56	324.5 – 498.3
85CC-15CB	99.1	56	231.1 – 447.9
70CC-30CB	99.9	79	272.5 – 435.6
50CC-50CB	100	70	201.3 – 375.7

In general increasing the percentage of brick indicates a reduction of resilient modulus value of cement treated crushed concrete blends. This is expected as brick is being added as a supplementary material to crushed concrete and furthermore is a slightly less durable material compared to crushed concrete. Since the specimens were not at the same moisture content level after dry-back for the RLT test, it is difficult to solely isolate the effect of crushed brick on resilient modulus of cement treated crushed concrete blends.

Typical quarry aggregates would exhibit resilient modulus values of between 225-400 MPa at 70% of the OMC based on the computation of resilient modulus from the permanent deformation testing phase (Arulrajah and Wilson, 2008). All the blends, were found to perform within the ranges expected of bound quarry sub-base materials, with 50CC-50CB on the borderline. It is to be noted, the RLT testing is not a specified in VicRoads Section 821 as a requirement for cement treated crushed concrete in pavement applications, but was undertaken in this project in order to better understand the behaviour of the crushed concrete blends under simulated traffic loading.

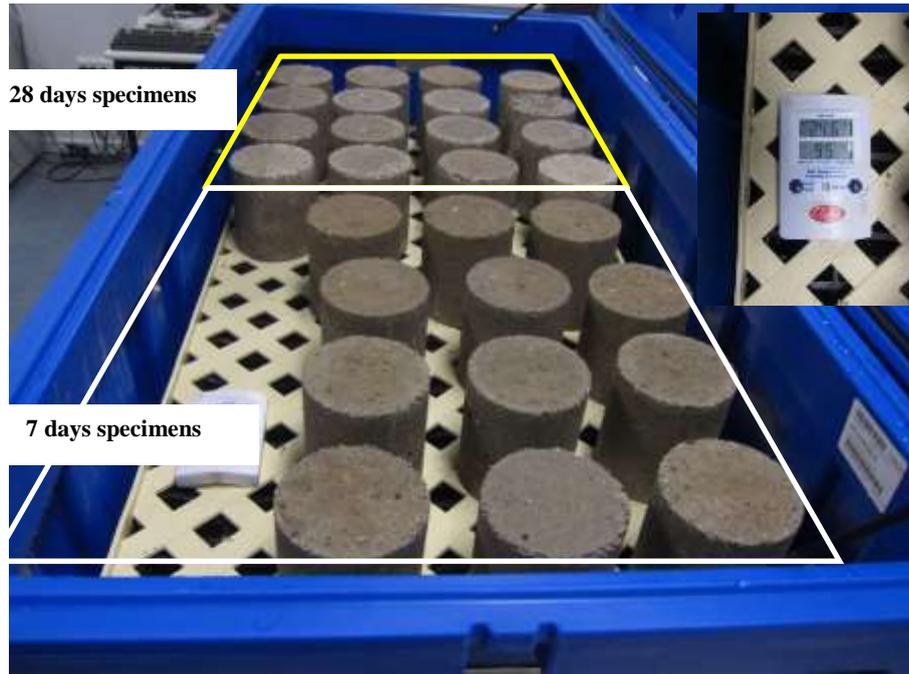
## 6.9 Unconfined Compression Strength Test

The minimum UCS values for a minimum curing period of 7 days are specified in Table 10. based on the requirements of VicRoads Section 821 (VicRoads, 2011a). Generally in cement stabilisation, hydration of the cement occurs in association with cement-clay interaction: the hydrated cement fills voids in the soil by both diffusion and volumetric growth of the resulting compounds. The strength usually increases as the cement content increases, with an increase in unconfined compressive strength (UCS) between 0.5-1.0 MPa being achieved for each 1% of cement added (Sharp, 2009).

**Table 10. Cementitious binder content and unconfined compressive strength (UCS) (VicRoads, 2011a)**

Pavement Design Modulus (MPa)	Minimum Design Cementitious Binder Content (% by mass)	Minimum 7 day Mean UCS (MPa)		
		Rapid Setting (GP Cement)	Medium Setting (GB Cement)	Slow Setting (Supplementary Cementitious Blends)
≤ 500	3	4	#	#
> 500 or ≤ 3500	3	5	3.5	3

UCS samples were compacted in five layers of pre-determined mass using a Proctor compaction machine and a one-piece split mould (modified compaction as per AS1141.51). A portion of the remaining material was dried in an oven for the determination of moisture content of the sample at the time of compaction. Compacted samples were immediately taken to the fog chamber for moist curing. Seven days samples (four sets of three specimens) were left in the fog room until the time of testing while samples (four sets of four specimens) subjected to longer curing periods were removed from the fog room after 28 days (Figure 14). All samples were subjected to 4 hours of immersing in water prior to the UCS test.



**Figure 14. UCS specimens being cured in fog chamber**

The UCS results for all the cement treated specimens are summarised in Table 11. For 7 days curing period the mean UCS value obtained was between 4 to 4.63 MPa for the cement treated crushed concrete blends. The cement treated crushed concrete blends were therefore found to meet the minimum 7 day mean UCS value of 4 MPa specified in VicRoads Section 821 (VicRoads, 2011a) for rapid setting (GP) cement.

The 28 days curing period was found to lead to an increase in the mean UCS value for all the blends to between 5.2 and 7.02 MPa. This is consistent with expectations that a longer curing period would result in a higher mean UCS value. It is noted that only the 7 day curing period is specified in VicRoads Section 821(VicRoads, 2011a) but the 28 day curing period tests were undertaken as an extra measure to determine the performance of the cement treated crushed concrete blends under increased curing period.

**Table 11. UCS results of cement treated crushed concrete-crushed brick blends**

Sample Type	Sample ID	Curing Days	Strength, MPa			MC %OMC	Dry Density %MDD
			individual	mean	Std Dev		
100CC (3%GP)	100CC-28-1	28	6	5.35	0.47	92.8	97.1
	100CC-28-2		4.9			97.7	95.4
	100CC-28-3		5.6			96	97.6
	100CC-28-4		4.9			100	96.1
	100CC-7-5	7	3.8	4.0	0.17	100.2	96.1
	100CC-7-6		4.2			103.1	96.0
	100CC-7-7		4			98.7	96.1
85CC-15CB (3%GP)	85CC-28-1	28	6	7.02	0.76	92.3	97.8
	85CC-28-2		6.6			94.3	95.8
	85CC-28-3		7.9			97.1	98.0
	85CC-28-4		7.6			95.7	97.7
	85CC-7-5	7	3.8	4.0	0.29	101.5	97.6
	85CC-7-6		3.6			100.6	97.7
	85CC-7-7		4.3			101.8	98.2
70CC-30CB (3%GP)	70CC-28-1	28	4.6	5.6	0.63	96.4	97.0
	70CC-28-2		5.8			95.7	97.1
	70CC-28-3		6.3			94.5	99.1
	70CC-28-4		5.9			95.4	98.1
	70CC-7-5	7	4.8	4.63	0.17	93.2	98.9
	70CC-7-6		4.7			95.7	99.8
	70CC-7-7		4.4			98.3	98.3
50CC-50CB (3%GP)	50CC-28-1	28	5.6	5.2	0.54	89.1	98.7
	50CC-28-2		5.8			93.0	98.5
	50CC-28-3		4.5			94.8	97.6
	50CC-28-4		4.8			95.9	98.2
	50CC-7-5	7	4.6	4.2	0.28	96.2	98.2
	50CC-7-6		4			99.9	97.9
	50CC-7-7		4			97.1	97.8

## 6.10 Beam Fatigue Test

A rectangular mould with internal dimensions of 400 mm long x 320 mm wide x 145 mm high was used to compact the slabs by using BP Slab Compactor at an external laboratory facility (Figure 15).



**Figure 15. Slab compaction using BP compactor at an external laboratory facility**

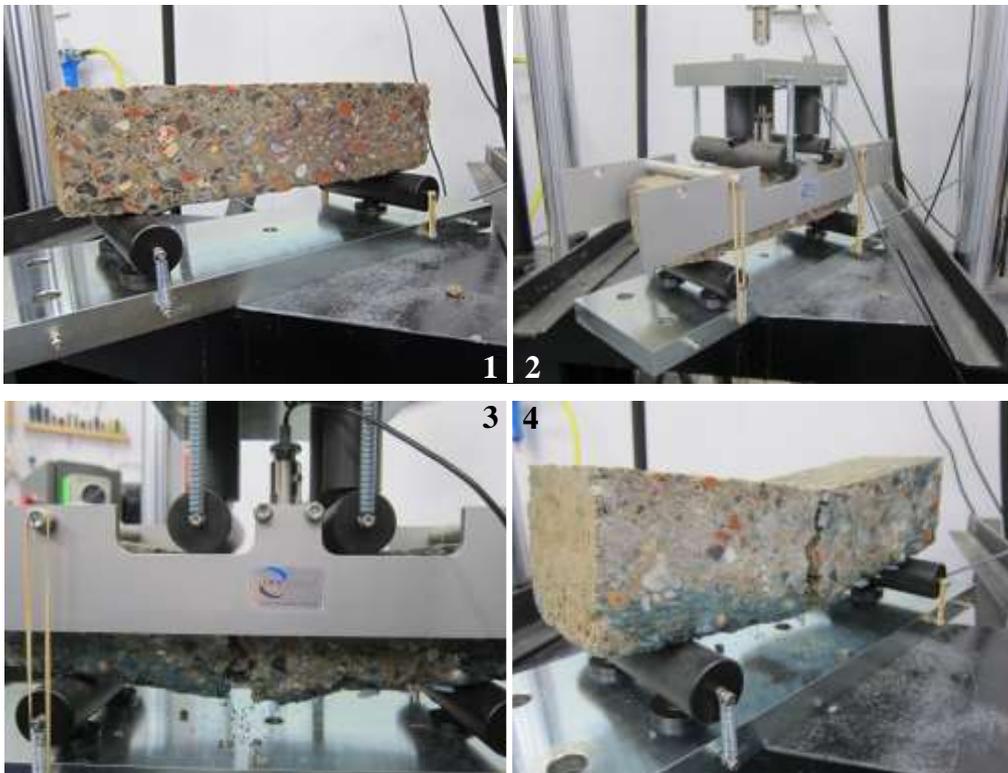
The compacted slabs were left in the closed mould and covered with a wet cloth and lid to minimise moisture loss and stored at 23°C for a minimum of 2 days before being de-moulded and moist cured in a fog room at an external laboratory facility. Each slab was subsequently cut into two beams after a minimum curing period of 14 days to ensure the slab was strong enough to be cut. All the beams were cured in fog room for a total of 28 days.

Figure 16 shows three compacted slabs being cured in the fog room. Each slab was cut into two identical beams which were then used for the flexural beam testing.



**Figure 16. Compacted slabs in fog room**

The fatigue testing was conducted in a controlled stress mode. This was considered the most appropriate simulation of normal repetitive wheel loads, particularly for a given Accelerated Loading Facility experiment at a given axle load (Yeo, 2008). In accordance with Austroads method (Yeo, 2008), the first beam from the same slab (Beam A) was used to determine the peak load required to break the beam using the Modulus of Rupture test method. AS 1012.11 (2000) was used to run this test under a monotonic load. A set of pictures showing the different stages of four point beam fatigue test are presented in Figure 17.



**Figure 17. Four point beam fatigue test**

The results of the modulus of rupture tests are presented in Table 12. The modulus of rupture or tensile stress ranged from 0.88 MPa for 70CC-30CB cement treated crushed concrete to 1.23 MPa for 100CC cement treated crushed concrete. The peak load varied between 3.6 kN for 70CC-30CB cement treated crushed concrete to 4.29 kN for 100CC cement treated crushed concrete. According to these results, the increase in crushed brick content in the cement treated crushed concrete blends results in a corresponding decrease in the peak load and modulus of rupture, which is as expected.

**Table 12. Modulus of rupture results**

	<b>Sample Type</b>			
	<b>100CC (3% GP cement)</b>	<b>85CC- 15CB (3% GP cement)</b>	<b>70CC- 30CB (3% GP cement)</b>	<b>50CC- 30CB (3% GP cement)</b>
width, <i>mm</i>	100.9	101.5	100.23	100.6
height, <i>mm</i>	101.66	101.4	101.08	100.7
moisture content, <i>%OMC</i>	99.1	96.5	106	100.3
dry density, <i>% MDD</i>	96.5	96.5	96	95.4
peak load, <i>kN</i>	4.29	4.28	3.6	3.7
modulus of rupture, <i>MPa</i>	1.23	1.23	0.88	1.09
tensile strain at 95% of peak load, <i>microstrain</i>	94.22	93.08	57.85	87.48

On completion of the modulus of rupture test on the first beam of each blend, the second beam from the same slab (Beam B) was used for modulus testing. 40% of the peak load from the previous test was applied on this second paired beam from the same slab with a haversine pulse of 1 Hz comprising 250 ms for loading and 750 ms for resting for 100 cycles. This load was selected to be low enough so as to not damage the sample but high enough to produce sufficient displacement at the middle of the beam in order to accurately estimate the tensile strain and consequently resilient (flexural in this case) modulus.

Beam B was subsequently used for fatigue testing. The load was increased to 70% of the peak load with an increased frequency of 2 Hz comprising 250 ms for loading and 250 ms for resting. By definition the number of cycles to achieve half the initial modulus is termed as fatigue life. The half initial modulus is usually very close to the ultimate failure of the sample for the flexural beam fatigue test. The fatigue life is highly sensitive to the applied load, the

less the applied load the greater the fatigue life. Therefore some samples may fail after a few hundred cycles while some other samples may last for several thousand cycles. Table 13 shows the results of flexural modulus and flexural fatigue beam tests. As evident from Table 13 the fatigue life for 100CC was 130 cycles while for 50CC-50CB it was 29401 cycles. This variation in cycles could be due to the fact that 80% of peak load was applied on 100CC while 70% of peak load was applied on 50CC-50CB. To obtain a wider spectrum of fatigue life versus the applied load for each blend, it is recommended to undertake testing on additional beams to determine true fatigue life characteristics as this is highly dependent on load sensitivity.

**Table 13. Four point flexural beam fatigue test results**

	<b>Sample type</b>			
	<b>100CC (3% GP cement)</b>	<b>85CC- 15CB (3% GP cement)</b>	<b>70CC- 30CB (3% GP cement)</b>	<b>50CC- 50CB (3% GP cement)</b>
width, <i>mm</i>	100.62	102.3	101.05	101.1
height, <i>mm</i>	101.68	100.3	100.6	100.6
moisture content, % <i>OMC</i>	100.8	97.4	107	103.5
dry density, % <i>MDD</i>	95.5	96.2	96.1	95.4
<b>flexural modulus test</b>				
applied load, % <i>peak load</i>	40	40	40	40
mean flexural modulus (cycles 50-100), <i>MPa</i>	11463.25	11846.20	11351.33	11780.75
tensile stress for modulus test, <i>kPa</i>	494.15	496.79	420.26	432.91
<b>flexural fatigue test</b>				
applied load, % <i>peak load</i>	80	70	70	70
tensile stress for fatigue test (mean of first 50), <i>kPa</i>	978.28	872.18	737.711	758.21
Tensile strain (mean of first 50), <i>microstrain</i>	102.05	83.06	78.26	70.95
initial modulus (first 50), <i>MPa</i>	9601.05	10505.14	9435.30	10700
stress ratio	0.79	0.70	0.84	0.69
strain ratio	1.08	0.89	1.35	0.81
cycles to half initial modulus	130	6597	396	29401

A shift factor of about one third of the initial flexural modulus may give a rough estimation of field design modulus, though this has yet to be adopted by Austroads protocols

(Choummanivong et al., 2006). Assuming a shift factor of one third of flexural modulus leads to a minimum design modulus of 3700 MPa for the cement treated crushed concrete blends.

The results of the flexural beam tests were compared with previous works by Yeo et al. (2008) on cement treated base materials including hornfel and siltstone. The modulus of rupture and flexural modulus for all the cement treated blends were found to be consistent with the previous works which indicates that these blends are suitable for cement treated sub-bases. The fatigue life was also within the range that has been previously reported, though additional testing would appropriately determine the true fatigue life as just one test per blend would not determine this sufficiently.

## **7 CONCLUSIONS**

Samples of crushed concrete and crushed brick for this project were collected from Delta Recycling site at Sunshine in Victoria to evaluate the influence of crushed brick as a supplementary material in cement treated crushed concrete pavement applications. Basic geotechnical tests and specialised tests with the RLT, UCS and flexural beam test were used to determine the engineering properties of cement treated crushed concrete blends with crushed brick.

The findings of the advanced tests including RLT, UCS and beam fatigue tests were:

- It was found that all the crushed concrete blends had physical properties which comply with VicRoads Section 821.
  
- The results of RLT were used to ascertain the performance of cement-treated crushed concrete blends under simulated traffic loading conditions. Based on the results 100CC demonstrated the highest resilient modulus range and 50CC-50CB demonstrated the lowest resilient modulus range, which is expected. The results of RLT were found to be very sensitive to moisture content and degree of compaction. All blends, were found to perform within the ranges expected of bound quarry sub-base materials with 50CC-50CB on the borderline. It is noted that the RLT test method is not a Vicroads specification requirement for use of cement treated aggregates but was undertaken to understand the performance of the cement treated aggregates under simulated traffic loading.

- Mean UCS values met the minimum requirement of 4 MPa for minimum of 7 days curing for all blends. 20 and 24% increase in strength was observed for 28 days samples of 70CC-30CB and 50CC-50CB respectively compared to the 7 days samples, while the average 28 days strength of 85CC-15CB samples improved significantly from 4 to 7.02 MPa (by almost 75%). The notable increase in strength after 28 days of curing compared to just 7 days of curing is as expected. It is noted that only the 7 day curing period is specified in Vicroads Section 821. The achieved mean UCS values, particularly after 7 days of curing were slightly lower than anticipated, and further assessment of this aspect showed that the moulding moisture content will have a significant influence on the final outcome. The water/cement ratio's in the prepared UCS samples were commonly around 4.0 or above, whereas industry practice is more to target a maximum water/cement ratio of 3.5 as this provides certainty that the achieved UCS values will comfortably achieve the specification limits.
  
- The modulus of rupture varied from 0.88 MPa to 1.23 MPa while the flexural modulus ranged from 11351.33 MPa to 11846.20 MPa. Assuming a shift factor of 0.3, the design modulus was estimated based on the flexural modulus which ranged from 3405.39 MPa to 3553.86 MPa. The range of flexural fatigue life was between 130 to 29401 cycles. The wide range of fatigue life is due to the fact that flexural fatigue test is highly sensitive to the applied load. The results of the flexural beam tests were noted to be consistent with past works with cement treated quarry produced crushed rock products.
  
- Based on this laboratory assessment, up to 15% crushed brick can be initially recommended for incorporation as a supplementary material in cement treated crushed concrete pavement sub-base applications. Depending on the results of field trials, it may be possible to increase the percentage of crushed brick added in the future.

## 8 REFERENCES

- ARULRAJAH, A. & WILSON, J. 2008. Engineering properties and suitability of recycled crushed brick for pavement sub-base and as a bedding / granular filter material for drainage systems. Swinburne University of Technology
- AUSTROADS. 2007. Commentary to AG:PT/T053 - determination of permanent deformation and resilient modulus characteristics of unbound granular materials under drained conditions.
- CHOUMMANIVONG, L., YEO, R. & LOURENSZ, S. 2006. Laboratory assessment of cemented materials. arrb.
- SHARP, K. 2009. *Guide to Pavement Technology - Part 1: Introduction to Pavement Technology*, Austroads Limited.
- STANDARDS AUSTRALIA. 1997. Methods of testing soils for engineering purposes AS 1298.4.3.1
- STANDARDS AUSTRALIA. 1998a. Method of testing soils for engineering purposes. AS 1289.1.2.1-1998
- STANDARDS AUSTRALIA. 1998b. Methods of testing soils for engineering purposes. AS 1289.6.1.1-1998
- STANDARDS AUSTRALIA. 2000. Methods of testing concrete. AS 1012.11 - 2000
- STANDARDS AUSTRALIA. 2003a. Method of testing soils for engineering purposes. AS 1289.3.6.3-2003
- STANDARDS AUSTRALIA. 2003b. Methods of testing soils for engineering purposes. AS 1289.5.2.1-2003
- STANDARDS AUSTRALIA. 2008. Methods for preparation and testing of stabilized materials. AS 5101.4 - 2008
- STANDARDS AUSTRALIA. 2009a. Method of testing soils for engineering purposes. AS 1289.3.1.1-2009
- STANDARDS AUSTRALIA. 2009b. Method of testing soils for engineering purposes. AS 1289.3.2.1-2009
- STANDARDS AUSTRALIA. 2009c. Method of testing soils for engineering purposes. AS 1289.3.4.1-2008
- STANDARDS AUSTRALIA. 2009d. Methods for sampling and testing aggregates. AS 1141.11.1-2009
- VICROADS. 2008. Manual of Testing: Foreign Materials in Crushed Concrete. RC 372.04
- VICROADS. 2011a. Cementitious treated crushed concrete for pavement subbase. Section 821
- VICROADS. 2011b. Crushed concrete for pavement subbase and light duty base. Section 820
- VUONG, B. 2000. Technical basis in the development of the Austroads repeated load triaxial test method and assessment method for granular materials. Vermont South, Victoria. : ARRB Transport Research.
- VUONG, B. & ARNOLD, G. 2006. Predicting in-service performance of alternative pavement materials for New Zealand conditions. Wellington, NZ: Land Transport New Zealand.
- VUONG, B. T., LUKE, R. & LOURENSZ, S. 2010. Laboratory Performance of Recycled Glass as Subbase Filler. Melbourne: Australian Road Research Board (arrb).
- YEO, R. 2008. The Development and Evaluation of Protocols for the Laboratory Characterisation of Cemented Materials. Austroads.