Crushed Glass as a Supplementary Material in Cement Treated Crushed Concrete Pavement Applications

Sustainability Victoria

Victoria State Government

SWINBURNE UNIVERSITY OF TECHNOLOGY

Centre for Sustainable Infrastructure

Crushed Glass 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 increasing impetus from state government sustainability initiatives to use recycled materials where appropriate and where they are fit for purpose, particularly in roads and other infrastructure.

This project proposes to investigate the use of <u>recycled crushed glass (5mm minus glass fines) as a supplementary material with recycled concrete aggregates in cement treated bound pavement applications.</u> Two types of recycled concrete aggregate being class CC3 and CC4 were studied in this research, CC4 of which comprises up to 40% crushed brick content. 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 common.

Currently in Victoria approximately 2.0 million tonnes of crushed concrete, 0.3 million tonnes of crushed glass 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. <u>The focus of this new research project is on the laboratory evaluation of crushed glass (5mm minus glass fines) when used as</u>

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 as a supplementary material in cement treated crushed concrete in pavement subbase applications (VicRoads Standard Specifications 821)
- 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 recycled crushed glass (5mm minus glass fines) when used as a supplementary material in cement treated crushed concrete pavement sub-base applications.

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. Crushed concrete and crushed brick are commonly obtained from construction and demolition (C&D) activities while recycled glass fines are produced from the glass component of household waste collections. Construction wastes are produced during different phases of construction. Demolition waste materials arise from demolition activities.

3 RECYCLED MATERIAL SOURCES

Samples of crushed concrete and crushed glass (5mm minus glass fines) for this project were collected from Alex Fraser Group sites at Clayton and Laverton in Victoria. At these sites, recycled materials such as crushed glass and crushed concrete are produced in various classes. Crushed glass (5mm minus glass fines) from Laverton site typically comprises particles up to 5 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 glass. The following geotechnical laboratory tests are described in this section to determine the engineering properties of recycled crushed glass when blended with crushed concrete Class 3 (CC3) and Class 4 (CC4), with the addition of 3% GB cement:

- 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

The investigated blends in this research were:

- 10% recycled crushed glass + 90% recycled crushed concrete class 3: 10RCG/90CC3
- 20% recycled crushed glass + 80% recycled crushed concrete class 3: 20RCG/80CC3
- 30% recycled crushed glass + 70% recycled crushed concrete class 3: 30RCG/70CC3
- 10% recycled crushed glass + 67.5% recycled crushed concrete class 3 + 22.5% recycled crushed concrete class 4: 10RCG/67.5CC3/22.5CC4
- 20% recycled crushed glass + 40% recycled crushed concrete class 3 + 40% recycled crushed concrete class 4: 20RCG/40CC3/40CC4

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 material 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 was undertaken for the coarse materials. (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). However it is described that this method is not applicable if less than 10% of the material passes the 75 µm sieve.

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 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.

4.8 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.

4.9 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 (5 pairs in total) was prepared at an external laboratory facility (ARRB Laboratory – Vermont South). 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 Value			
Test	Class CC2	Class CC3	Class CC4
Liquid Limit %(Max)	35	35	40
Plasticity Index (Max)	6	10	20
California Bearing Ratio % (Min)	100	80	20
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 (GB cement as used in this project) is currently specified to comply with the requirements of Class CC3 as presented in Table 2 (VicRoads, 2011a). The addition of crushed glass (or brick) 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 crushed 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 glass and glass 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 allows for a maximum of 2-3% breakdown on the finer sieve sizes for sub-base products which includes for some reworking, if required.

6 ENGINEERING PROPERTIES OF CEMENT TREATED CRUSHED CONCRETE BLENDED WITH CRUSHED GLASS

Laboratory tests were undertaken on prepared samples of cement treated crushed concrete blended with crushed glass obtained from the Alex Fraser site at Laverton. 3% GB cement was used in the cement treated crushed concrete blends. The engineering properties of the five (5) cement treated crushed concrete blends investigated were: 10% crushed glass blended with 90% crushed concrete class 3 (10RCG/90CC3), 20% crushed glass blended with 80% crushed concrete class 3 (20RCG/80CC3), 30% crushed glass blended with 70% crushed concrete class 3 (30RCG/70CC3), 10% crushed glass blended with 67.5% crushed concrete class 3 and 22.5% crushed concrete class 4 (10RCG/67.5CC3/22.5CC4) and 20% crushed glass blended with 40% crushed concrete class 3 and 40% crushed concrete class 4 (20RCG/40CC3/40CC4).

6.1 pH

The pH values of the 5 nominated blends are presented in Table 4. The range of pH value for crushed concrete is between 11.5-11.9 which indicates that all the blends are alkaline by nature. These values are consistent with previous works by

Type of Material	10RCG/ 90CC3	20RCG/ 80CC3	30RCG/ 70CC3	10RCG/ 67.5CC3/ 22.5CC4	20RCG/ 40CC3/ 40CC4
pH Value	11.9	11.9	11.6	11.5	11.8

Swinburne on C&D materials.

Table 4. pH value of crushed glass-crushed concrete blends

Composition of Samples	Crushed Concrete Class 3	Crushed Concrete Class 4
Crushed brick (%)	1	20
Other high density materials (%)	0	1
Low density materials (%)	0	0
Wood and vegetable matter (%)	0	0.1

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 crushed concrete class 3 and crushed concrete class 4 samples are presented in Table 5. Low density materials include plastic, rubber, plaster, clay lumps and other friable materials.

Table 5. Foreign material content of crushed concrete

With reference to Table 2, the crushed concrete class 3 sample is below the allowable percentage of foreign material content. Foreign Materials in Crushed Concrete was undertaken for the coarse materials. The presence of foreign materials in crushed concrete was visually identified and a photo snapshot of the materials is presented in Figure 1.

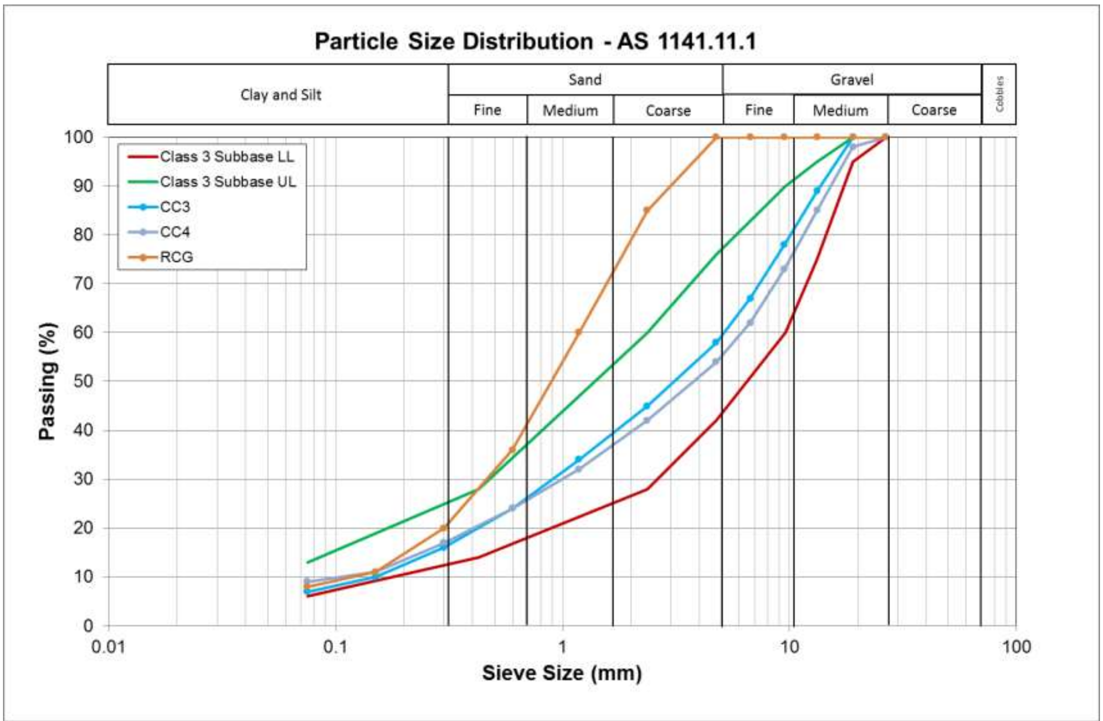
Crushed Concrete Class 3

Crushed Concrete Class 4

Figure 1. Foreign material contents in crushed concrete

6.4 Particle Size Distribution

The particle size distributions of crushed concrete class 3, crushed concrete class 4 and crushed glass are shown in Figure 2. The grading limits of both crushed



concrete samples were found to be within the VicRoads specified limit for class 3 sub-base. The actual grading of all five nominated blends are also presented in Figure 3. The samples used in this test were prepared by quartering which was the best practice in order to keep the gradation consistency of the prepared samples. Although extra care was taken to maintain the gradation consistent, loss of some fine size particles was observed which could be due to the dry blending process (Figure 3).

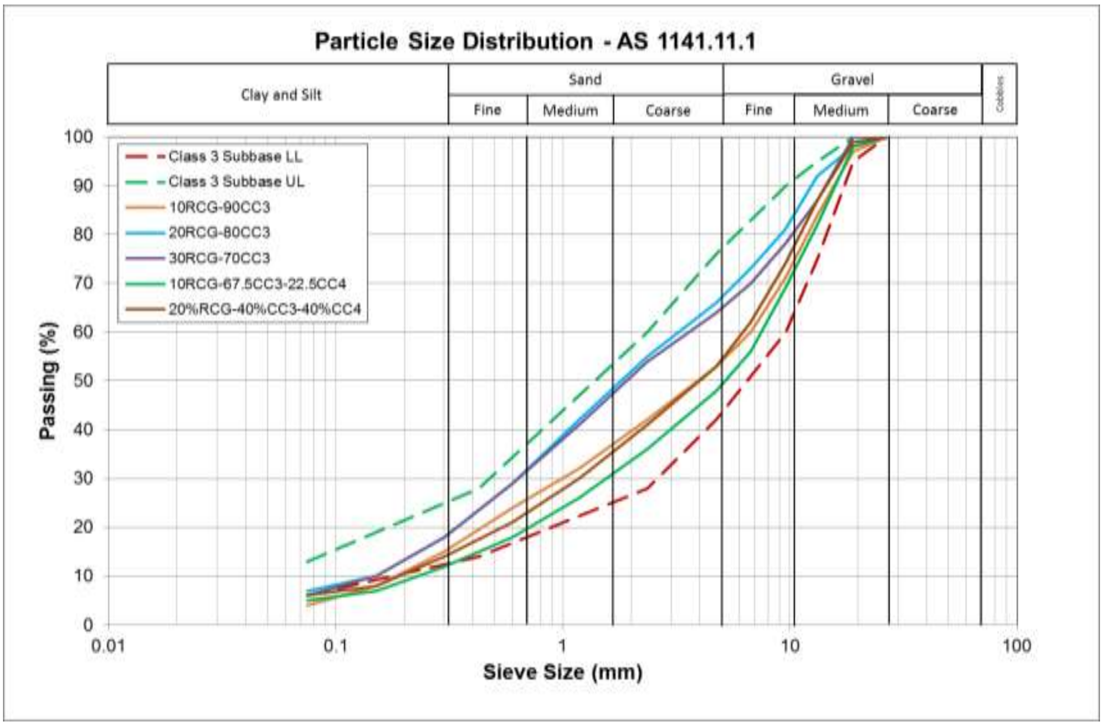


Figure 3. Particle size distribution of all five nominated blends

6.5 Linear Shrinkage Test

Due to the low clay content of crushed concrete and the blends, the linear shrinkage of all blends was negligible.

6.6 Modified Compaction Test

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

Table 6. Modified compaction results of cement treated (3% GB Cement)

Figure 4. Quartering process of nominated blends
crushed concrete- -crushed glass blends

Type of Material	10RCG/ 90CC3	20RCG/ 80CC3	30RCG/ 70CC3	10RCG/ 67.5CC3/ 22.5CC4	20RCG/ 40CC3/ 40CC4
OMC, %	10.5	10.4	10.3	10.2	10.1
MDD, t/m^3	2.008	2.000	2.005	2.037	2.018

OMC slightly decreased from 10.5% for 10RCG/90CC3 to 10.1% for 20RCG/40CC3/40CC4 while the MDD remained relatively the same (2.00 -2.01t/m3) for 10RCG/90CC3 to 2.005 t/m3 for 30RCG/70CC3. Introduction of CC4 increased MDD to 2.037 for 10RCG/67.5CC3/22.5CC4. However further addition of CC4 decreased MDD to 2.018 for 20RCG/40CC3/40CC4, which can be attributed to the higher crushed glass content. Overall the OMC and MDD values were found to be generally consistent, with only minor variations.

6.7 California Bearing Ratio (CBR)

The CBR value of cement treated crushed concrete blends was high and varied from 458 for 10RCG/90CC3 to 596 for 10RCG/67.5CC3/22.5CC4. Due to high strength of

CBR samples, the CBR test was carried out using a MTS-250kN equipment at Swinburne.

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 GB cement was added as a stabiliser to crushed concrete and its blends.

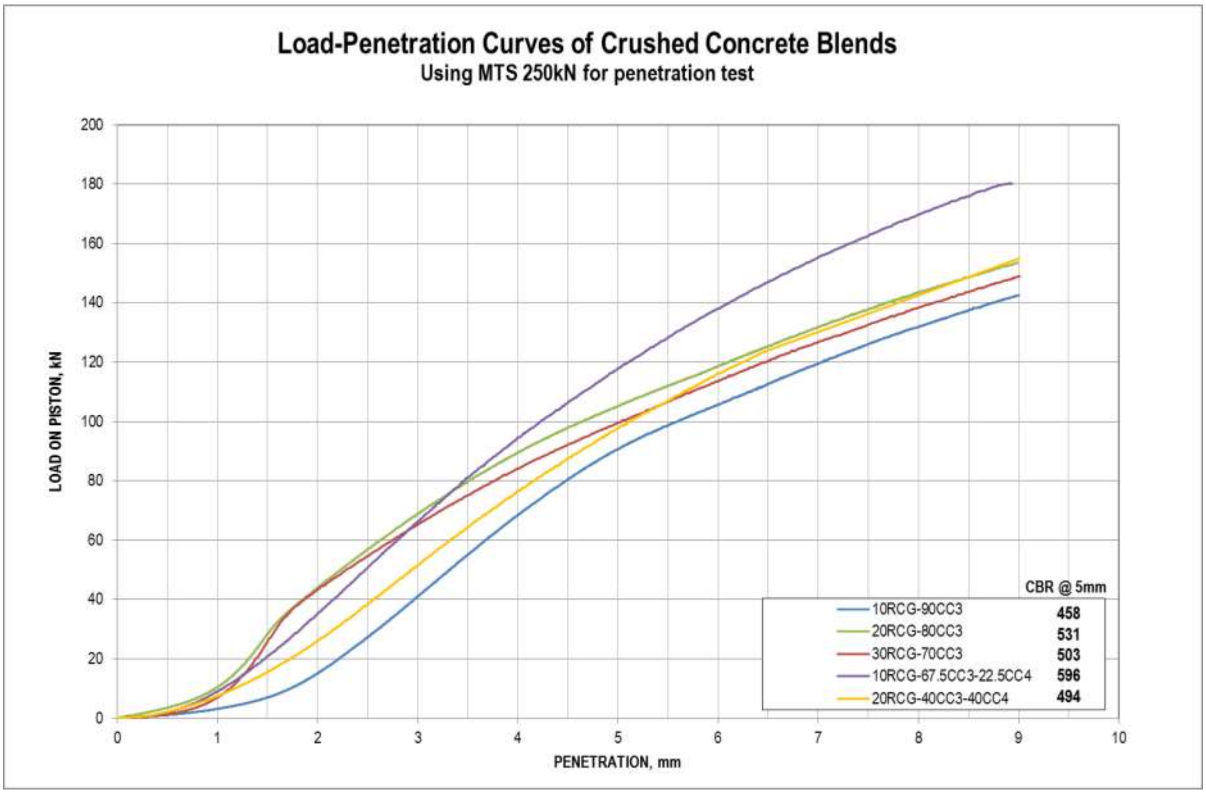


Figure 5. Load-Penetration curves of cement treated crushed concrete-crushed glass blends

6.8 Repeated Load Triaxial Test

Five 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 condition 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.

Specimen	Target MC, (% OMC)	Actual MC– after RLT test (% OMC)	Target degree of compaction, %	Actual degree of compaction, %
10RCG/ 90CC3	70	66.7	100	100.6
20RCG/80CC3	70	56.7	100	100
30RCG/70CC3	70	60.2	100	99.8
10RCG/67.5CC3/22.5CC4	70	68.3	100	98.4
20RCG/ 40CC3/ 40CC4	70	66.3	100	99.7

Table 7. RLT specimens moisture contents and degree of compaction

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 glass blends are presented in Figure 6 to Figure 14.

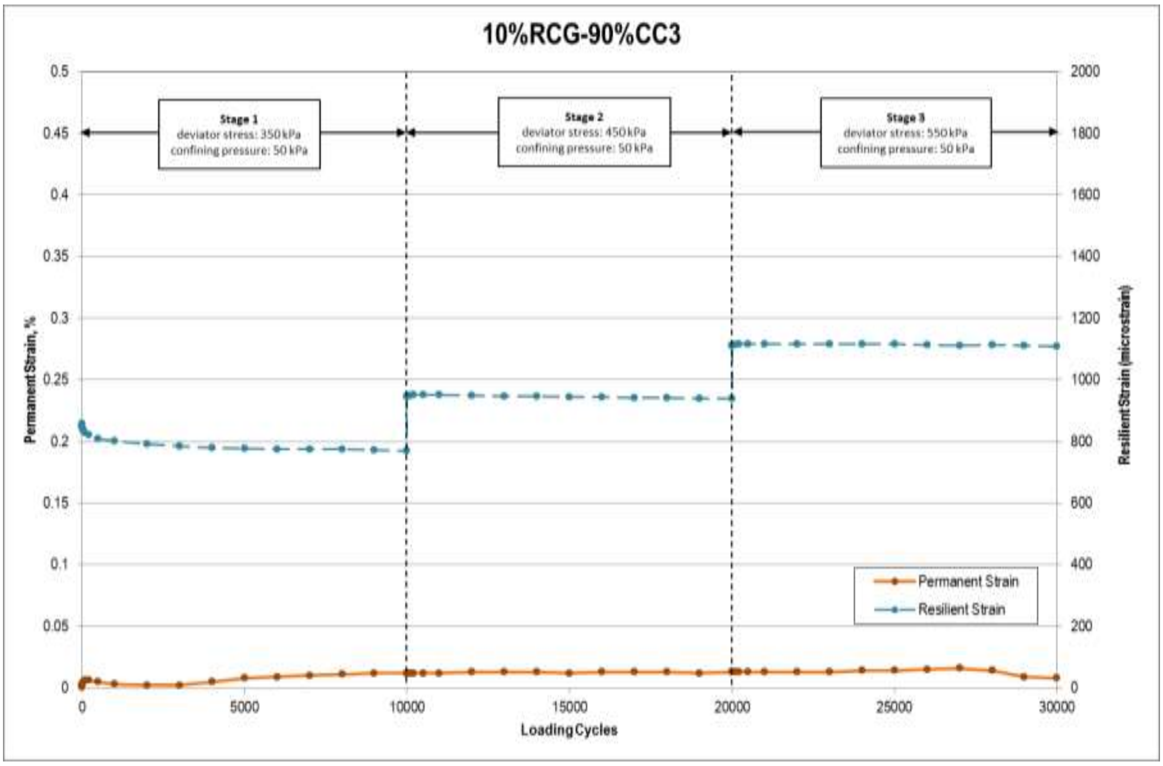


Figure 6. Permanent deformation of cement treated crushed concrete-crushed glass (10RCG-90CC3)

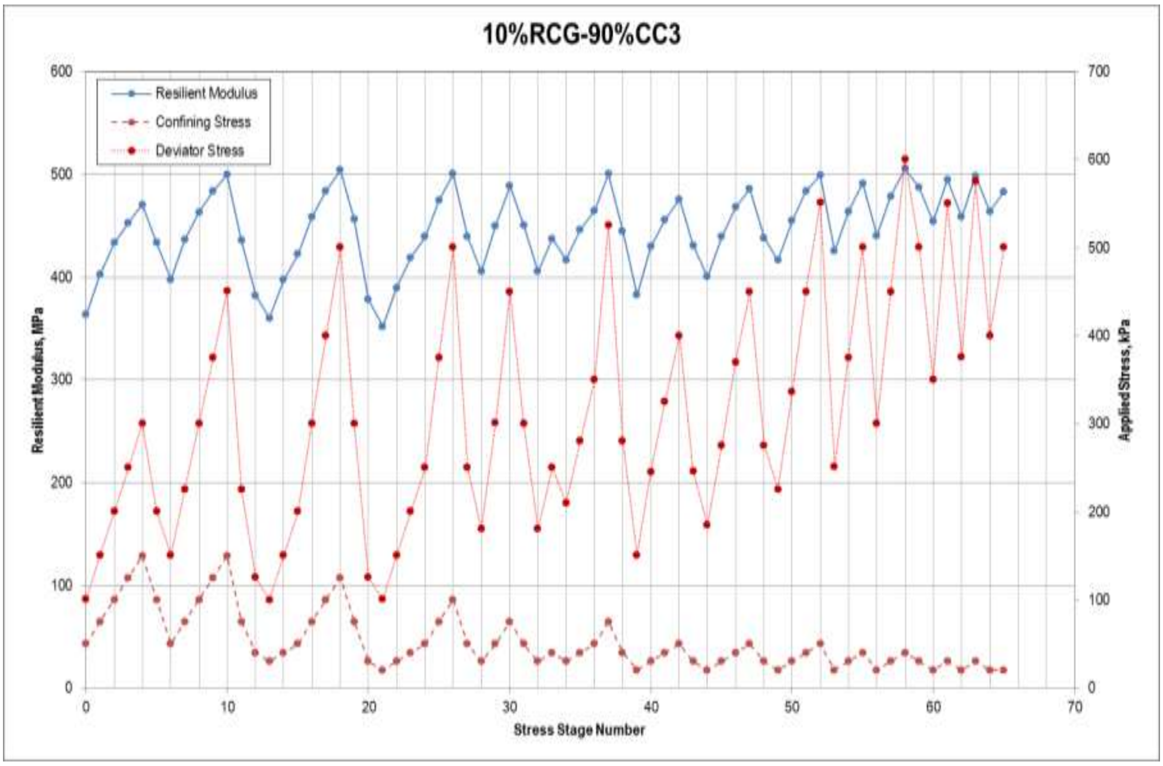


Figure 7. Resilient modulus of cement treated crushed concrete -crushed glass (10RCG-90CC3)

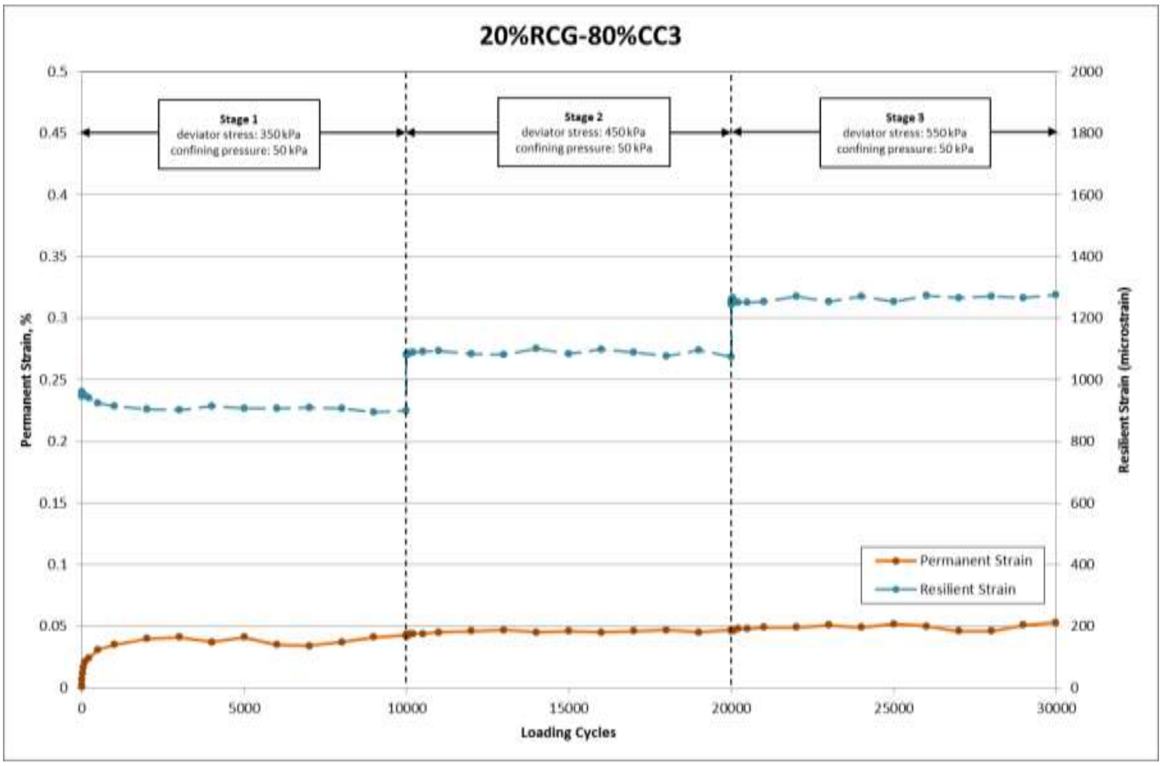


Figure 8. Permanent deformation of cement treated crushed concrete-crushed glass (20RCG-80CC3)

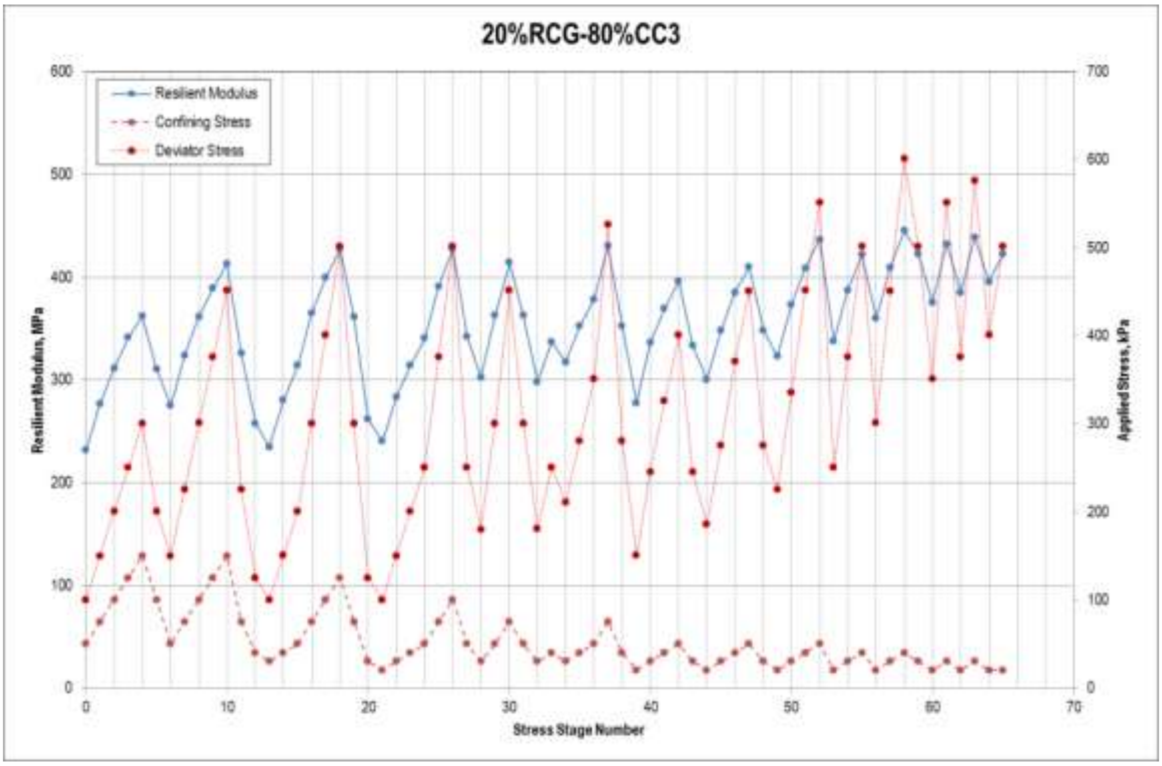


Figure 9. Resilient modulus of cement treated crushed concrete -crushed glass (20RCG-80CC3)

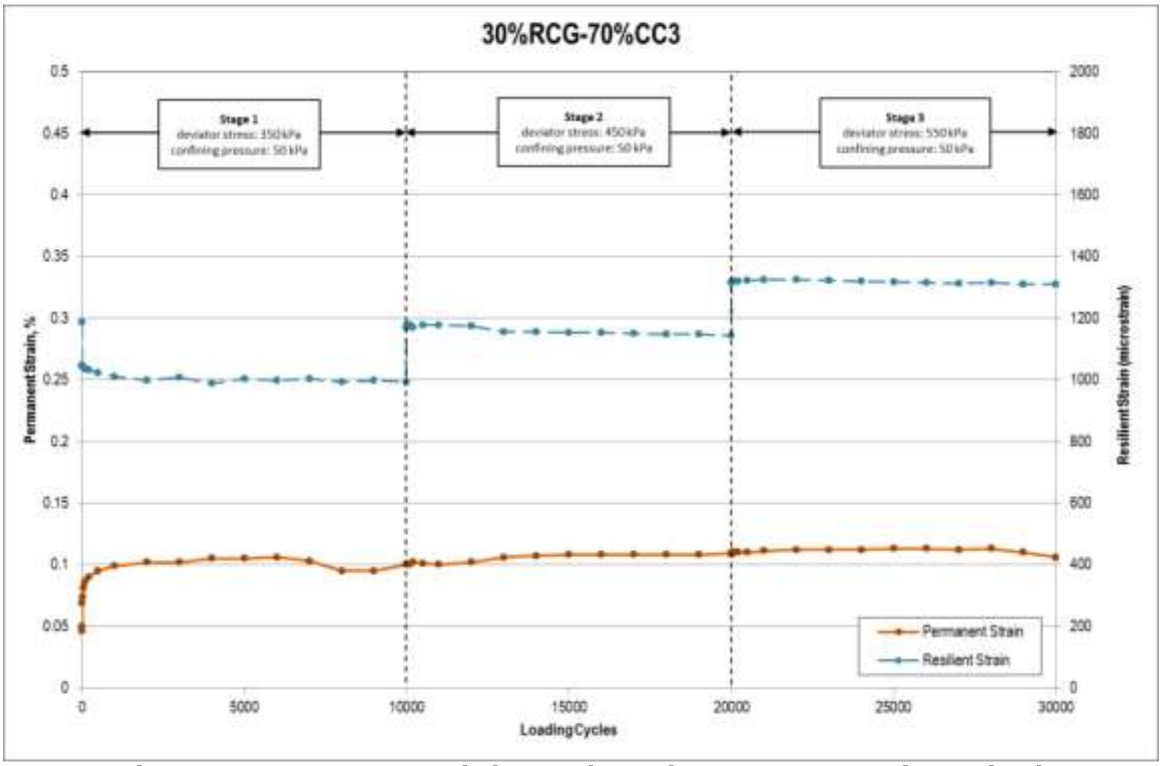


Figure 10. Permanent deformation of cement treated crushed concrete-crushed glass (30RCG-70CC3)

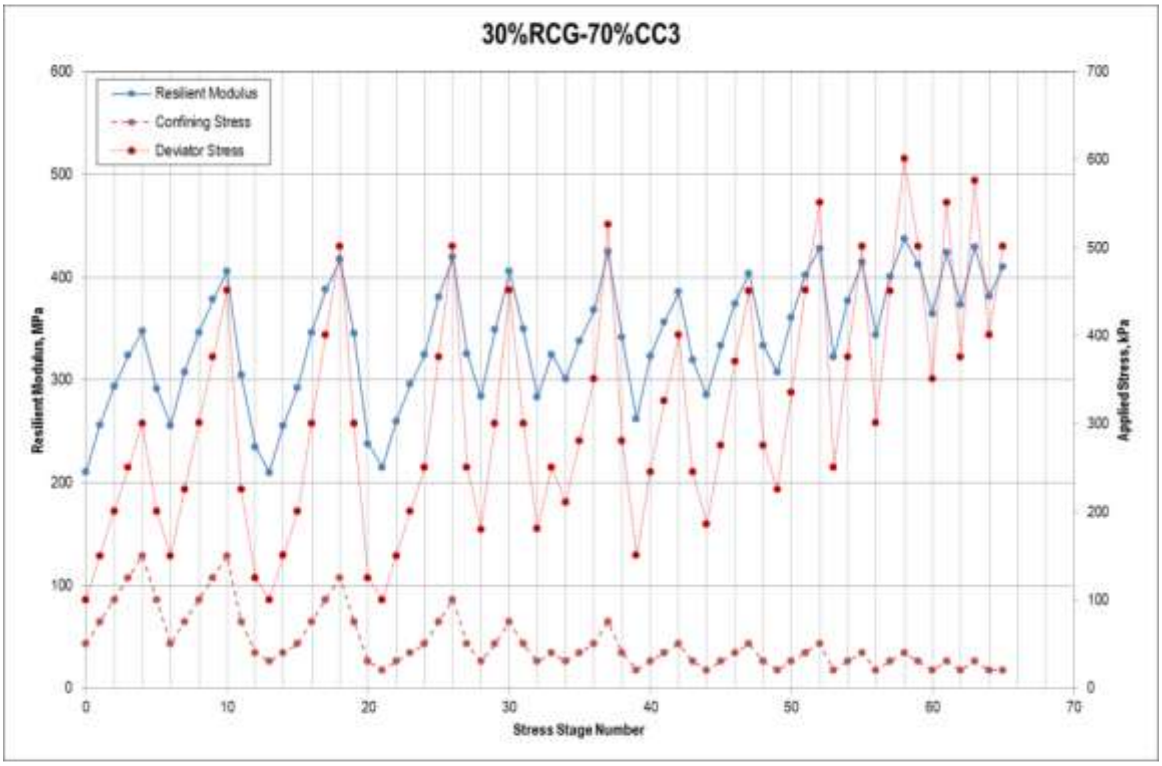


Figure 11. Resilient modulus of cement treated crushed concrete - crushed glass (30RCG-70CC3)

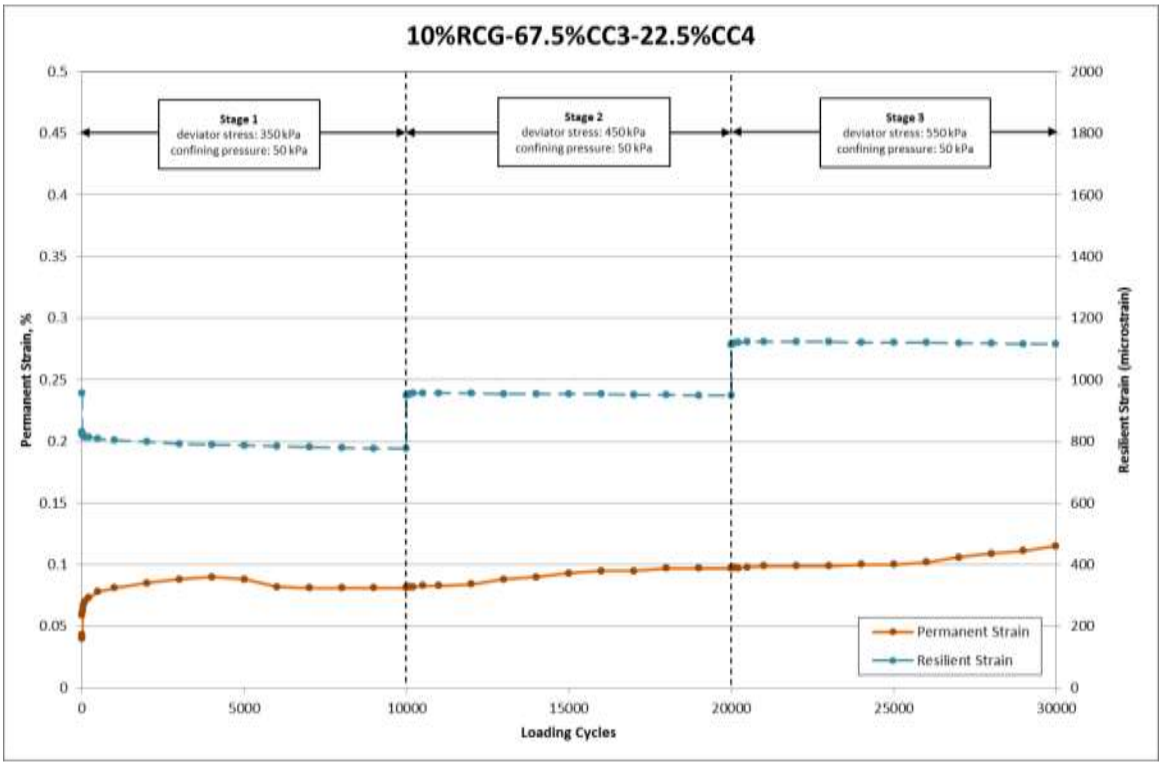


Figure 12. Permanent deformation of cement treated crushed concrete-crushed glass (10RCG-67.5CC3-22.5CC4)

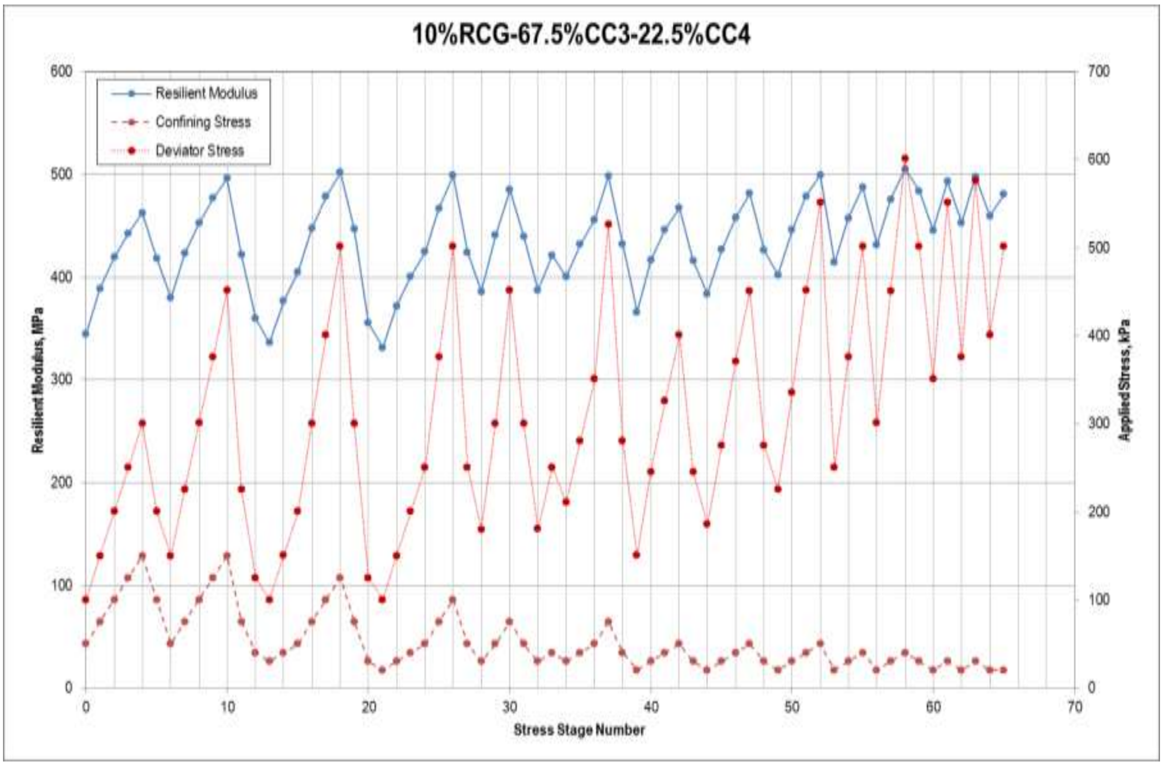


Figure 13. Resilient modulus of cement treated crushed concrete - crushed glass (10RCG-67.5CC3-22.54)

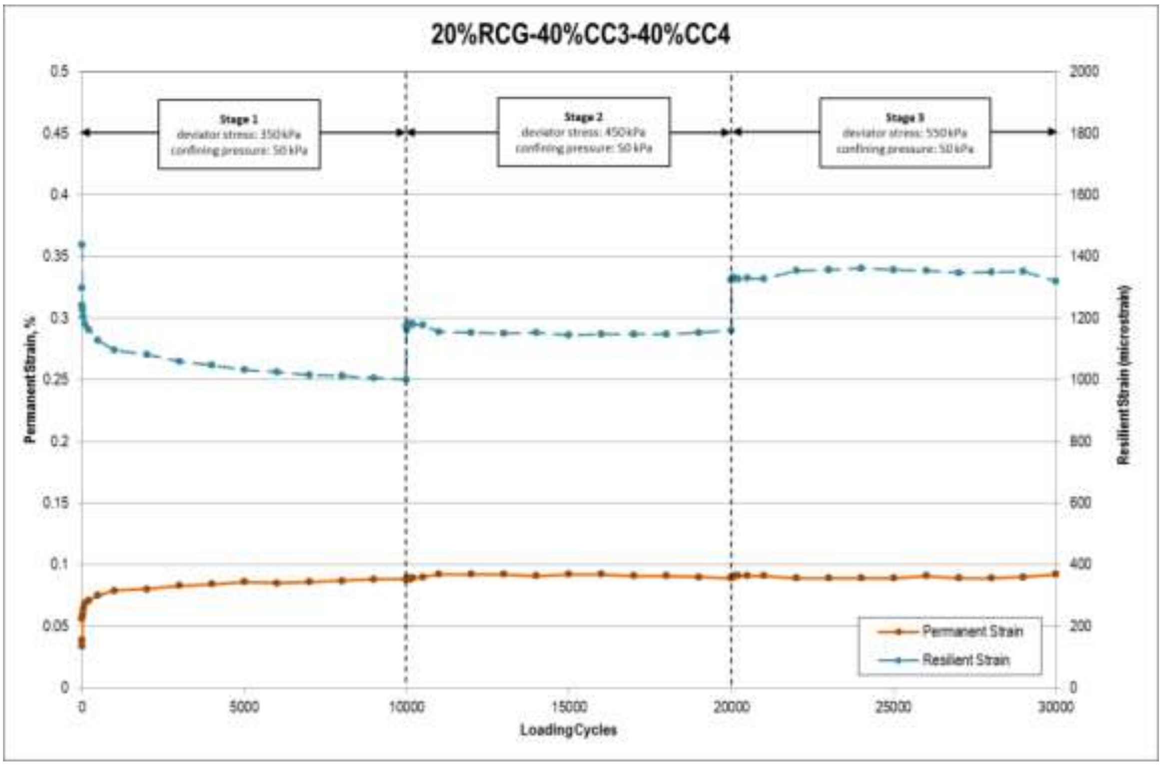


Figure 15. Permanent deformation of cement treated crushed concrete-crushed glass (20RCG-40CC3-40CC4)

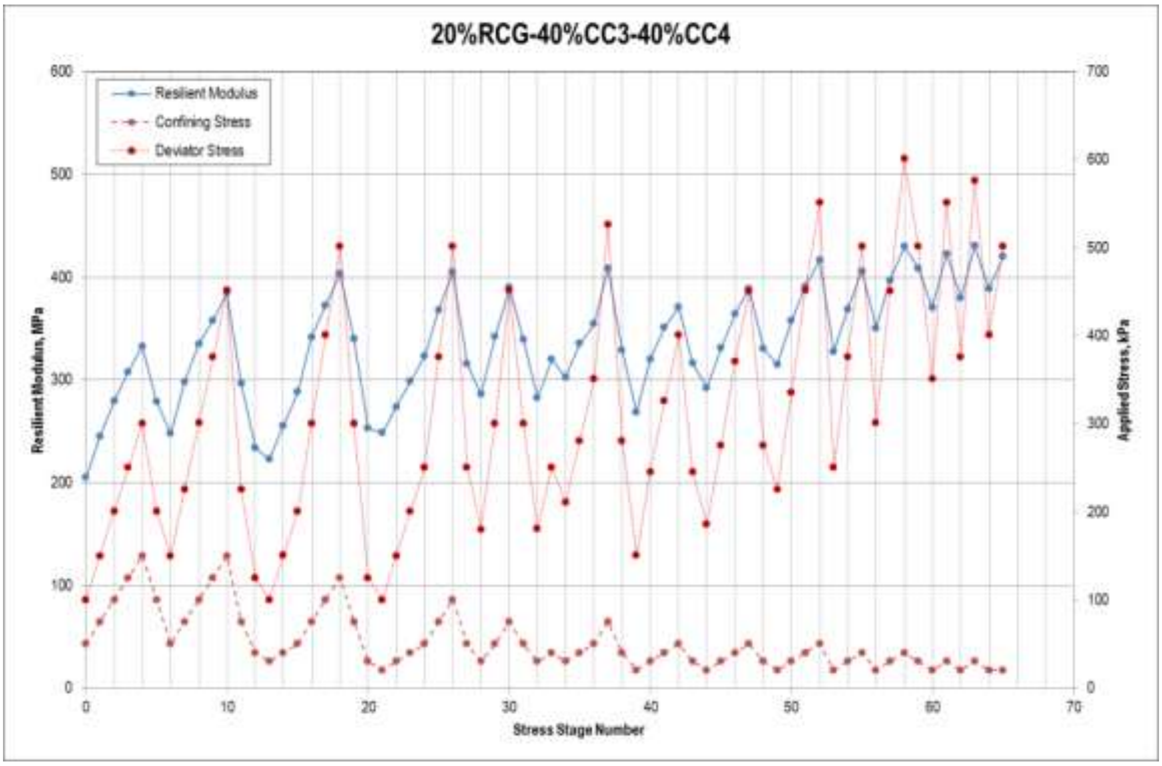


Figure 14. Resilient modulus of cement treated crushed concrete -crushed glass (20RCG-40CC3-40CC4)

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 glass blends

Specimen (with 3%GB)	Actual dry density (% MDD)	Actual moisture content (% OMC)	Permanent Strain at the end of each stage, microstrain		
			Stage 1	Stage 2	Stage 3
10RCG/90CC3	100.6	66.7	120	130	80
20RCG/80CC3	100	56.7	430	470	530
30RCG/70CC3	99.8	60.2	1000	1009	1006
10RCG/67.5CC3/22.5CC4	98.4	68.3	810	970	1150
20RCG/40CC3/40CC4	99.7	66.3	880	890	920

In general, there was an increasing trend for permanent deformation with the increase of crushed glass, which is expected due to the fact that crushed glass is an unbound non cohesive material like sand. However it was difficult to compare the effect of added crushed glass 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 glass- blends are presented in Table 9.

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

Specimen (with 3%GB)	Actual dry density (% MDD)	Actual moisture content (% OMC)	Resilient Modulus Range MPa
10RCG/90CC3	100.6	66.7	352.04-505.70
20RCG/80CC3	100	56.7	231.36-445.05
30RCG/70CC3	99.8	60.2	209.71-437.24
10RCG/67.5CC3/22.5CC4	98.4	68.3	331.21-505.27
20RCG/40CC3/40CC4	99.7	66.3	204.94-430.56

In general increasing the percentage of crushed glass indicates a reduction of resilient modulus value of cement treated crushed concrete blends in the first three blends. This is expected since crushed glass is being added as a supplementary material to crushed concrete and furthermore is a slightly less durable material compared to crushed concrete. Introduction of CC4 at 22.5% into the blend reduced the resilient modulus compared to 10RCG/90CC3. Further increase in CC4 led to more reduction in resilient modulus which is in agreement with a similar study conducted at Swinburne (Disfani et al., 2014). 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 glass on resilient modulus of cement treated crushed concrete blends.

Typically a quarry produced Class 3 crushed rock 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 above the lower spectrum expected of bound quarry sub-base materials, with 30RCG/70CC3 and 20RCG/40CC3/40CC4 on the lower borderline. It is to be noted, the RLT testing is not specified in VicRoads Section 821 as a requirement for cement treated crushed concrete in pavement applications, but was undertaken nevertheless in this project in order to better understand the behaviour of the crushed concrete blends under simulated traffic loading and to compare the performance of blends under repeated 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 four specimens) as seen in Figure 16 were kept in the fog chamber 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. All samples were subjected to 4 hours of immersing in water prior to the UCS test.

Figure 16. UCS specimens being cured in fog chamber for 7 days

The UCS results for all the cement treated specimens are summarised in Figure 17 and Table 11. For 7 day curing period the mean UCS value obtained was between 4.5 to 5.6 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 3.5 MPa specified in VicRoads Section 821 (VicRoads, 2011a) for medium setting (GB) cement. In fact all blends achieved 7 day mean UCS values well in excess of the standard requirement of 4MPa for rapid setting cement.

The 28 day curing period was found to lead to an increase in the mean UCS value for all the blends to between 6.9 and 8.4 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

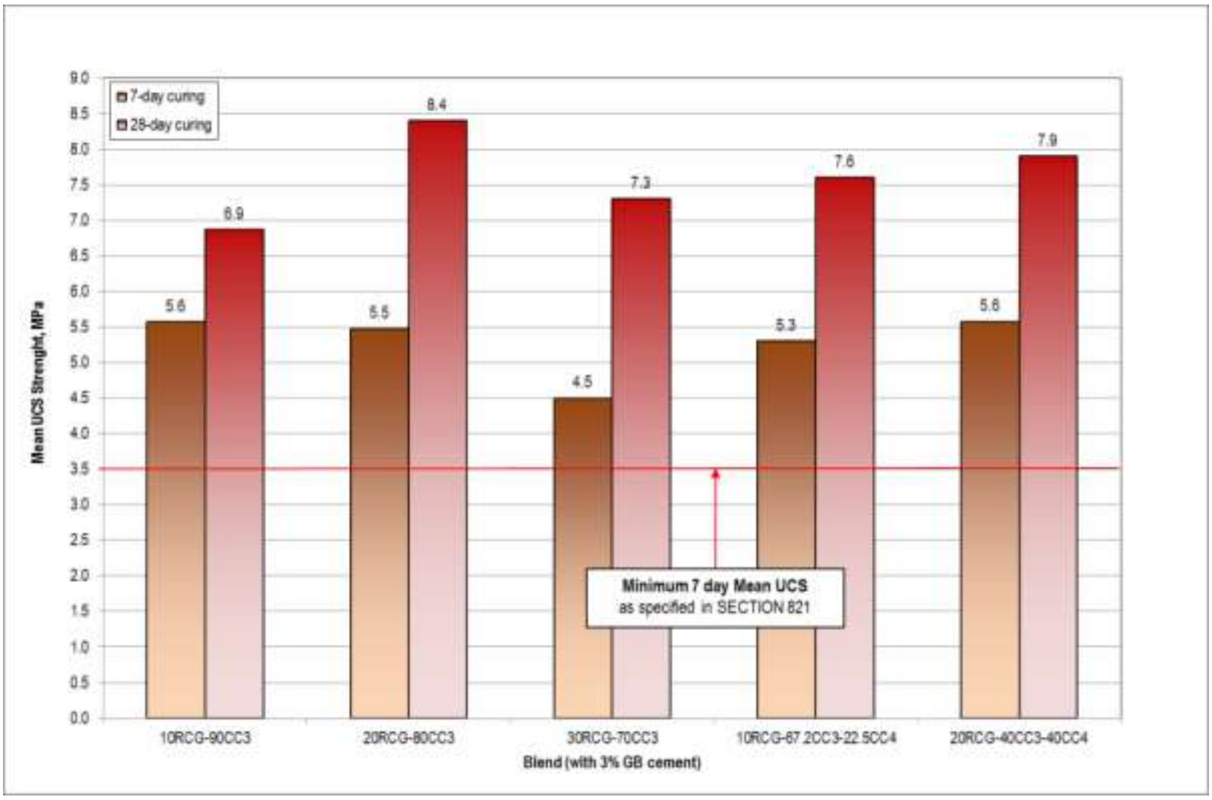


Figure 17. UCS results of 7-day and 28-day GB cement treated crushed concrete blended with crushed glass

increased curing period.

Blend (with 3% GB cement)	**Curing**	**Sample**	**Strength, MPa**	**Moisture Content**	**Dry Density**

Table 11. UCS results of cement treated crushed glass blended with crushed concrete

			individual	average	%OMC	%MDD
10RCG-90CC3	7 days	10-90-1	6.1	5.6	95	99
		10-90-2	5.9		95	99
		10-90-3	4.7		94	97
20RCG-80CC3		20-80-1	5.4	5.5	101	97
		20-80-2	5.8		93	99
		20-80-3	4.7		95	97
		20-80-4	6		93	101
30RCG-70CC3		30-70-1	4.6	4.5	97	98
		30-70-2	4.6		99	99
		30-70-3	4.3		100	98
		30-70-4	4.5		97	99
10RCG-67.2CC3-22.5CC4		10-67.2-22.5-1	4.5	5.3	102	97
		10-67.2-22.5-2	5.1		96	98
		10-67.2-22.5-3	6.1		106	97
		10-67.2-22.5-4	5.5		106	97
20RCG-40CC3-40CC4		20-40-40-1	5.6	5.6	98	98
		20-40-40-2	5.3		98	98
		20-40-40-3	5.8		98	99
		20-40-40-4	5.6		97	99
10RCG-90CC3	28 days	10-90-28-1	7.2	6.9	90	100
		10-90-28-2	6.5		92	98
		10-90-28-3	6.9		96	97
		10-90-28-4	5.4		90	96
20RCG-80CC3		20-80-28-1	8.2	8.4	88	98
		20-80-28-2	8.5		88	99
		20-80-28-3	8.7		89	100
		20-80-28-4	8.2		88	99
30RCG-70CC3		30-70-28-1	6.1	7.3	91	100
		30-70-28-2	7.7		86	98
		30-70-28-3	6.9		90	99
		30-70-28-4	7.3		86	98
10RCG-67.2CC3-22.5CC4		10-67.2-22.5-28-1	7.2	7.6	92	96
		10-67.2-22.5-28-2	5.2		102	97
		10-67.2-22.5-28-3	7.8		97	99
		10-67.2-22.5-28-4	7.8		92	98
20RCG-40CC3-40CC4		20-40-40-28-1	6	7.9	91	98
		20-40-40-28-2	7.7		91	98
		20-40-40-28-3	7.8		89	101
		20-40-40-28-4	8.2		95	100

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.

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. Upon completion of curing, the beams were transferred to Swinburne and kept in fog chamber to be tested (Figure 18).

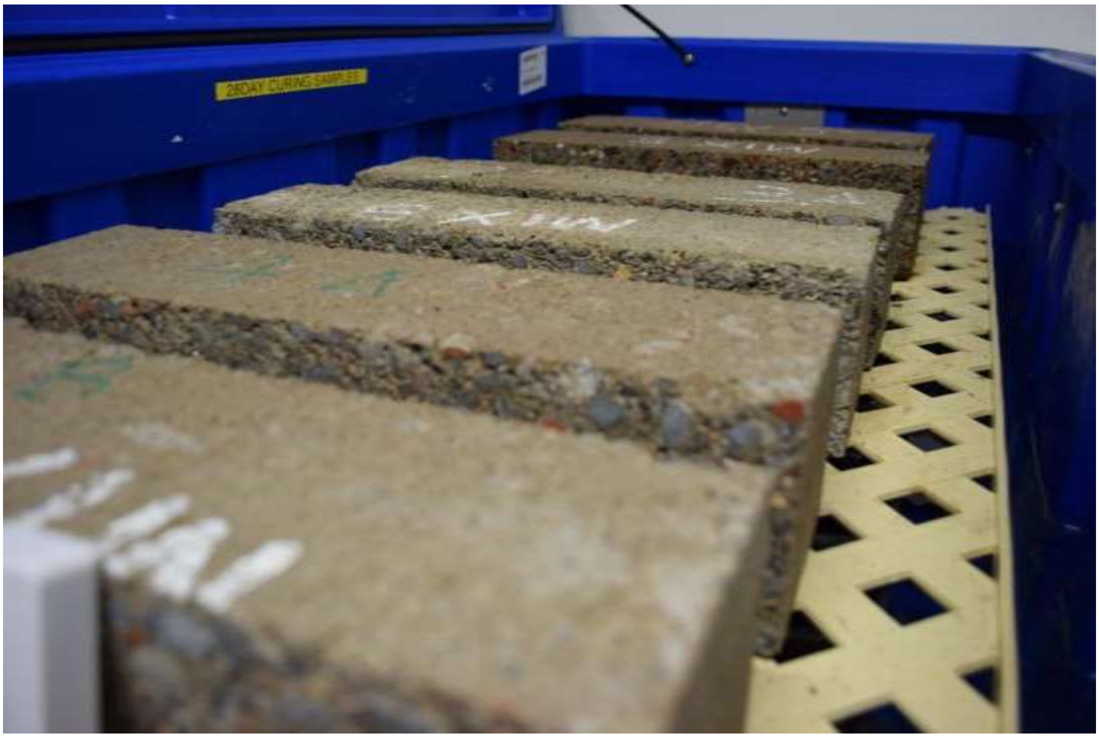


Figure 18. Cut beams in fog chamber

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 of 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 series of pictures showing the process of this test are presented in Figure 19.

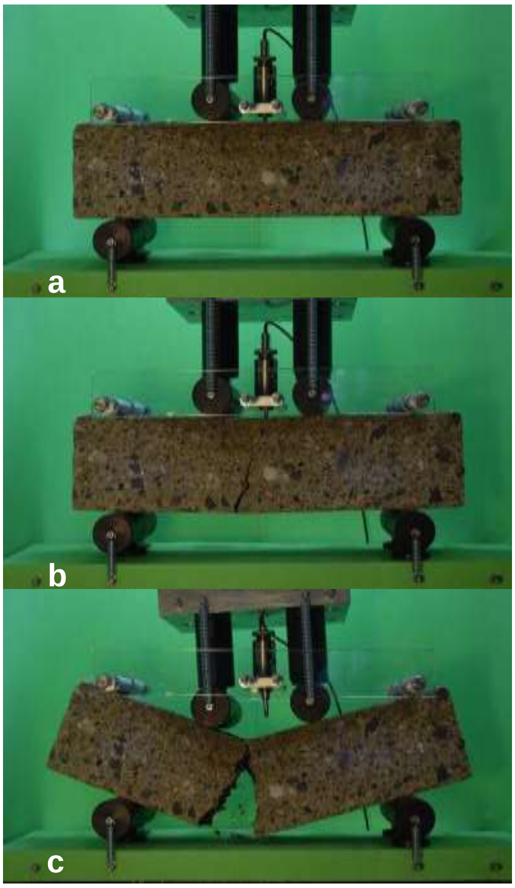


Figure 19. Four point beam fatigue test

The results of the modulus of rupture tests are presented in Table 12. The modulus of rupture (tensile stress) ranged from 1.85 MPa for 10RCG/90CC3 cement treated crushed concrete to 1.44 MPa for 20RCG/40CC3/40CC4 cement treated crushed concrete. The peak load varied between 6.12 kN for 10RCG/90CC3 cement treated crushed concrete to 1.44 kN for 20RCG/40CC3/40CC4 cement treated crushed concrete. The declining trend of modulus of rupture has been clearly observed as the percentage of RCG and CC4 into CC3 cement treated blends increased.

Table 12. Modulus of rupture results

	Sample Type (blended with 3% GB cement)				
	10RCG/ 90CC3	20RCG/ 80CC3	30RCG/ 70CC3	10RCG/ 67.5CC3/22.5CC4	20RCG/ 40CC3/ 40CC4
width, *mm*	100.46	100.21	100.75	100.78	100.1
height, *mm*	99.36	100.12	99.44	100.27	99.9
moisture content, *%OMC*	99.0	98.1	90.3	99.0	96.0
dry density, *% MDD*	97.5	97.5	98	97.6	98.4
peak load, *kN*	6.12	5.57	5.20	5.67	4.8
modulus of rupture, *MPa*	1.85	1.66	1.56	1.67	1.44
tensile strain at 95% of peak load, *microstrain*	-	190.71	136.08	196.98	192.48

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 not to 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. The mean flexural modulus of10RCG/90CC3 is almost double comparing to the other samples due to a very low central deformation of the sample under the flexural modulus test.

Table 13. Four point flexural beam fatigue test results

	Sample type (blended with 3% GB cement)				
	10RCG/ 90CC3	20RCG/ 80CC3	30RCG/ 70CC3	10RCG/ 67.5CC3/ 22.5CC4	20RCG/ 40CC3/ 40CC4
width, *mm*	100	99.9	101.1	101.03	99.9
height, *mm*	99.5	100.2	100.6	100.71	100.1
moisture content, *%OMC*	100.9	97.1	92.2	101	96
dry density, *% MDD*	98.4	98.3	98.3	96.5	98.4
flexural modulus test					
applied load, *% peak load*	40	40	40	40	40
mean flexural modulus (cycles 51-100), *MPa*	27308.48	13941.67	14158.30	13688.45	13674.25
tensile stress for modulus test, *kPa*	740.62	947.15	1323.19	729.46	569.73
flexural fatigue test					
applied load, *% peak load*	70	70	70	70	70
tensile stress for fatigue test (mean of first 50), *kPa*	1252.53	1644.35	1323.46	1285.22	991.63
Tensile strain (mean of first 50), *microstrain*	55.44	123.01	90.86	94.98	80.39
initial modulus (first 50), *MPa*	22600.22	13375.62	14577.31	13536.55	12350.03
stress ratio	0.68	0.99	0.84	0.77	0.69
strain ratio	0.34	0.64	0.67	0.48	0.52
cycles to half initial modulus	10200	401	2552	2849	did not fail

Sample 20RCG/70CC3 failed very quickly (after 401 cycles) under the flexural fatigue test due to the fact that the applied load was very close to the peak force determined in flexural strength test. On the contrary, sample 20RCG/40CC3/40CC4 did not reach to its half initial modulus and did not fail because of a very low applied force comparing to the peak force of flexural strength test. Although extra care is taken in preparing two identical beams for each set of tests, the results are highly dependent on samples' physical properties. While the results produced are considered fully representative, further testing of each blend will provide confirmation of the fatigue life and other characteristics.

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 4102.28 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 hornfels 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, however further testing should be undertaken to confirm the range of fatigue life values likely to be experienced.

7 CONCLUSIONS

Samples of crushed concrete (CC3 and CC4), crushed glass for this project were collected from Alex Fraser Group sites at Clayton and Laverton in Victoria to evaluate the influence of crushed glass as a supplementary material in cement treated crushed concrete pavement applications. 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 glass. The findings of the advanced tests including RLT, UCS and beam fatigue tests were:

- It was found that all the crushed glass/crushed concrete blends had physical properties which comply with the current version of 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, 10RCG/90CC3 demonstrated the highest resilient modulus range and 20RCG/40CC3/40CC4 demonstrated the lowest resilient modulus range. 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 30RCG/70CC3 and 20RCG/40CC3/40CC4 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 nevertheless undertaken to understand the performance of the cement treated aggregates under simulated traffic loading.

- Mean UCS values comfortably met the minimum requirement of 3.5 MPa for minimum of 7 days curing for all blends. An increase of 23% in strength was observed for 28 days samples of 10RCG/90CC3 while the 28 day strength of 30RCG/70CC3 considerably increased by 62% compared to the 7 days samples. The average 28 day strength of other samples fell within the range of 23%-62%. 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 of UCS samples were kept at 3.5 in order to be consistent with the common practice of industry.

- The modulus of rupture varied from 1.44 MPa to 1.85 MPa while the flexural modulus ranged from 13674.25MPa to 27308.48MPa. Assuming a shift factor of 0.3, the design modulus was estimated based on the flexural modulus which ranged from 4102.28 MPa to 8192.54 MPa. The range of flexural fatigue life varied between 401 to 1,000,000 cycles. The wide range of fatigue life is due to the fact that flexural fatigue test is highly sensitive to the applied load. Another influencing factor is the fact that it is assumed both beams of each slab are identical in terms of compaction, moisture content and gradation. 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 glass can be initially recommended for incorporation as a supplementary material in cement treated crushed concrete pavement sub-base applications. Depending on the results of future field trials, it may be possible to increase the percentage of crushed glass added in the future. It would also appear possible to add up to 10% crushed brick to these blends as well as 15% Recycled Glass Fines and still achieve an outcome which would be comfortably within VicRoads current specifications for cement treated crushed concrete.

- The current research has also shown that the control of moisture is a critical parameter in achieving consistent properties within the cement treated layer. Where the water/cement ratio is kept around 3.5 a consistent outcome will be achieved, otherwise, if this control is not in place the physical properties of the cement treated layer can be potentially substantially compromised.

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