NACOE
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FINAL REPORT

O24: Using Recycled Materials in Stabilised Pavements

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Summary

Due to various economic and environmental benefits, the Queensland Department of Transport and Main Roads (TMR) has increased their focus on reducing the reliance on non-renewable resources by using recycled materials in pavements. This project aims to investigate the feasibility and to optimise the use of different recycled material blends as host materials for foamed bitumen stabilisation and cement stabilisation.

The scope of Year 1 (2021–22) of this project was to evaluate the performance and mechanical properties of 3 recycled material blends treated by foamed bitumen stabilisation and cement stabilisation using a range of laboratory tests.

The scope of Year 2 (2022–23) of this project was to extend the investigation of Year 1 into an additional 5 recycled material blends to improve the quantity of information on the laboratory performance of stabilised recycled materials to enhance the confidence prior to the field-testing phase in Year 3.

Over Year 1 and Year 2, a total of 8 recycled material blends were selected for the laboratory testing assessments. The indirect tensile modulus test was undertaken on the foamed bitumen stabilised recycled blends, and the unconfined compressive strength test was carried out on the cement stabilised recycled materials. Additionally, the selected foamed bitumen stabilised recycled blends in Year 2 were also tested for indirect tensile strength and unconfined compressive strength.

Results were assessed against DTMR specifications for both unbound (MRTS05) and stabilised pavement materials (MRTS9 and MRTS10).

The results indicated the feasibility of cement stabilisation and foamed bitumen stabilisation in improving the engineering properties of recycled material blends.

Generally, the stabilised recycled material blends satisfied the current TMR specification mix design testing requirements for lightly bound and foamed bitumen stabilised materials, with limited exceptions. Note that TMR specifications require a mix design test process for any stabilised material; to identify a suitable stabilisation additive(s) type and amounts.

The outcome of this project will assist in creating better opportunities for the use of recycled material blends in pavement engineering applications, which will potentially result in significant environmental and cost benefits.

Acknowledgements

The project team would like to acknowledge TMR Bulwer Island Laboratory and Rockhampton Laboratory for undertaking the laboratory testing for this project. Also, the team wish to thank Mr. Damian Volker (Principal Engineer-Pavement Rehabilitation, TMR) for his support throughout the project. The team would also like to acknowledge the contribution of Rino Recycling in Pinkenba and Alex Fraser and its Nudgee Recycling Facility, who supplied the recycled material blends for Years 1 and 2 of this project. Additionally, we would like to acknowledge the team of NACOE P94 project 'Optimising the Use of Recycled Materials in Unbound and Stabilised Pavements in Queensland'.

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1. Introduction

1.1 Background

There is an emphasis on reducing the dependence on non-renewable resources worldwide, driven by various economic and environmental benefits. The use of recycled materials in road pavement applications as a replacement for natural aggregate has been investigated over the past few decades by several researchers.

In parallel, stabilisation techniques, such as foamed bitumen stabilisation (FBS) and cement stabilisation, have been utilised in the construction of new pavements or structural rehabilitation treatments internationally and across Australia.

However, the performance and mechanical properties of different recycled material blends stabilised using foamed bitumen and cement have not been well studied. This project aims to investigate the feasibility of using different recycled material blends as host materials for foamed bitumen stabilisation and cement stabilisation. This will help to create better opportunities for the use of recycled material blends in pavement engineering applications which could result in significant environmental and cost benefits for various road agencies in Australia.

1.2 Objective

The main objective of this project (Year 1 (2021–22) and Year 2 (2022–23)) is to evaluate and understand the performance of recycled host material blends treated by foamed bitumen stabilisation and cementitious stabilisation using a laboratory testing program. In particular, the project aims to assess if the stabilised recycled material blends can meet the current TMR specification requirements including:

- TMR MRTS09
- TMR MRTS10

The future year of this project (Year 3 (2023-24) will focus on field trial construction and monitoring.

This research will provide insight for possible future works on assessing the performance and suitability of various types of recycled material blends stabilised with various binders or additives in pavement applications.

1.3 Methodology

Laboratory testing was performed on several recycled host material blends. Recycled crushed concrete (RCC) material was considered as the reference mix and was partially replaced with reclaimed asphalt pavement (RAP), recycled crushed brick (CB) and recycled crushed glass (RCG) at varying proportions. A total of 8 selected materials for the laboratory investigation were evaluated (across Year 1 and Year 2) comprising the following blends:

- 100% RCC
- 70% RCC, 10% RAP, 10% CB and 10% RCG blend
- 40% RCC, 20% RAP, 20% CB and 20% RCG blend.

The mechanical properties of the stabilised candidate blends (FBS and cementitiously stabilised) were then investigated using the selected laboratory testing protocols. The planned laboratory testing included indirect tensile modulus tests, indirect tensile cracking/strength tests and unconfined compressive strength tests on the foamed bitumen stabilised materials and unconfined compressive strength tests on the cement stabilised materials.

2. Background Information

2.1 Previous NACOE and Austroads Projects

This section provides an overview of existing or previous research undertaken in Queensland and nationally regarding recycled aggregates in unbound, lightly bound and stabilised pavements. Where research is still underway, a summary of project objectives and scopes have been provided.

2.1.1 NACOE P94 – Optimising the Use of Recycled Materials in Queensland for Unbound and Stabilised Products

This project focused on increasing the use of recycled materials in unbound pavements, with the first year of the project delivering a literature review of existing practices in Australia. The findings are summarised as follows (Latter et al. 2020):

- The use of recycled materials is widely accepted in unbound and stabilised pavement materials throughout Australia, with suitable performance for base and subbase applications.
- State road agencies have a strong alignment between specifications for traditional quarried materials and recycled materials.
- Recycled materials such as RCC, CB, RAP, and RCG have been widely used in Australia and may have scope for allowing increased percentages in Queensland pavements.
- Regarding environmental considerations, there is general alignment across Australia in the testing and threshold values allowed.

In the second year of the project, laboratory testing with various recycled material mixes for unbound pavement application was conducted and compared with natural quarried materials. The findings of this report are summarised below (Latter 2020):

- MRTS05 *Unbound Pavements* specification has been updated (July 2020 edition) to provide a single specification for the supply of natural, quarried and recycled materials based on the findings of this project.
- Queensland suppliers producing RM001 and RM003 recycled materials consistently met the characterisation and performance requirements of (now superseded) MRTS35 *Recycled Materials in Pavements.* These materials show improved performance compared to natural quarried materials and, therefore, offer a suitable alternative.
- One recycled material mix incorporating up to 20% glass showed improved mix characterisation properties and performance compared to the same material with 0% glass.

2.1.2 NACOE P122 – Improved Characterisation of Lightly Bound Materials

In Year 1 of this project, several aspects of lightly bound materials were evaluated to improve their characterisation. The aims of Year 1 were as follows (Tarr 2023):

- Assess the repeatability and compliance issues raised regarding the unconfined compressive strength (UCS) test method.
- Investigate the use of modified compaction during UCS preparation for the mix design process as per MRTS10 *Plant-Mixed Lightly Bound Pavements*.
- Investigate historical working time data.
- Investigate the use of modified compaction during UCS preparation for determining working times as per Q136.
- Determine the suitability of using the Compactus vibrating hammer as an alternative compaction apparatus for the UCS.

Data obtained from industry on production UCS were analysed and it was found that the results complied with the specifications of MRTS10 *Plant-Mixed Lightly Bound Pavements*.

An analysis of historical working time data found that some suppliers are adding retarders to their mixes, thereby gaining longer working times; more investigation into the use of additives is required. The analysis also found that different rock types appear to produce similar working times when controlling for stabilising agent type, suggesting that stabilising agents influence the working times more than rock type.

Laboratory testing was undertaken to determine the working times of lightly bound materials using the Q136A method using standard compaction and modified compaction for specimen preparation, and it found that using modified compaction did not increase the working times. A limited amount of testing found that by varying the hammer blows and targeting constant density at 100% maximum dry density (MDD) during the Q136A test, the resulting working time was increased. Further testing is planned for Year 2 to evaluate this.

A field trial was planned for Year 2 of the project (2021–22) that will expand on the investigations carried out in Year 1, with a particular focus on the relationship between the laboratory and field working times.

2.1.3 NACOE P135 – Optimisation of Recycled Material Blend Limits for Queensland Unbound Road Pavements

NACOE P135, through Years 1 (2021–22) and 2 (2022–23), investigated the laboratory testing performance of recycled material blends, including natural quarried materials, recycled crushed concrete, concrete washout, reclaimed asphalt materials and coal combustion products as unbound pavement materials. The project aims to facilitate the increased use of recycled materials for Queensland by determining permissible blending proportions for crushed rock and recycled materials.

The laboratory testing results suggest that the current recycled material blend constituent limits for unbound pavements can be expanded to further increase the use of recycled materials. Future years of this project will focus on the performance results from field trials.

The findings of this project will inform TMR on the allowable recycled material blend constituent limits in unbound pavements and recommend updates to the TMR Technical Specification MRTS05: *Unbound Pavements*.

2.1.4 Austroads TT1897 – Development of Design Procedures for Lightly Bound Cemented Materials in Flexible Pavements

This project's objective was to improve understanding of the mechanisms of crack formation associated with lightly bound cementitious (LBC) materials and to develop Austroads guidance in terms of pavement design (Austroads 2020).

A pavement design method was developed from:

- field deflection testing to estimate the in situ moduli of LBC bases
- laboratory testing and analysis that confirm LBC materials are very susceptible to fatigue, and it would not be appropriate to develop a design method to inhibit fatigue of LBC.

It was also recommended that Austroads adopt the TMR specification for LBC which is a 28-day UCS range of 1.0–2.0 MPa. TMR has recommended additional requirements be included in the definition, namely that there needs to be a 'steady' increase in UCS between 7 and 28 days along with a minimum 7-day UCS of 1.0 MPa.

A structural design method was developed for pavements considering the use and performance of LBC for moderate to heavily trafficked roads. This included a new elastic characterisation method for LBC materials and heavily bound cemented (HBC) materials in the fatigue cracked state and design charts to select LBC base thicknesses to inhibit the development of block cracking and crocodile cracking.

2.1.5 Austroads APT6157 – Laboratory Fatigue Characterisation of Foamed Bitumen Stabilised Materials

This project focused on the development of a new laboratory fatigue relationship to predict the performance of foamed bitumen stabilised materials to improve the Austroads design procedure of FBS materials (Austroads 2022).

Extensive laboratory testing and analysis was performed to determine the modulus, strength and fatigue characteristics of 5 different host materials, including 3 crushed rocks and 2 recycled blends.

The key findings are summarised as follows (Austroads 2022):

- Generally, 3% foamed bitumen and 2% hydrated lime were found to be optimum dosages in terms of indirect tensile modulus and strength.
- Curing duration shows FBS materials develop strength and stiffness over time.
- Fatigue performance of FBS materials correlates with a combination of different properties, which provides a means of predicting the fatigue life of different FBS mixes.
- The average strain damage exponent was found to be 7.8 for FBS materials, unlike 5 in asphalt fatigue relationship.
- The results showed that, unlike the asphalt fatigue relationship that has a negative correlation with modulus, the fatigue life of the FBS materials increases with the increase in the flexural modulus.
- Overall, a difference was observed between the fatigue life predictions using the asphalt Shell laboratory fatigue relationship and the FBS measured fatigue life, highlighting the need to improve the current Austroads thickness design method for FBS material.

Austroads (2022) recommended that to appropriately predict the in-service fatigue life, the development of a laboratory-to-field shift factor for FBS materials is required.

2.2 Other Research

This section provides an overview of the research conducted with recycled aggregates with cement stabilised materials. In the past few years, research into the use of recycled aggregates from construction and demolition (C&D) waste has increased significantly due to the focus on moving away from natural quarried materials. Developing and developed countries alike have aimed to re-use their C&D waste rather than sending it to landfill.

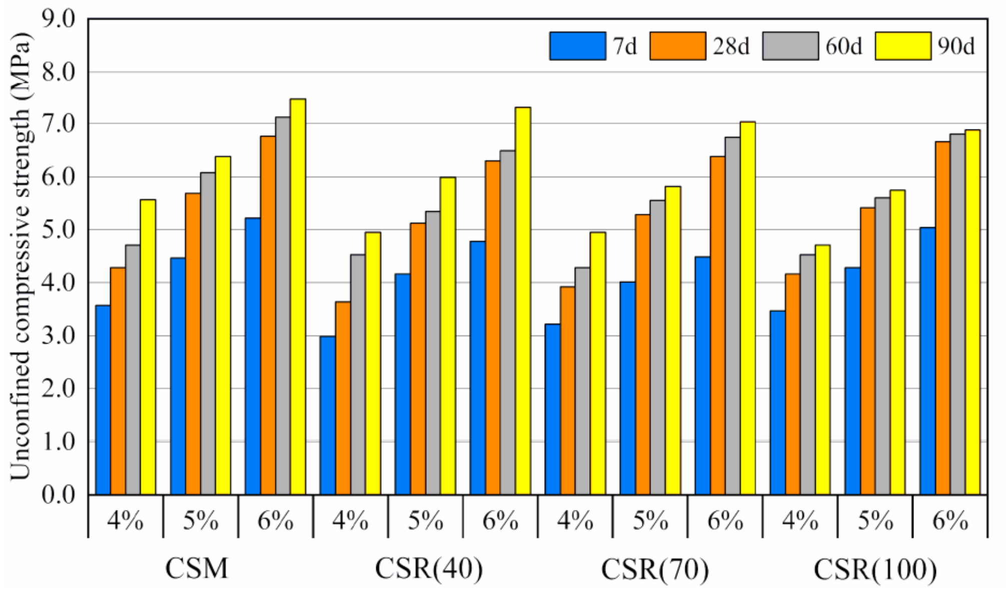
Various studies have been carried out into recycled materials with cement stabilisation. Meng et al. (2021) conducted research into the use of 100% mixed recycled aggregates into cement stabilised materials. The mechanical properties were tested through UCS tests, indirect tensile strength (ITS) tests and drying shrinkage tests. The microstructures of the cement stabilised mixed recycled aggregates (CSMRA) were investigated through X-ray diffraction analysis, mercury intrusion porosimeter and scanning electron microscopy.

Meng et al. (2021) showed that the ultimate compressive strains and tensile strains of CSMRA materials gradually increased with increased cement content (from 0% to 6% cement).

Li and Hu (2020) performed a similar study into the use of recycled concrete aggregate (RCA) as a partial replacement of natural aggregate on the mechanical and durability-related properties of a cement stabilised recycled (CSR) concrete aggregate mixture. UCS, ITS and drying shrinkage tests were carried out on mixes containing up to 6% cement and up to 100% RCA. A reference cement stabilised macadam (CSM) mixture was engaged as a control.

The results from this study showed a similar trend to research done by Meng et al. (2021). They found a general increase in UCS as cement content increased; however, a decrease in UCS with increasing RCA content was observed (see Figure 2.1). Also, compared to the reference mix, the CSR mixtures showed a lower UCS value.

Figure 2.1: Relationship between UCS and cement content



Source: Li and Hu (2020).

ITS data showed the strength of the control mixture to be higher than that of the 3 groups of CSR mixtures with the same cement content. The ITS value increased slowly with increasing RCA content, with the strength of 40% CSR about 0.9 time that of the control. The strength of 100% CSR was about 98%. Further analysis by Li and Hu (2020) found that the cement content had no significance on the strength growth of CSR mixtures.

Li and Hu (2020) also showed a linear relationship between UCS and ITS values of CSM and CSR mixtures at different content levels of RCA. The UCS value was about 10 times the ITS value, which was similar to the results Meng et al. (2021) achieved.

3. Experimental Evaluation Program

3.1 Selected Materials

The materials used for the laboratory characterisation stage of the project were recycled crushed concrete (RCC), recycled crushed brick (CB), reclaimed asphalt pavement (RAP) and recycled crushed glass (RCG). The recycled blend types selected for the laboratory investigation included:

- recycled material blend: 100% RCC
- recycled minimum blend: 70% RCC, 10% RAP, 10% CB and 10% RCG
- recycled maximum blend: 40% RCC, 20% RAP, 20% CB and 20% RCG.

Table 3.1 summarises the 8 recycled material blends evaluated as part of the detailed laboratory investigation in Years 1 and 2.

Table 3.1: Summary of materials evaluated

Material	Supplier	Project year
100% RCC	Supplier #1	Year 1
70% RCC, 10% RAP, 10% CB and 10% RCG blend. (Min. blend)		
40% RCC, 20% RAP, 20% CB and 20% RCG (Max. blend)		
100% RCC (Material 1)	Supplier #2	Year 2
100% RCC (Material 2)	Supplier #3	
100% RCC (Material 3)		
70% RCC, 10% RAP, 10% CB and 10% RCG blend. (Min. blend)		
40% RCC, 20% RAP, 20% CB and 20% RCG blend (Max. blend)		

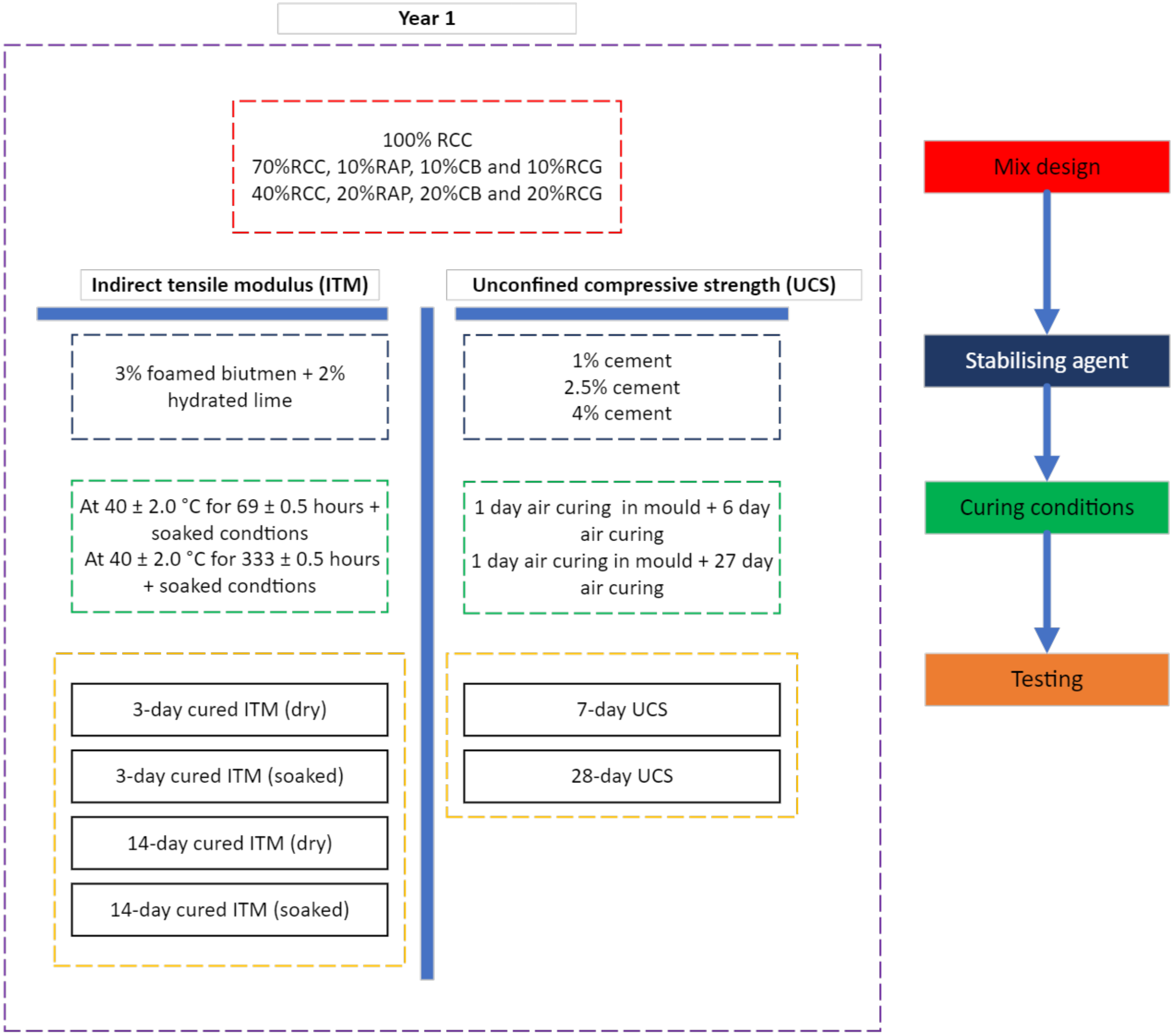
3.2 Laboratory Testing Program

The laboratory testing program is summarised in the table below (Table 3.2). The overall experimental testing plan of the project is presented in Figure 3.1 and Figure 3.2.

Table 3.2: Summary of laboratory testing program

Testing	Method	Year 1	Year 2
Particle size distribution	TMR Q103A (2021/2022)	✓	✓
Foreign materials content	TMR Q477 (2018)	✓	
Compacted density of foamed bitumen stabilised materials	TMR Q147B (2018)	✓	✓
Working time of cement stabilised materials	TMR Q136A (2021/2022)	✓	✓
Atterberg limits	TMR Q104A (2020/2022) TMR Q105 (2018), TMR Q106 (2021)	✓	✓
Compaction properties (maximum dry density and optimum moisture content using standard compactive effort)	TMR Q142A (2021)	✓	✓
Indirect tensile modulus (ITM) test of foamed bitumen stabilised (FBS) materials	TMR Q139 (2021/2022)	✓	✓
Indirect tensile cracking (ITC)/strength test of FBS materials	ASTM International (2019)		✓
Unconfined compressive strength (UCS) test of FBS materials	TMR Q115 (2022)		✓
Unconfined compressive strength (UCS) test of cement stabilised materials	TMR Q115 (2020/2022)	✓	✓

Figure 3.1: Year 1 experimental testing plan



Note: UCS samples were air cured as per Cl Q135B Cl 4.2 c) ii – lightly misted and sealed in a plastic bag and placed in a water bath to maintain the temperature.

Figure 3.2: Year 2 experimental testing plan

Note:

100% RCC (Material 1) was evaluated at 0.8%, 1.5% and 2.5% cement.

Standard curing conditions were adopted. For materials prone to damage and/or material loss, during early demoulding and handling, longer mould curing was opted. Total curing duration was not exceeded (7/28-day).

3.2.1 ITM Specimen Preparation and Testing – FBS Materials

A Wirtgen WLB 10 S laboratory equipment was used for the production of FBS materials. Bitumen Class 170 (C170) and hydrated lime were used for preparing the FBS materials. A foaming agent (Interfoam) was used for this study and 0.5% by mass of bitumen was added to the bitumen. The FBS materials had a target design of 3% bitumen and 2% hydrated lime.

The FBS materials were then transferred to a compaction mould having an internal diameter of 152.4 mm and a height of 114.3 mm, compacted using 50 blows of the Marshall hammer on each side of the specimen (TMR Q138A, 2021, 2022).

The prepared specimens were extruded from the mould using an extrusion device and were subjected to the relevant curing procedures before ITM testing.

An accelerated curing procedure at elevated temperature is commonly adopted for FBS materials to simulate the long-term field curing process. The specimens are typically cured at elevated temperatures to allow hydration of the secondary binder and evaporation of the moisture, resulting in strength and stiffness enhancements. The prepared sets of specimens were cured in the following conditions (TMR Q135C, 2021):

- 69 ± 0.5 hours at 40 ± 2.0 °C plus 3 ± 0.5 hours in environmental chamber at 25 ± 0.5 °C (3-day cured dry ITM)
- 333 ± 0.5 hours at 40 ± 2.0 °C plus 3 ± 0.5 hours in environmental chamber at 25 ± 0.5 °C (14-day cured dry ITM).

After determining the dry ITM, the specimens were soaked in potable water at 25 ± 0.5 °C and placed in the vacuum chamber, applying a partial vacuum of 13 kPa for 10 minutes. The soaked ITM was subsequently determined at the following curing conditions:

- 3-day cured (3-day cured soaked ITM)
- 14-day cured (14-day cured soaked ITM).

Over the last few decades, ITM testing has been widely used for characterising the tensile behaviour of bituminous materials. In the ITM test, a cylindrical specimen is placed between 2 loading strips and is subjected to loading on the vertical diameter, which causes tensile stresses along and perpendicular to the loading plane direction.

The ITM test was undertaken in accordance with the Queensland TMR Q139 test method (2021, 2022). The testing requirements, including the temperature, rise time, pulse repetition period and recovered horizontal strains, are summarised in Table 3.3.

The testing involved applying 5 conditioning load pulses to adjust the peak load to achieve resilient horizontal strains within the target range, followed by 5 additional load pulses with a specified rise time at the specified pulse repetition period. The resulting horizontal recoverable strains were measured using 2 on-specimen linear variable differential transformers (LVDTs). The ITM was calculated by averaging the resilient modulus of the last 5 cycles, calculated for each cycle using Equation 1 (TMR Q139, 2021/2022).

$$P_e = \frac{ED\varepsilon h_c}{(\upsilon + 0.27)10^6} \tag{1}$$

where

P_e = peak estimated load (N)

E = estimated ITM of the specimen (MPa)

D = mean diameter of the specimen (mm)

ε = recovered horizontal strain in the range of 50 ± 20 (με)

h_c = mean height of the specimen (mm)

υ = Poisson ratio (estimated as 0.4)

Table 3.3: ITM testing requirements

Parameter	ITM testing requirements
Test temperature	25 °C ± 0.5 °C
Rise time (10% to 90%)	0.04 ± 0.005 seconds
Pulse repetition period (10% to 10%)	3.0 ± 0.005 seconds
Recovered horizontal strain	50 ± 20 με

3.2.2 UCS Specimen Preparation and Testing

The UCS test was undertaken to investigate the peak strength of the stabilised recycled material blends, according to TMR Q115 (2020, 2022). As part of the Year 2 testing program, both cement stabilised materials and FBS materials were evaluated for UCS strength.

For the preparation of the cement stabilised materials, the oven-dried materials were initially mixed with cement, and the required moisture, i.e. the OMC of the untreated material was then added to the mix in small increments. The mixing continued until a uniform mix was achieved. The investigated cement contents ranged from 0.8% to 4% (by mass) and are summarised in Table 3.4. FBS materials were prepared following Section 3.2.1.

Table 3.4: Evaluated cement proportions

Project year	Material	Cement proportions (% by mass)
Year 1	100% RCC (Reference mix 1)	1%, 2.5%, 4%
	70% RCC, 10% RAP, 10% CB, and 10% RCG blend. (Min. blend)	
	40% RCC, 20% RAP, 20% CB, and 20% RCG (Max. blend)	
Year 2	100% RCC (Material 1)	0.8%, 1.5%, 2.5%
	100% RCC (Material 2)	1%, 2%, 3%
	100% RCC (Material 3)	
	70% RCC, 10% RAP, 10% CB, and 10% RCG blend (Min. blend)	
	40% RCC, 20% RAP, 20% CB, and 20% RCG blend (Max. blend)	

Triplicate specimens were prepared for each mix. The specimens were prepared by standard compactive effort at their OMC of untreated materials to achieve relative compaction of approximately 100% for cement stabilised materials, and at 70% OMC for FBS materials (TMR Q251A, 2021/2022 and TMR Q251B, 2021/2022).

The specimens for UCS testing were prepared in cylindrical moulds having an internal diameter of 105 mm and a height of 115.5 mm. Generally, in both Years 1 and 2, the UCS tests were carried out on the specimen cured as follows (TMR Q135B):

- 1 day air curing in mould plus 6 days air curing (7-day cured)
- 1 day air curing in mould plus 27 days air curing (28-day cured).

Note that for materials prone to damage and/or material loss, during early demoulding and handling, longer mould curing was opted. However, the total curing duration was not exceeded (7/28-day).

The UCS value was determined by applying a compressive load to the specimen and is defined as the maximum load at the failure point divided by the cross-sectional area.

The allowable working time of the cemented blends was investigated by compacting the samples with a one-hour delay to establish a reference MDD and a reference UCS. Further specimens were prepared with a delay in mixing and compaction, which was between 2 and 24 hours. The allowable working time is defined as the delay time that produces a 3% reduction in the achieved MDD (that is, 100% to 97%) or a 20% reduction in achieved UCS (that is, 100% to 80%), whichever is the shortest delay time.

3.2.3 Indirect Tensile Cracking (ITC)/Strength Specimen Preparation and Testing – FBS Materials

The ITC test was undertaken to evaluate the cracking and strength resistance of FBS materials by adopting the principles from the ASTM D8225 test method (ASTM International 2019). FBS materials were prepared and compacted following Section 3.2.1.

The compacted specimens were cured in the following conditions:

- 72 hours at 40 °C and conditioned for 2.5 hours in environmental chamber at 25 °C (3-day cured)
- 336 hours at 40 °C and conditioned for 2.5 hours in environmental chamber at 25 °C (14-day cured).

The cured FBS specimens were tested at both dry and soaked conditions. The cured specimens were soaked in potable water at 25 ± 0.5 °C and placed in the vacuum chamber, applying a partial vacuum of 13 kPa for 10 minutes. The ITC was subsequently determined by applying a constant load-line displacement rate of 10 mm/min at the following curing conditions:

- 3-day cured dry ITC
- 3-day cured soaked ITC
- 14-day cured dry ITC
- 14-day cured soaked ITC.

The ITC test is typically used to determine the cracking tolerance index of asphalt mixtures to evaluate their resistance to cracking. Similar to ITM testing, a cylindrical specimen is placed between 2 loading strips and is subjected to strain-controlled loading (10 mm/min) on the vertical diameter.

The resulting tensile deformation (or strain) perpendicular to the direction of the load leads to the tensile failure of the specimen. Generally, the greater the cracking tolerance (CT) index value, the better the cracking resistance and, consequently, less cracking is reflected in the field.

The peak load from the ITC testing was used to determine the indirect tensile strength (ITS). The cracking index and ITS were calculated using Equations 2 and 3.

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \qquad 2$$

where

CT_{index} = cracking tolerance index

G_f = failure energy

$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m)

l_{75} = displacement at 75% the peak load after the peak (mm)

D = specimen diameter (mm)

t = specimen thickness (mm)

$$ITS = \frac{2000}{\pi L D} \tag*{3}$$

where

ITS = indirect tensile strength (MPa)

P = maximum applied force (kN)

L = specimen length (mm)

D = specimen diameter (mm)

4. Laboratory Testing Results – Year 1

This section presents the laboratory test results from Year 1 testing program.

4.1 Physical Properties

Figure 4.1 and Table 4.1 present the particle size distribution (PSD) of the recycled material blends and the requirements of Queensland TMR MRTS05 (2022a). The selected requirements are based on the grading envelopes for types 2.3 and 2.4 of recycled blends containing more than 70% recycled materials. Types 2.3 and 2.4 materials are typically used in subbase courses.

The PSD parameters, physical and engineering properties of recycled material blends are summarised in Table 4.2. The test results that did not meet the specification requirements are presented in red font.

The PSD of the 40% RCC blend almost fell within the specified limits of TMR MRTS05 (2022a), while the PSD of the 70% RCC blend was marginally below the lower limit by having lower fines content than the 3% minimum requirement. The 100% RCC material did not meet the PSD requirement by showing lower percentages passing some sieve sizes. Based on the PSD, the coefficient of uniformity (Cu) and the coefficient of curvature (Cc), the recycled material blends were classified as well-graded gravel (GW) according to the Unified Soil Classification System.

It should be noted that the 2 recycled blends including RAP, CB and RCG were sourced from the suppliers as already blended materials, and the exact actual percentages of these recycled materials in each blend might slightly differ from the reported percentages in the blends.

The Atterberg limit results indicated that the liquid limit of the 100% RCC blends was slightly higher than the TMR MRTS05 (2022a) requirement, and the linear shrinkage limit for all recycled blends was slightly lower than the 1.5% minimum requirement.

The recycled material blends contained a limited portion of foreign materials and satisfied the requirements.

The compaction test results indicated that the optimum moisture content (OMC) decreased with reducing the RCC content and increasing the RAP, CB and RCG in the mix. The higher OMC of the RCC than other blends seemed to be attributed to the high moisture absorption of RCC due to the residual cement particles, which is well-established in the published literature (Ghorbani et al. 2021b). In addition, RAP and RCG particles are known to have lower moisture absorption values than RCC, which could result in the reduction of the OMC in those mixes (Arulrajah et al. 2014; Ghorbani et al. 2021a).

Figure 4.1: PSD of the recycled materials blends (Year 1)

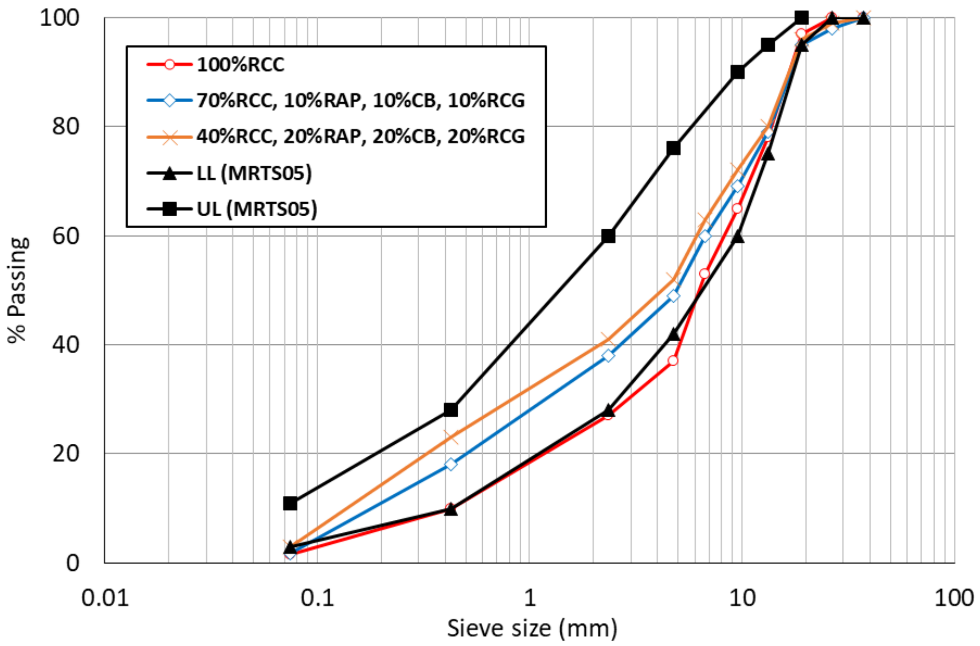


Table 4.1: PSD of the recycled materials and the requirements of TMR MRTS05 (2022a) (Year 1)

	100% RCC	70% RCC, 10% RAP, 10% CB, 10% RCG	40% RCC, 20% RAP, 20% CB, 20% RCG	MRTS05 limits (Type 2.3)	
Sieve size (mm)	%Passing			Min	Max
75	–	–	–	–	–
53	–	–	–	–	–
37.5	100	100	100	–	–
26.5	100	98	99	100	–
19	97	95	96	95	100
13.2	78	79	80	75	95
9.5	65	69	72	60	90
6.7	53	60	63	–	–
4.75	37	49	52	42	76
2.36	27	38	41	28	60
0.425	10	18	23	10	28
0.075	1.5	1.8	3	3	11

Table 4.2: Physical and engineering properties of recycled material blends (Year 1)

Property	100% RCC	70% RCC, 10% RAP, 10% CB, 10% RCG	40% RCC, 20% RAP, 20% CB, 20% RCG	MRTS05 requirement (Type 2.3)	
				Min	Max
Gradation parameters					
D_{10} (mm)	0.43	0.25	0.20		
D_{30} (mm)	3.1	1.6	1.2		
D_{60}	8.3	6.7	6.2		
Cc	2.7	1.5	1.1		
Cu	19.6	26.6	31.2		
Gravel content (%)	73	62	59		
Sand content (%)	25.5	36.2	38		
Fine content (%)	1.5	1.8	3		
Soil classification	GW	GW	GW		
Atterberg limits					
Liquid limit (%)	36.6	33.8	31.6		≤ 35
Plastic limit (%)	34.2	30.4	28.4		
Plasticity index (%)	2.4	3.4	3.2		
Linear shrinkage (%)	1.2	1	0.8	1.5	4.5
WPI(1) (%)	24	61.2	73.6		
WLS(2) (%)	12	18	18.4		≤ 110
Foreign materials					
Type 1 – brick and glass (%)	0.0	0.2	0.0		–
Type 2 – Metal, ceramics and slag (other than blast furnace slag) (%)	0.1	0.0	0.2		≤ 3%
Type 3 – plaster, clay lumps and other friable material (%)	0.0	0.0	0.1		≤ 1%
Type 4 – Rubber, plastic, bitumen (not part of asphalt), paper, cloth, paint, wood and other vegetable matter (%)	0.1	0.1	0		≤ 0.2%
Type 5 – asphalt (%)	1.4	4.0	8.2		-
Total	1.6	4.3	8.5		-
Compaction properties					
OMC (%)	16	14.6	12.7		
MDD (t/m^3)	1.78	1.76	1.92		

1. Weighted plasticity index.
2. Weighted linear shrinkage.

4.2 Indirect Tensile Modulus – FBS Materials

4.2.1 Mix Design Results

Figure 4.2 presents the 3-day cured ITM of the FBS mixes. The 3-day cured ITM (dry), 3-day cured ITM (soaked), along with the requirements of TMR MRTS09 (2021a) are presented in this figure. The ITM requirements for the average daily equivalent standard axles (ESA) in design year of opening less than 100 and ESA between 100 and 3,000 are also shown.

As noted, both dry and soaked 3-day cured ITM values increased as the RCC was replaced with RAP, CB and RCG. This enhancement in the ITM could be associated with several reasons. With decreasing the RCC and increasing the RAP, CB and RCG in the blend, the portion of fines content increased, which could lead to enhancement of the ITM. The residual bitumen coating of aggregates and the compatibility residual bitumen with the foamed bitumen could be another contributing factor to the increase in ITM. In addition, with increasing the sand-sized RCG aggregates in the mix, the overall grading, and therefore the compatibility of the blend, was improved, which could improve the ITM.

Table 4.3 summarises the 3-day cured ITM of the recycled material blends. In addition, the average retained ITM and average dry density values are summarised in this table. The retained ITM was defined as the ratio of the dry to soaked 3-day cured ITM values for each mix.

The experimental data for all tested specimens are presented in Appendix A. The values that did not satisfy the requirements for ESA less than 100 and between 100 and 3,000 are presented in red and blue font, respectively. As noted in Table 4.3, replacing the RCC with RAP, CB and RCG increased the dry density of the blends and resulted in a denser structure with higher achieved ITM values.

Table 4.4 summarises the compliance of the selected recycled material blends with the requirements of TMR MRTS09 (2021a). A ✓ denotes that the mix satisfied the requirement, while an X denotes that the mix failed to meet the requirement.

The 40% RCC blend satisfied dry and soaked 3-day ITM requirements for both ESA ranges, the 70% RCC blend only satisfied the dry and soaked 3-day ITM requirements for ESA less than 100, and 100% RCC failed to satisfy the requirements of both ESA ranges. However, all mixes complied with the minimum retained modulus requirements for both ESA levels of 100 and 100–3,000.

Figure 4.2: 3-day cured ITM values for recycled material blends (Year 1)

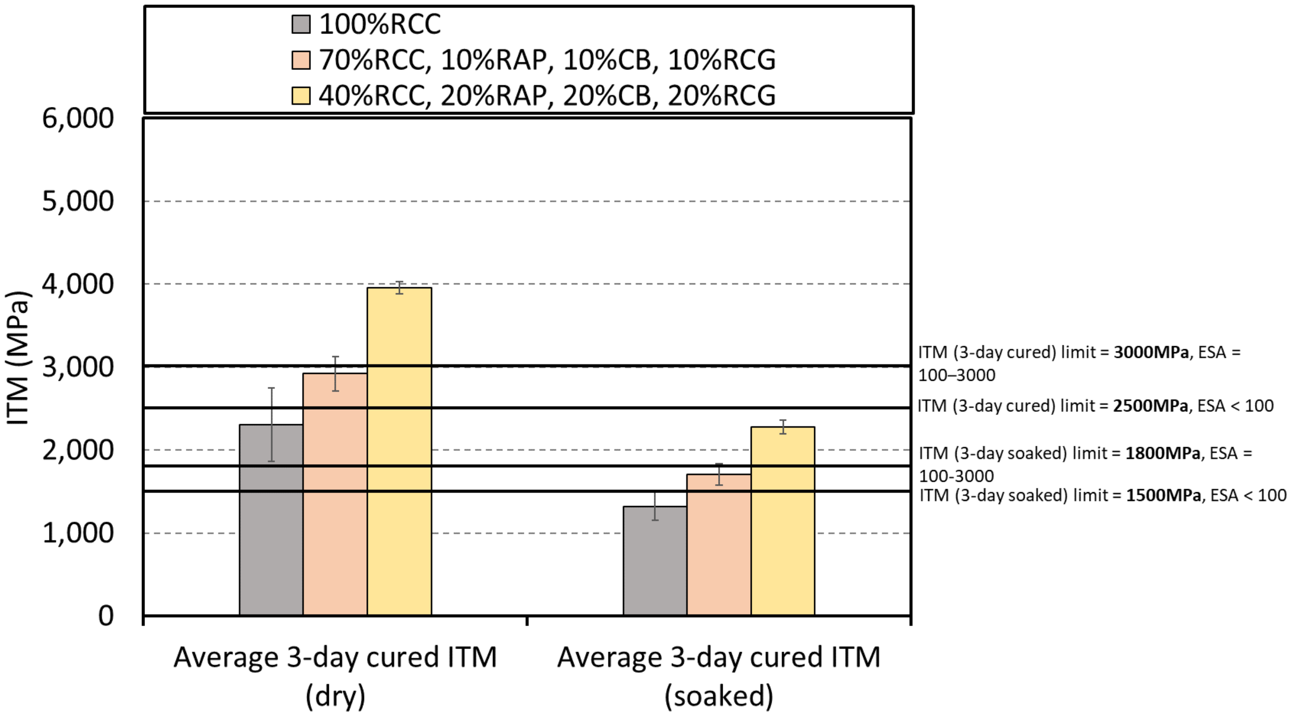


Table 4.3: Summary of the ITM for recycled material blends (Year 1)

Material	Average 3-day cured ITM, dry (MPa)	Average 3-day cured ITM, soaked (Mpa)	Average retained modulus (%)	Average dry density (t/m^3)
100% RCC	2,306	1,321	59	1.89
70% RCC, 10% RAP, 10% CB, 10% RCG	2,920	1,703	58	1.92
40% RCC, 20% RAP, 20% CB, 20% RCG	3,956	2,275	57	1.94

Table 4.4: Compliance of recycled material blends with MRTS09 requirements

Material	3-day cured ITM (dry)		3-day cured ITM (soaked)		Minimum retained modulus	
	ESA < 100	ESA = 100–3,000	ESA < 100	ESA = 100–3,000	ESA < 100	ESA = 100–3,000
100% RCC	X	X	X	X	✓	✓
70% RCC, 10% RAP, 10% CB, 10% RCG	✓	X	✓	X	✓	✓
40% RCC, 20% RAP, 20% CB, 20% RCG	✓	✓	✓	✓	✓	✓

4.2.2 Effect of Curing Time on ITM

Figure 4.3 presents the effect of curing time on the dry and soaked ITM of the FBS materials.

In relation to the dry ITM, the influence of curing was lowest for the 100% RCC and became more pronounced as more RCC was replaced with RAP, CB and RCG. As such, the 40% RCC blend achieved the highest improvement in the ITM after the selected curing time with an increase of approximately 32% from 3,956 MPa to 5,212 MPa. Similar trends were observed for the soaked ITM results, whereby the 100% RCC exhibited negligible improvement in the ITM (1% ITM increase), and the effect of curing became more evident with increasing the RAP, CB and RCG contents.

In addition, the relative performance of the blends in terms of ITM is compared in Figure 4.3 based on the values shown on the arrows. For example, the 14-day cured ITM (dry) of the 40% RCC blend was 37.2% and 59.9% higher than the 70% RCC blend and 100% RCC, respectively, indicating the primary impact of the mix composition on the ITM.

Table 4.5 and Table 4.6 summarise the results of the effect of curing on the ITM of the tested mixes. The ratio of the 14-day/3-day ITM for both dry and soaked conditions are also included in these tables. The 40% RCC blend showed the highest 14-day/3-day ITM ratio in both dry and soaked conditions, indicating a higher rate of modulus gain with time compared to the other 2 blends. It can also be observed that the curing time had a negligible effect on the ITM of the 100% RCC, possibly due to the gradation deficiency and the limited portion of fines content.

These results are consistent with the ITM results for the different blends that were presented in the previous section, indicating that replacing RCC with RAP, CB and RCG improved the ITM values and modulus gain over time. As elaborated earlier, this performance could be attributed to the combined effects of increased fines in the matrix, improved gradation and compaction properties. Additionally, a better performance in the blends including RAP might be due to the contribution of and better bonding of the aged bitumen from RAP in those mixes.

Note that given the inclusion of different recycled materials (RAP, CB and RCG) in the blends, the improvement of the mechanical properties of the 70% RCC and 40% RCC compared to the 100% RCC seemed to be attributed to the combined effect of these recycled materials and improvements in physical properties (that is, grading and PI), but the individual effect of RAP, CB or RCG on the mechanical performance of the blends could not be assessed.

Figure 4.3: Effect of curing time on (a) dry ITM, (b) soaked ITM (Year 1)

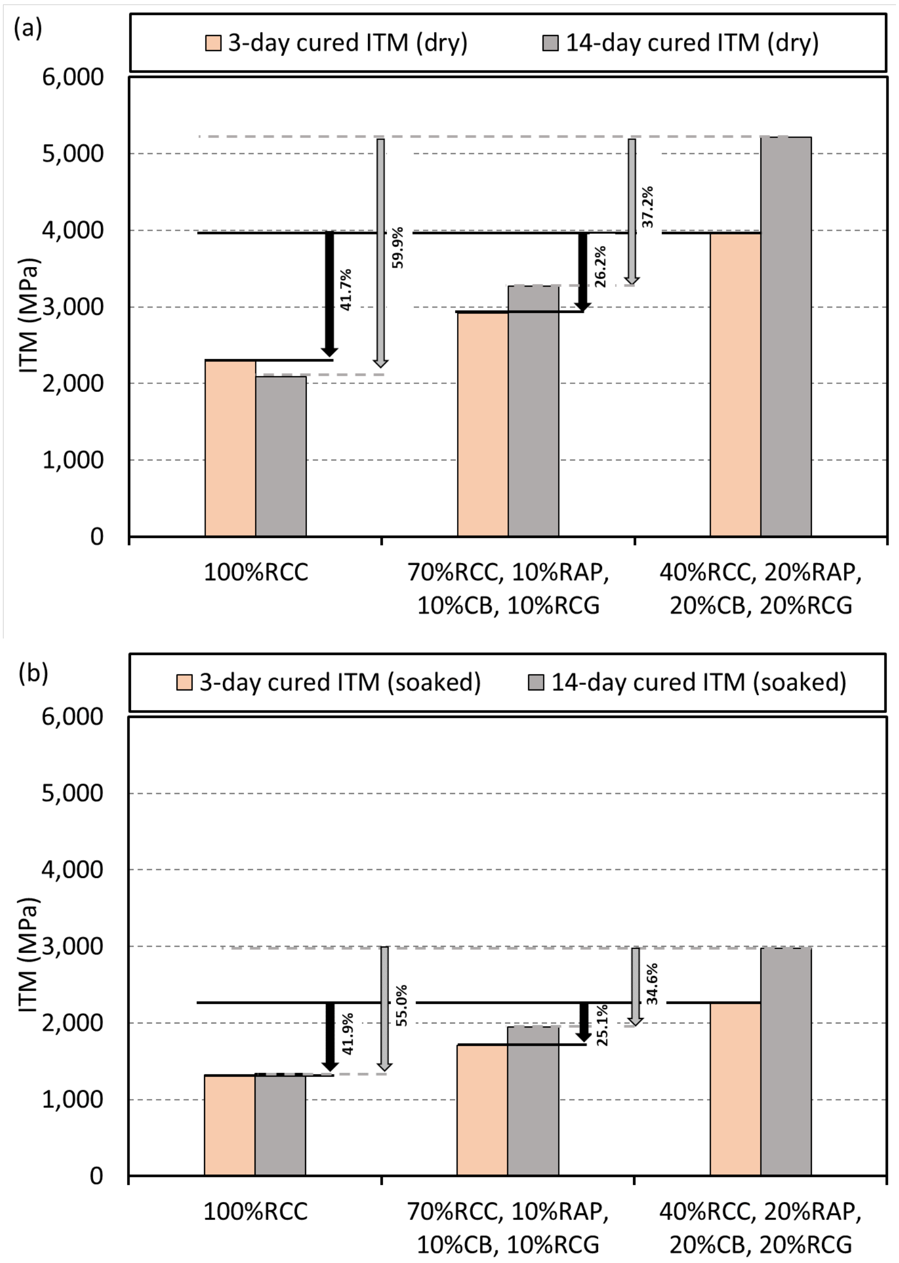


Table 4.5: Effect of curing time on the ITM (dry) (Year 1)

Material	3-day cured ITM, dry (MPa)	14-day cured ITM, dry (MPa)	14-day/3-day ITM ratio
100% RCC	2,306	2,091	0.91
70% RCC, 10% RAP, 10% CB, 10% RCG	2,920	3,272	1.12
40% RCC, 20% RAP, 20% CB, 20% RCG	3,956	5,212	1.32

Table 4.6: Effect of curing time on the ITM (soaked) (Year 1)

Material	3-day cured ITM, soaked (MPa)	14-day cured ITM, soaked (MPa)	14-day/3-day ITM ratio
100% RCC	1,321	1,336	1.01
70% RCC, 10% RAP, 10% CB, 10% RCG	1,703	1,945	1.14
40% RCC, 20% RAP, 20% CB, 20% RCG	2,275	2,973	1.31

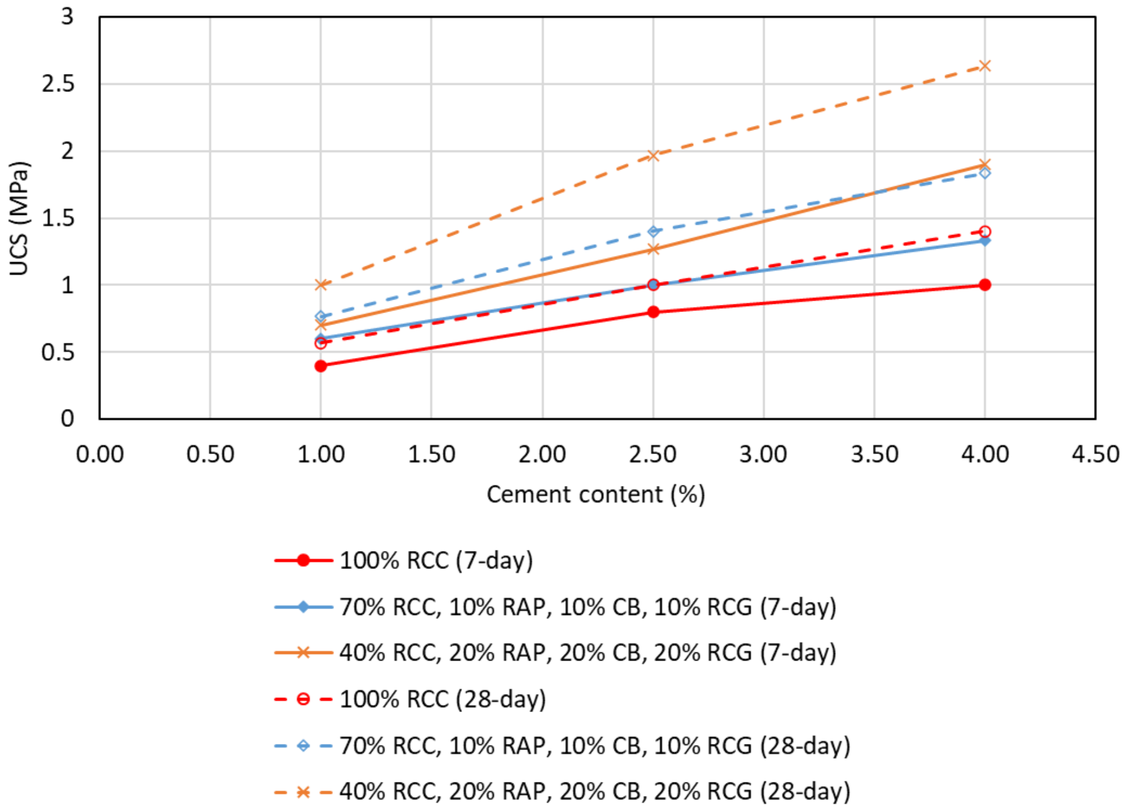
It should be added that TMR MRTS09 (2021a) has separate requirements for the 3-day, 7-day and 14-day cured modulus (soaked) for production plant-mix FBS materials. For plant-mix FBS materials compliance of ITM materials shall be assessed based on the contractor's plant. This project focused on the lab-mix FBS materials at 3- and 14-days curing time. However, to relatively compare the 3 tested blends, the 14-day soaked ITM of the recycled blends (lab-mix) were assessed against the current TMR specification requirement for the 14-day soaked ITM (plant mix, that is minimum ITM of 1,800 MPa). The results showed that only the 70% RCC and 40% RCC blends conformed to the 14-day ITM requirement, which is generally consistent with the findings for the 3-day mix design ITMs from lab mixes (Section 4.2.1).

4.3 Unconfined Compressive Strength – Cement Stabilised Materials

4.3.1 Effect of Cement Content

Figure 4.4 presents the effect of cement content on UCS values at both 7-day and 28-day curing. As cement content increased, the UCS values increased with varying degrees of improvement for different blends. The higher UCS results are due to the increased cementation and bonding that occurs with greater cement content. The strength development occurs due to the development of cementitious compounds from the hydration reaction between cement and water.

Figure 4.4: Effect of cement content on UCS (Year 1)



4.3.2 Performance Feasibility

The UCS test results for the 7-day and 28-day curing conditions against varying cement contents are presented in Figure 4.5 and Figure 4.6, respectively. The requirements of TMR MRTS10 (2021b) for a lightly bound base/subbase and a lightly bound improved layer are also included in these figures.

None of the investigated blends with 1% cement complied with the 7-day UCS limit for the lightly bound improved layer specified by TMR MRTS10 (2021b). The 100% RCC with 2.5% cement did not meet the

7-day UCS requirement either, and the 70% RCC blend with 2.5% cement just met the requirement (UCS of 1 MPa). On the other hand, all 3 tested materials with 4% cement complied with the 7-day UCS minimum limit with 100% RCC just meeting the requirement (UCS of 1 MPa).

The 28-day UCS results showed that the 40% RCC blend was the only material with 1% cement that just met the minimum requirement of TMR MRTS10 (2021b) for 28-day UCS of a lightly bound base/subbase with a UCS of 1 MPa.

All 3 materials with 2.5% and 4% cement contents complied with the 28-day UCS requirements except the 40% RCC blend with 4% cement which showed a higher UCS than the maximum limit. Therefore, this specific mix (40% RCC with 4% cement) cannot be considered as a lightly bound cemented material.

Figure 4.5: The 7-day UCS test results (Year 1)

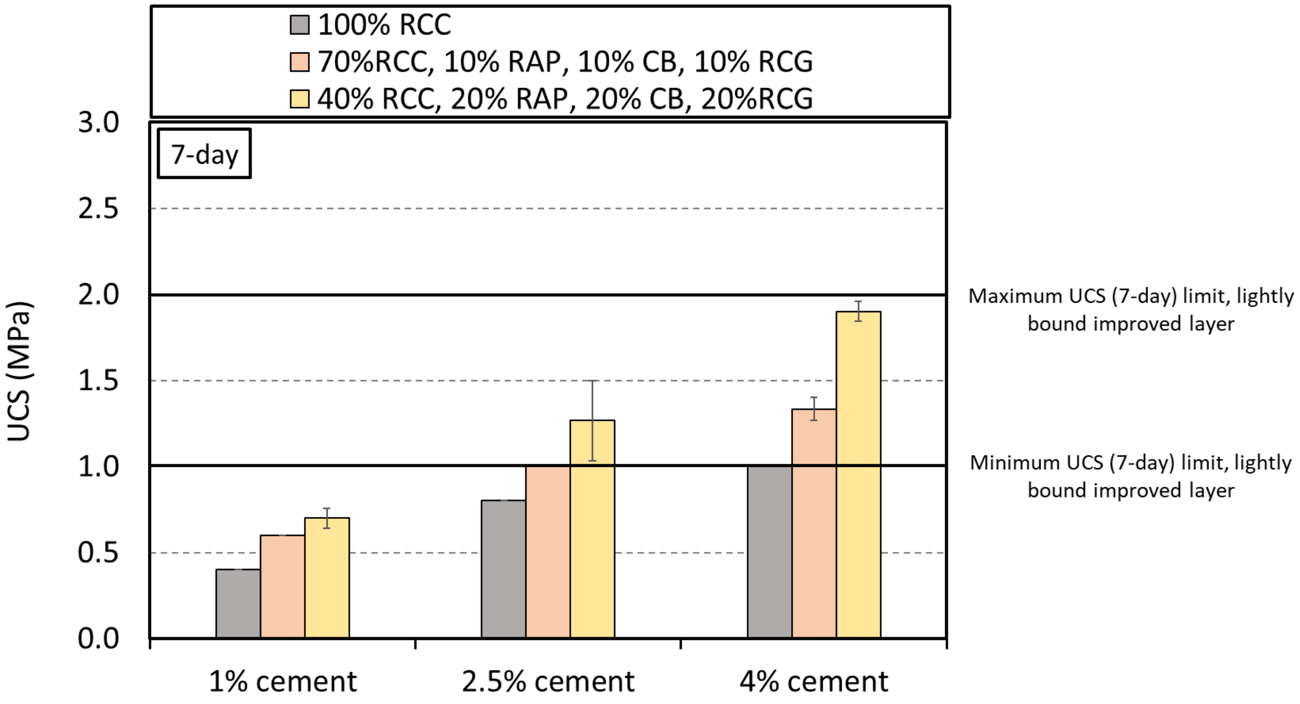
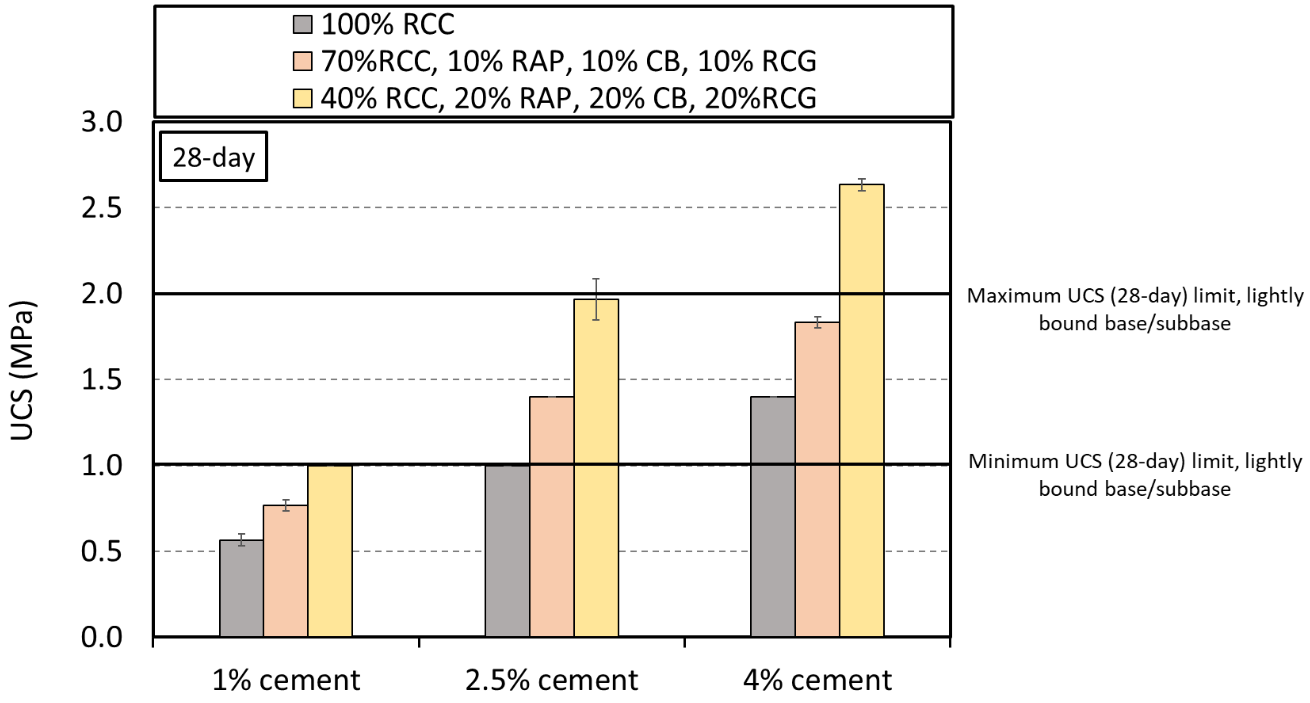


Figure 4.6: The 28-day UCS test results (Year 1)



4.3.3 Effect of Curing Time on UCS

The effect of curing time on UCS test results for cement contents of 1%, 2.5% and 4% are presented in Figure 4.7, Figure 4.8 and Figure 4.9, respectively.

As expected, the UCS of the blends increased with the curing time. Table 4.7 summarises the UCS test results for 7-day and 28-day curing conditions and the ratio of the 28-day/7-day UCS values. The numbers that were not within the requirements of TMR MRTS10 (2021b) are presented in red font.

The 28-day/7-day UCS values varied between 1.25 and 1.55, and there was not a noticeable pattern or trend in the ratios. However, a generally higher rate of strength gain was observed for the 40% RCC blend compared to the other 2 materials. The full data containing the results of the UCS test for each tested blend are presented in Appendix B.

Furthermore, the relative performance of the tested blends is compared based on the values shown on the arrows. For example, for 1% cement content, 40% RCC blend exhibited 14.3% and 42.8% higher 7-day UCS than the 70% RCC blend and 100% RCC, respectively. These numbers were 21% and 36.8%, respectively for the blends with 2.5% cement, and 29.8% and 47.4% for the blends containing 4% cement.

The allowable working time of the cement stabilised blends are also summarised in Table 4.8.

Figure 4.7: Effect of curing time on the UCS of recycled material blends containing 1% cement (Year 1)

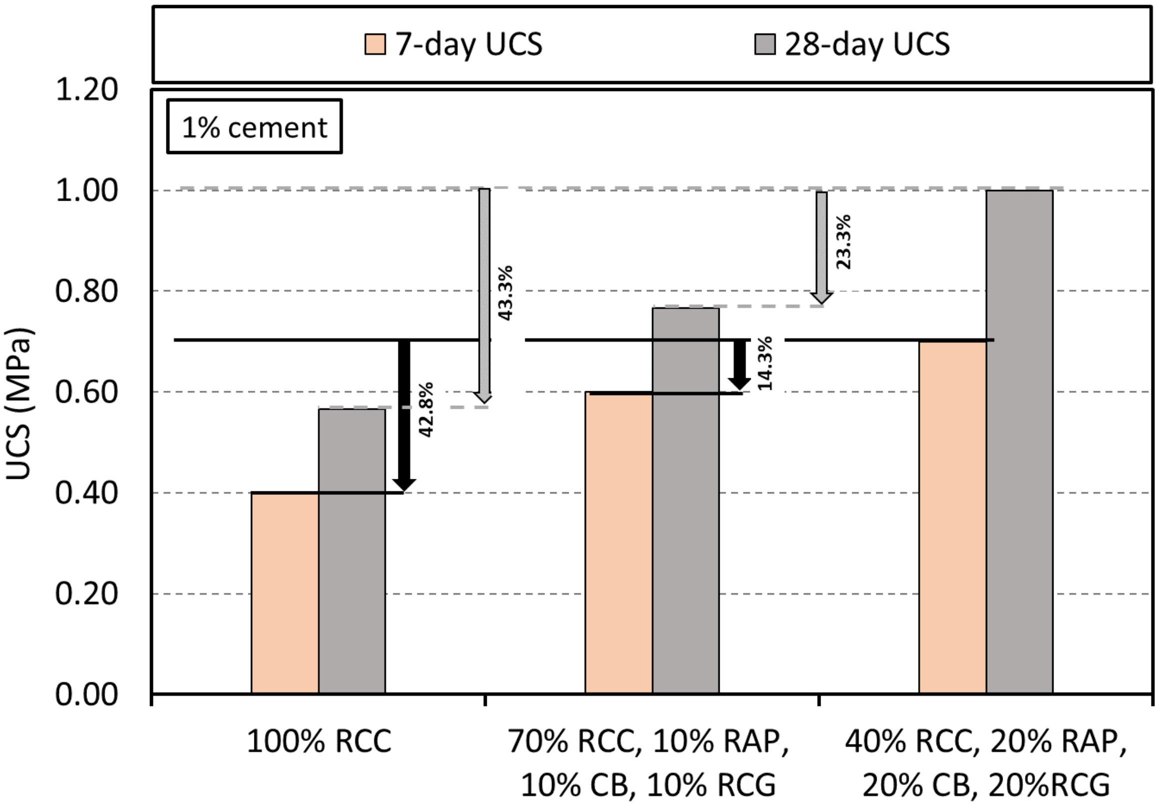


Figure 4.8: Effect of curing time on the UCS of recycled material blends containing 2.5% cement (Year 1)

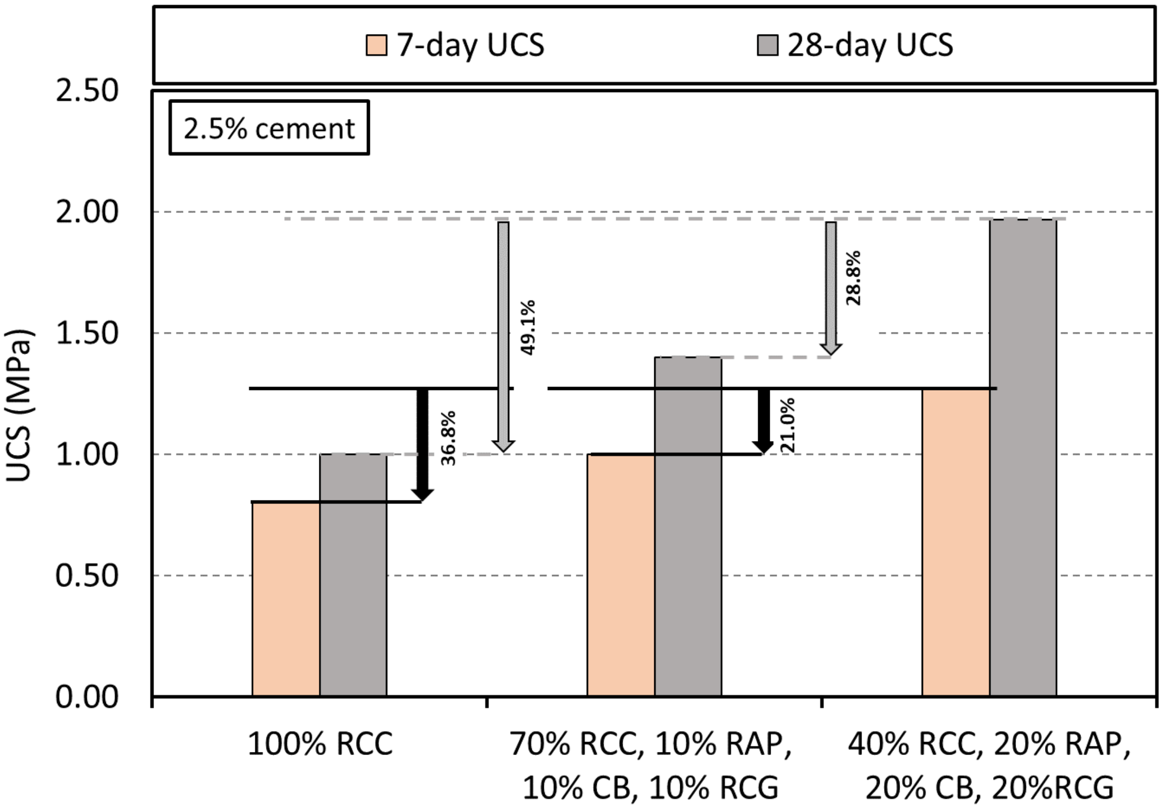


Figure 4.9: Effect of curing time on the UCS of recycled material blends containing 4% cement (Year 1)

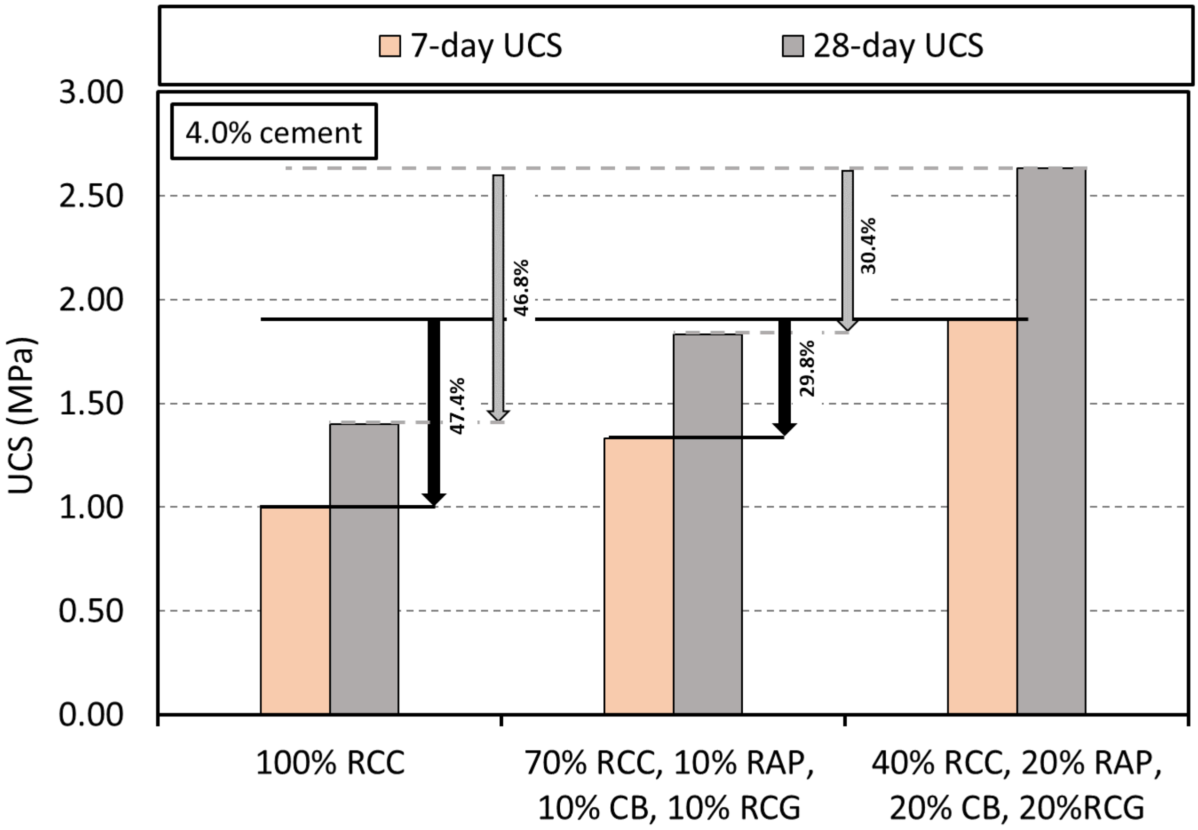


Table 4.7: Summary of the UCS test results (Year 1)

Material	Cement content (%)	Average 7-day UCs (MPa)	Average 28-day UCs (MPa)	28-day/7-day UCS ratio
100% RCC	1	0.40	0.57	1.42
	2.5	0.80	1.00	1.25
	4	1.00	1.40	1.40
70% RCC, 10% RG, 10% CB, 10% RAP	1	0.60	0.77	1.28
	2.5	1.00	1.40	1.40
	4	1.33	1.83	1.38
40% RCC, 20% RG, 20% CB, 20% RAP	1	0.70	1.00	1.43
	2.5	1.27	1.97	1.55
	4	1.90	2.63	1.39

Table 4.8: The allowable working time of the cement stabilised blends

Parameter	100% RCC	70% RCC, 10% RAP, 10% CB, 10% RCG	40% RCC, 20% RAP, 20% CB, 20% RCG
Cement content (%)	4	2.5	2.5
Dry density allowable working time (h)	0	14	6
UCS allowable working time (h)	10	7	5
Allowable working time (h)	0	7	5

4.4 Mix Design Assessment for Plant-mixed Blends

The mix design assessment process for plant-mixed blends, as outlined by TMR, involves evaluation of mixing plant variability (MPV). The MPV is an estimate of the likely variability in stabilising agent content during production from the actual mixing plant to be used in the projects. MPV is expressed as a percentage by dry mass of pavement material. Details can be found in TMR MRTS10 (2022c).

Figure 4.10 to Figure 4.12 show the acceptable target content range of stabilising agent for different tested materials, which is the results derived from the adopted mix design process. These figures are related to the 28-day UCS of lightly bound base and subbase materials (i.e. plant-mixed lightly bound base and subbase mix design assessment).

A brief step-by-step mix design assessment process includes:

- Obtain laboratory UCS test results.
- Adopt a best fit curve for mix design using a second order polynomial trendline.
- Determine the stabilising agent contents at 1 MPa and 2 MPa using the obtained polynomial trendline equation.
- Assume the MPV value based on TMR MRTS10 (2022c). Note that in this research study, an MPV of 0.2% was adopted.
- Obtain the acceptable target content range using the stabilising agent contents at 1 MPa and 2 MPa, and the assumed MPV value.

In this study, the nominated target content of stabilising agent was assumed to be the middle point of the acceptable target content range. Note that the nominated target content of stabilising agent in project works is potentially selected by the contractor.

Figure 4.10: Target contents of stabilising agent for 100% RCC (Year 1)

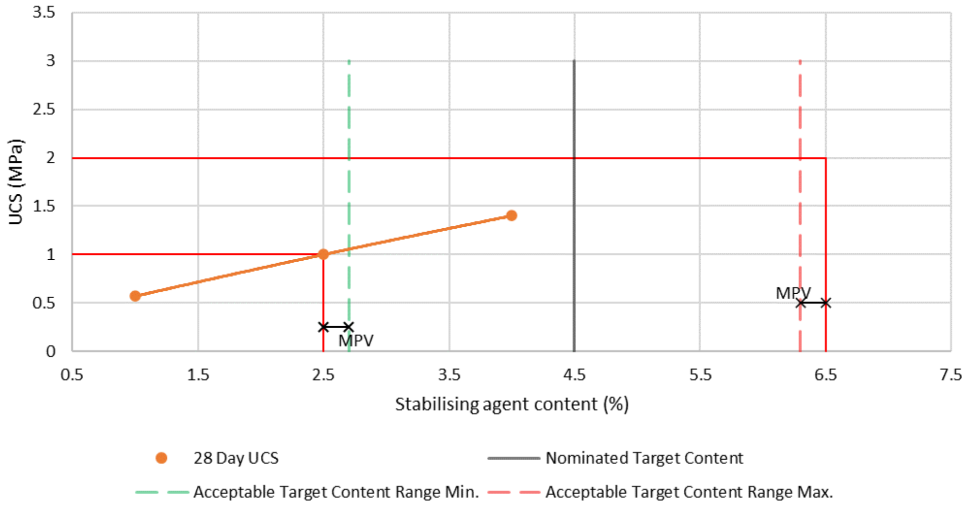


Figure 4.11: Target contents of stabilising agent for 70% RCC blend (Year 1)

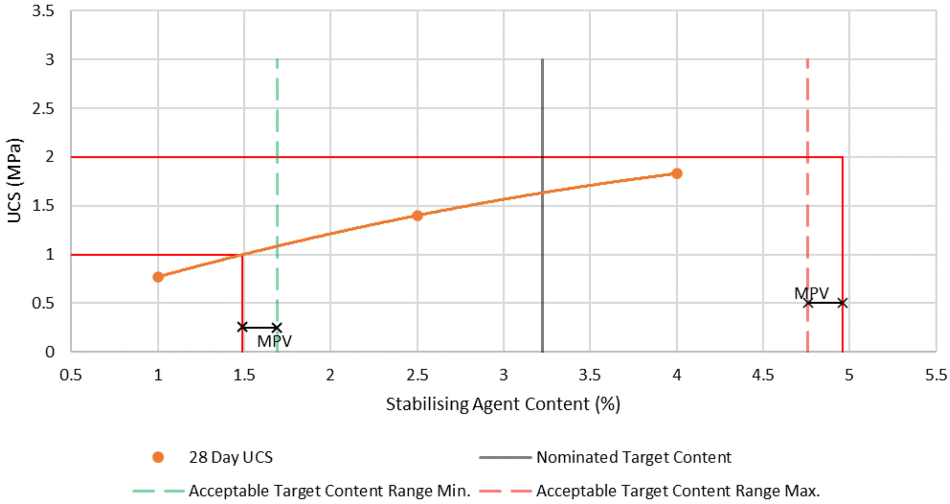
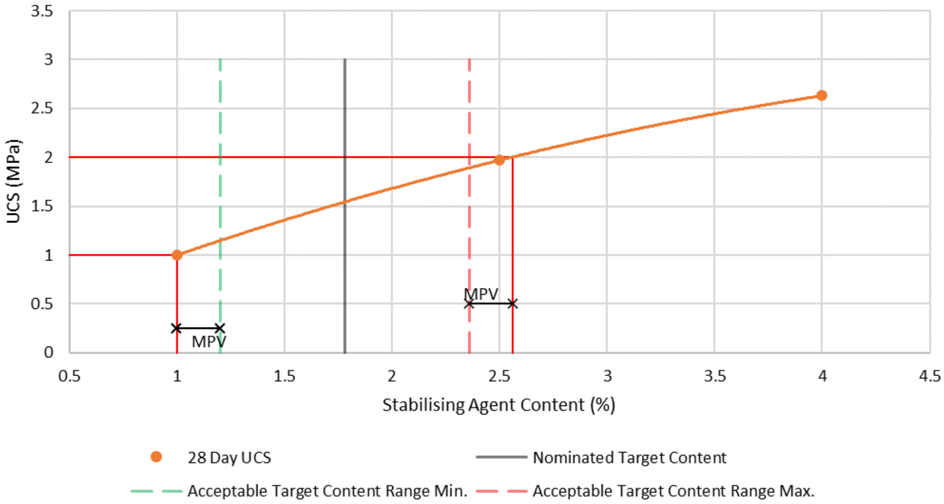


Figure 4.12: Target contents of stabilising agent for 40% RCC blend (Year 1)



5. Laboratory Testing Results – Year 2

This section presents the laboratory test results from Year 2 testing program.

5.1 Physical Properties

Figure 5.1 and Table 5.1 present the particle size distribution (PSD) of the recycled material blends against the requirements of Queensland TMR MRTS05 (2022a). The PSD parameters, physical and engineering properties of the recycled material blends are summarised in Table 5.2. The numbers presented in red font represent the non-conforming properties.

Both the 100% RCC Material 1 and the 70% RCC blend conformed to all TMR MRTS05 (2022a) grading requirements. The other recycled material blends marginally met the TMR MRTS05 (2022a) grading requirements, with slight non-conformance for some sieve sizes.

Note that the recycled material blends were supplied as already blended materials; therefore, the exact proportions of recycled materials in each blend might differ slightly from the reported percentages in the blends.

The Atterberg limits of the recycled material blends typically conformed to the TMR MRTS05 (2022a) requirements, except for the linear shrinkage values. The 70% and 40% RCC blends had a linear shrinkage (LS) of 0.2%, which is significantly lower than the minimum requirements (1.5%). The low LS generally suggests a lack of plasticity in the recycled material blends, which can lead to poor workability and a high permeability of the material. Also, it is common for porous aggregates such as those derived primarily from recycled crushed concrete to have a liquid limit (LL) of significantly more than 25%, despite displaying an acceptable plasticity index (PI) (Griffin et al. 2019).

Based on the PSD, coefficient of uniformity (Cu) and coefficient of curvature (Cc), the recycled material blends were classified as well-graded gravel (GW) according to the Unified Soil Classification System.

Figure 5.1: PSD of the recycled material blends (Year 2)

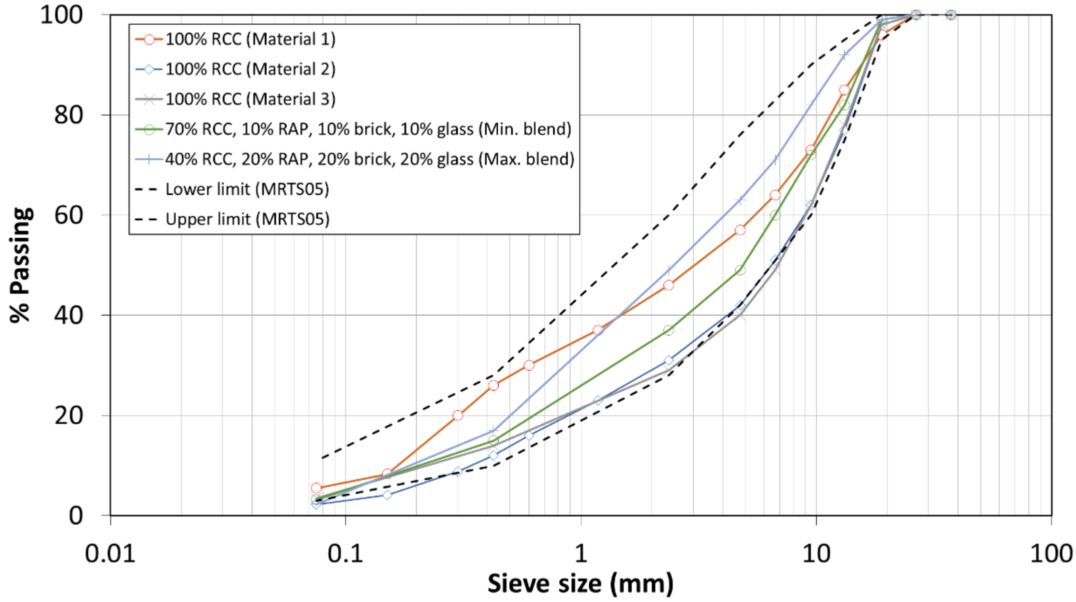


Table 5.1: PSD of the recycled materials and the requirements of TMR MRTS05 (2022a) (Year 2)

Sieve size (mm)	100% RCC (Material 1)	100% RCC (Material 2)	100% RCC (Material 3)	70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	MRTS05 limits (Type 2.3)	
	%Passing					Min	Max
37.5	100	100	100	100	100	–	–
26.5	100	100	100	100	100	100	–
19	96	98	98	99	99	95	100
13.2	85	77	78	82	92	75	95
9.5	73	62	62	72	82	60	90
6.7	64	51	49	60	71	–	–
4.75	57	42	40	49	63	42	76
2.36	46	31	29	37	49	28	60
1.18	37	23	–	–	–	–	–
0.600	30	16	–	–	–	–	–
0.425	26	12	14	15	17	10	28
0.300	20	8.8	–	–	–	–	–
0.150	8.3	4.1	–	–	–	–	–
0.075	5.5	2.2	3.5	3.2	2.3	3	11

Table 5.2: Physical and engineering properties of recycled material blends (Year 2)

Property	100% RCC (Material 1)	100% RCC (Material 2)	100% RCC (Material 3)	70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	MRTS05 requirement (Type 2.3)	
						Min	Max
Gradation parameters							
D_{10} (mm)	0.17	0.35	0.29	0.28	0.26		
D_{30} (mm)	0.6	2.2	2.6	1.7	2.3		
D_{60}	5.6	9.0	9.1	6.7	4.2		
Cc	0.4	1.6	2.5	1.6	4.8		
Cu	32.5	25.9	31.1	24.2	16.4		
Gravel content (%)	54	69	71	63	51		
Sand content (%)	40.5	28.8	25.5	33.8	46.7		
Fine content (%)	5.5	2.2	3.5	3.2	2.3		
Soil classification	GW	GW	GW	GW	GW		
Atterberg limits							
Liquid limit (%)	31.8	35	33.6	32.8	31.6		≤ 35
Plastic limit (%)	28.2	32	30	29.4	30		
Plasticity index (%)	3.6	3	3.6	3.4	1.6		
Linear shrinkage (%)	2.2	1.2	1.4	0.2	0.2	1.5	4.5
WPI(1) (%)	93.6	36	50.4	51	27.2		
WLS(2) (%)	57.2	14.4	19.6	3	3.4		≤ 110

Property	100% RCC (Material 1)	100% RCC (Material 2)	100% RCC (Material 3)	70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	MRTS05 requirement (Type 2.3)	
						Min	Max
Compaction properties							
OMC (%)	14	14.5	13	13.5	13		
MDD (t/m^3)	1.84	1.84	1.92	1.87	1.84		
Flakiness index							
Flakiness index (%)	10	5	8	7	10		
Degradation factor							
Degradation factor	6	11	12	32	28		

1. Weighted plasticity index.
2. Weighted linear shrinkage.

5.2 Indirect Tensile Modulus – FBS Materials

5.2.1 Mix Design Results

The 3-day cured ITM of the FBS mixes for dry and soaked conditions are presented in Figure 5.2 against the TMR MRTS09 (2022b) requirements. The experimental data for all tested specimens are presented in Appendix C.

All tested recycled material blends achieved an ITM greater than the 3,000 MPa limit under dry conditions which are suitable for an ESA between 100 and 3,000. Also, all materials met the ITM (soaked) requirement for ESA < 100 under soaked conditions. However, two of the 100% RCC materials (materials 1 and 3) did not meet the soaked ITM requirement for traffic greater than 100 ESA. Also, all mixes complied with the minimum retained modulus requirements for both ESA levels of 100 and 100–3,000.

Similar to the Year 1 results, overall, as RCC proportions decreased and RAP, CB and RCG blend proportions increased, the modulus generally increased. This could likely be due to the overall improved gradation in the blends as the result of increasing the sand-sized RCG aggregates in the mix. However, as illustrated in Figure 5.2, the performance of 100% RCC may vary depending on the source of the recycled materials, their particle size distribution and other physical properties.

Table 5.3 summarises the 3-day cured ITM results of the recycled material blends. The values that did not satisfy the requirements for ESA less than 100 and between 100 and 3,000 are presented in red and blue fonts, respectively.

Figure 5.2: 3-day cured ITM values for recycled material blends (Year 2)

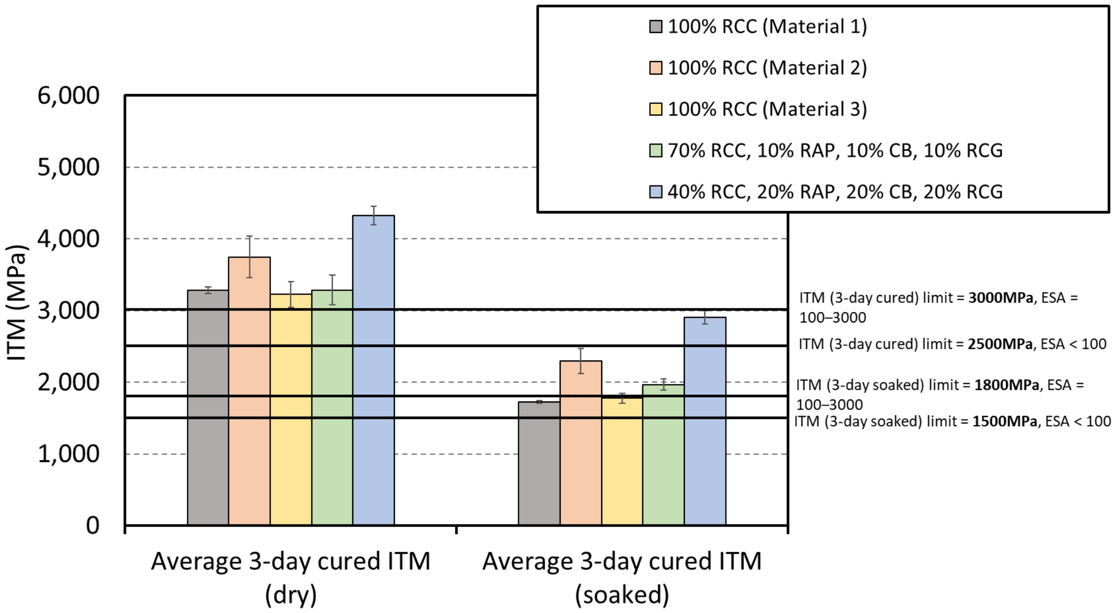


Table 5.3: Summary of the ITM for recycled material blends (Year 2)

Material	Average 3-day cured ITM, dry (MPa)	Average 3-day cured ITM, soaked (MPa)	Average retained modulus (%)	Average bulk density (t/m³)
100% RCC (Material 1)	3,285	1,722	52	1.88
100% RCC (Material 2)	3,747	2,296	61	1.94
100% RCC (Material 3)	3,225	1,779	55	1.95
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	3,285	1,965	60	1.93
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	4,324	2,909	67	1.92

5.2.2 Effect of Curing Time on ITM

Figure 5.3 presents the effect of curing on both dry and soaked ITM of the FBS materials. The influence of curing became more pronounced as the proportion of RCC was replaced with RAP, CB and RCG. As such, the increase of the RAP, CB and RCG content in the blend resulted in generally a higher rate of modulus gain with curing duration, which likely can be attributed to the effects of improved gradation. For example, the 40% RCC blend showed the greatest improvement in ITM with curing duration by more than 30% from around 4,300 to nearly 5,700 in dry conditions.

The relative ITM performance of the recycled blends, all relative to the 40% RCC blend, is indicated by the arrows in Figure 5.3. For example, the 14-day ITM (dry) of the 40% RCC blend is 43.6%, 22.7% and 37% greater than the 100% RCC from Materials 1, 2 and 3, respectively. Similar trends were observed for the soaked ITM results. This emphasises the importance of the original source and grading of the 100% RCC materials on their mechanical performance.

Table 5.4 and Table 5.5 summarise the results of the effect of curing on the ITM of the tested mixes and the ratio of the 14-day/3-day ITM for the dry and soaked conditions, respectively.

Figure 5.3: Effect of curing duration on (a) dry ITM, (b) soaked ITM (Year 2)

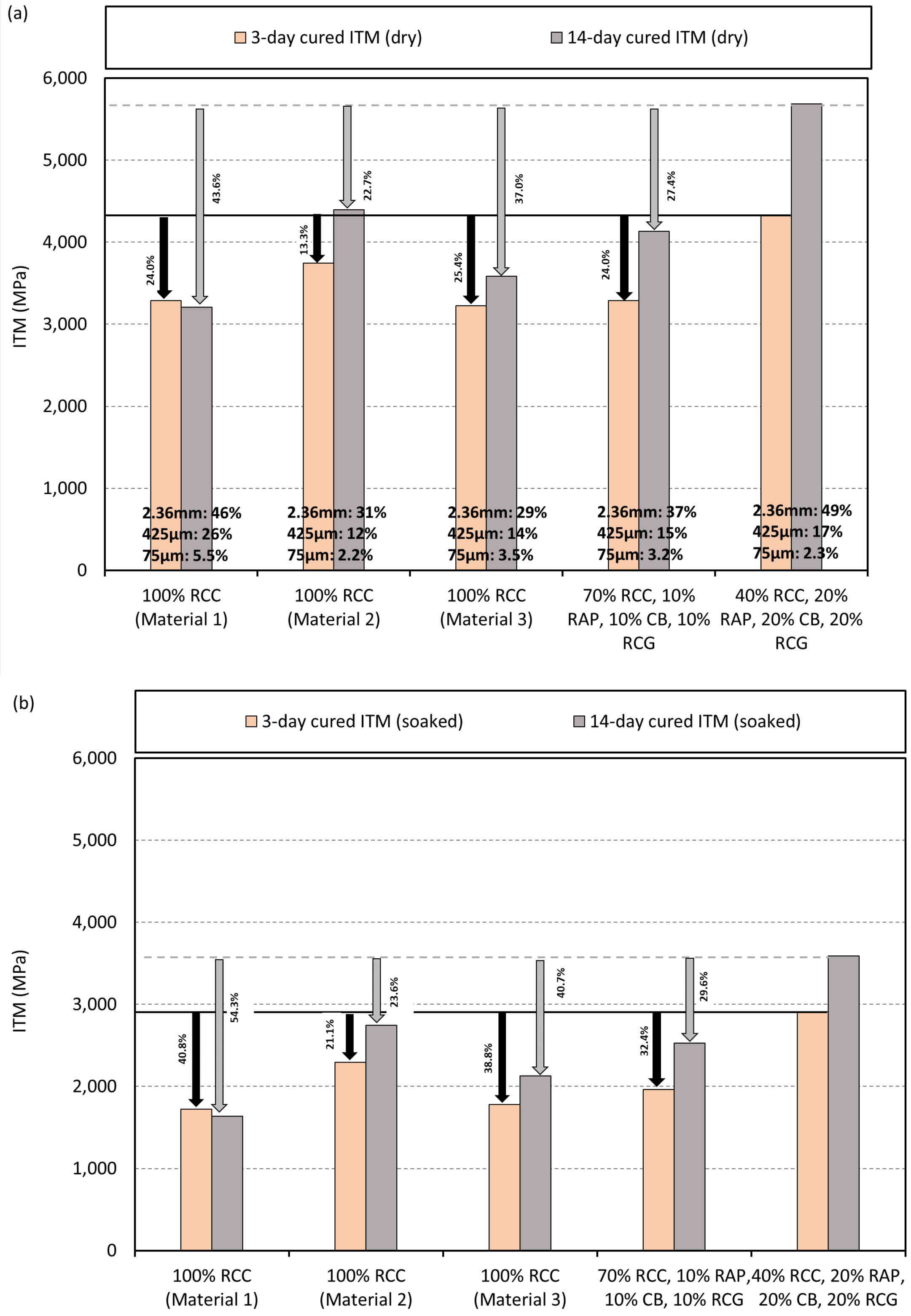


Table 5.4: Effect of curing duration on ITM (dry) (Year 2)

Material	Average 3-day cured (dry) ITm (MPa)	Average 14-day cured (dry) ITm (MPa)	14-day/3-day ITM ratio
100% RCC (Material 1)	3,285	3206	0.98
100% RCC (Material 2)	3,747	4398	1.17
100% RCC (Material 3)	3,225	3583	1.11
70% RCC, 10% RAP, 10% brick,10% glass (Min. blend)	3,285	4131	1.26
40% RCC, 20% RAP, 20% brick, 20% Glass (Max. blend)	4,324	5688	1.32

Table 5.5: Effect of curing duration on ITM (soaked) (Year 2)

Material	Average 3-day cured (soaked) ITm (MPa)	Average 14-day cured (soaked) ITm (MPa)	14-day/3-day ITM ratio
100% RCC (Material 1)	1,722	1,638	0.95
100% RCC (Material 2)	2,296	2,742	1.19
100% RCC (Material 3)	1,779	2,128	1.20
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	1,965	2,527	1.29
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	2,909	3,589	1.23

These results are consistent with the ITM results of Year 1, indicating that replacing RCC proportions with RAP, CB and RCG improved the ITM values and modulus gain over time.

5.3 Indirect Tensile Cracking/Strength – FBS Materials

The cracking test results (CT index) for the 7-day and 14-day cured dry and soaked conditions are presented in Table 5.6. A detailed summary of the results is provided in Appendix D. It should be noted that there are no such CT index requirements for FBS materials in TMR specifications for foamed bitumen stabilised materials.

Figure 5.4, Table 5.7 and Table 5.8 present the ITS of the different FBS recycled blends and the effect of curing on ITS. The figure illustrates that generally, the 40% RCC blend exhibited a higher ITS under 3-day and 14-day cured conditions, particularly in soaked condition. Although, it should be noted that the ITS of 100% RCC materials vary depending on the source and grading of recycled crushed concrete. For example, the 40% RCC blend exhibited similar strength to Material 2 and Material 3 in dry condition (100% RCC blends). The values shown on the arrows indicate the performance of the recycled material blends in relation to the 40% RCC blend.

Also, the 40% RCC blend appeared to have the greatest improvement in strength with curing, with almost 30% improvement after the 14-day curing, compared to one of the 100% RCC blend (Material 1) which had the lowest improvement of about 15%.

Additionally, as the proportion of RCC decreased, the strength retention after soaking seemed to increase. As such, the 100% RCC blend (Material 1) showed 53% reduction in 3-day strength after soaking compared to dry conditions, whilst there was only a 35% and 33% reduction in 3-day strength after soaking in the 70% RCC and 40% RCC blends, respectively.

It should be noted that there are no such ITS requirements for FBS materials. A previous study (Austroads 2002) evaluated the ITS performance of FBS specimens using force control testing as opposed to the strain control testing used in this project.

Table 5.6: CT index results

Material	CT index			
	Average 3-day cured (dry)	Average 3-day cured (soaked)	Average 14-day cured (dry)	Average 14-day cured (soaked)
100% RCC (Material 1)	2.38	2.59	2.58	1.97
100% RCC (Material 2)	5.13	3.24	2.96	5.19
100% RCC (Material 3)	4.57	4.02	3.20	4.14
70% RCC, 10% RAP, 10% CB, 10% RCG	7.75	6.14	3.16	5.16
40% RCC, 20% RAP, 20% CB, 20% RCG	5.73	8.31	2.84	4.13

Figure 5.4: Comparison of ITS of FBS materials (Year 2) (a) dry ITS, (b) soaked ITS

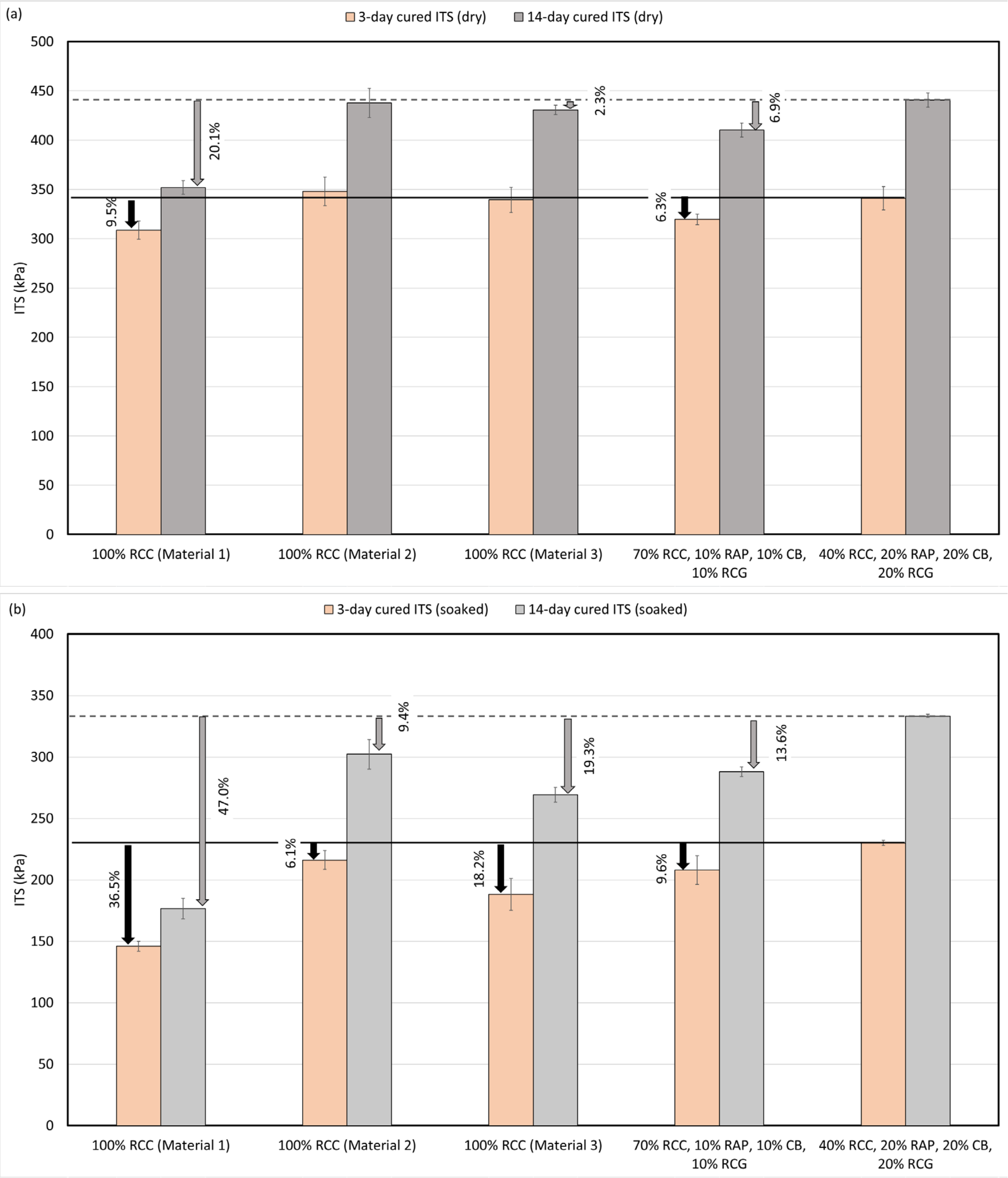


Table 5.7: Effect of curing on ITS (dry) (Year 2)

Material	Average 3-day (dry) ITS (MPa)	Average 14-day (dry) ITS (MPa)	14-day/3-day ITS ratio
100% RCC (Material 1)	309	352	1.14
100% RCC (Material 2)	348	438	1.26
100% RCC (Material 3)	339	431	1.27
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	320	410	1.28
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	341	441	1.29

Table 5.8: Effect of curing on ITS (soaked) (Year 2)

Material	Average 3-day (soaked) ITS (MPa)	Average 14-day (soaked) ITS (MPa)	14-day/3-day ITS ratio
100% RCC (Material 1)	146	177	1.21
100% RCC (Material 2)	216	302	1.40
100% RCC (Material 3)	188	269	1.43
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	208	288	1.39
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	230	333	1.45

5.4 Unconfined Compressive Strength – FBS Materials

The UCS test results of the FBS materials for the 7-day and 28-day curing conditions and the effect of curing on UCS are presented in Figure 5.5 and Table 5.9. A detailed summary of the results is provided in Appendix E. The UCS performance is shown relative to the 40% RCC blend and is indicated by the arrows in Figure 5.5.

Unlike the ITM and ITS assessments of the FBS materials, a reduction in RCC proportion appeared to generally result in a decrease in the UCS of the materials. For example, there was a 50% and 18% difference in the 28-day UCS when RCC (from Materials 2 and 3) decreased from 100% to 40%. It should be noted that the reduction in 28-day UCS was not observed for Material 1 (100% RCC). As such 100% RCC Material 1 showed comparable 28-day UCS compared to the 40% RCC blend, which again emphasised the importance of the recycled materials' source and their individual specific properties.

The 28-day/7-day UCS ratios varied between 1.4 and 1.8. As shown in Table 5.9, there was not a specific trend in the UCS ratio by the replacement of 100% RCC with other recycled blends, and the strength gain was dependent on the specific 100% RCC material.

It should be noted that there are no such TMR or Austroads UCS requirements for FBS materials in Australia.

Figure 5.5: UCS test results of the FBS materials (Year 2)

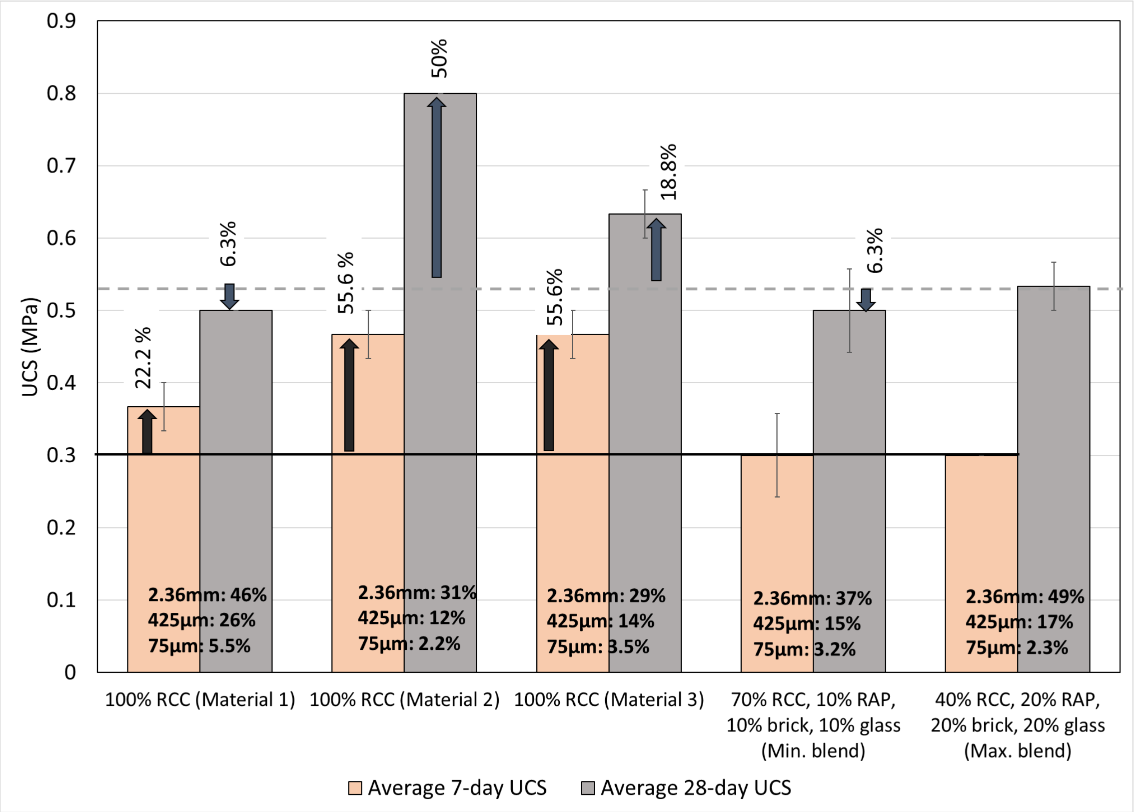


Table 5.9: Summary of UCS test results of the FBS materials (Year 2)

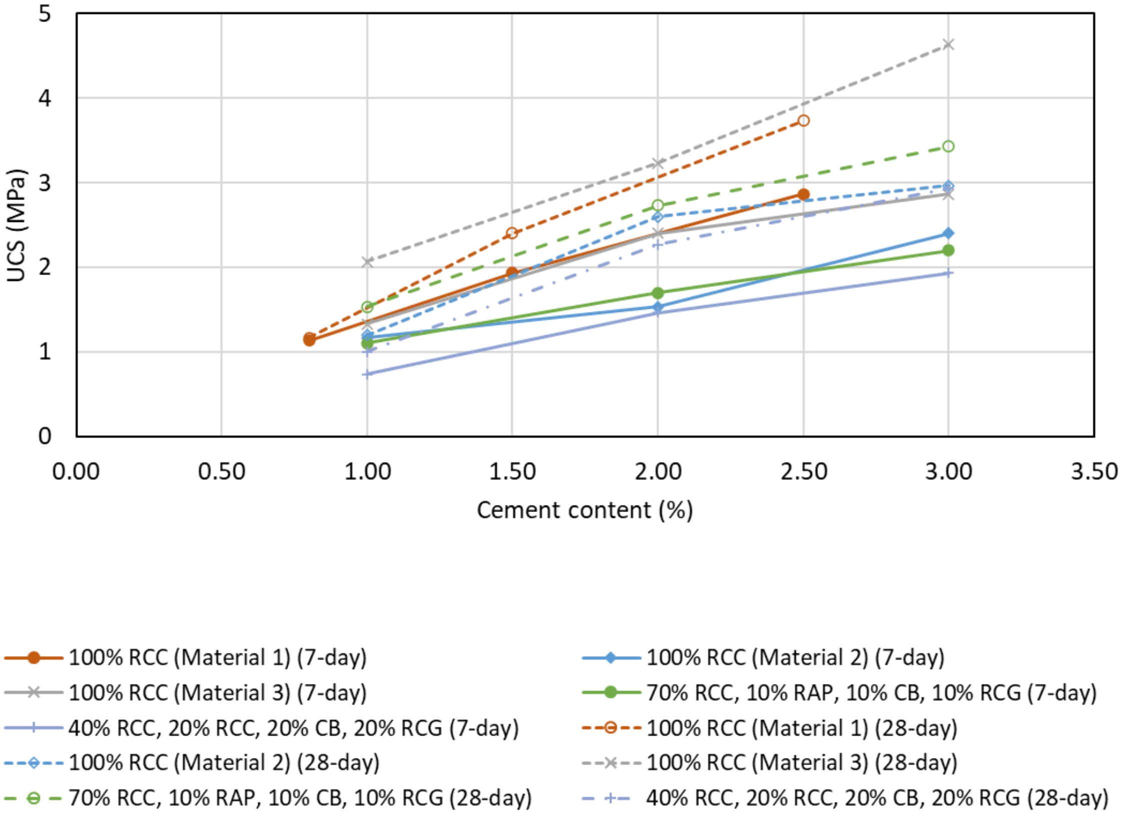
Material	Average 7-day UCS (MPa)	Average 28-day UCS (MPa)	28-day/7-day UCS
100% RCC (Material 1)	0.37	0.50	1.36
100% RCC (Material 2)	0.47	0.80	1.71
100% RCC (Material 3)	0.47	0.63	1.36
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	0.30	0.50	1.67
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	0.30	0.53	1.78

5.5 Unconfined Compressive Strength – Cement Stabilised Material

5.5.1 Effect of Cement Content

Figure 5.6 shows the effect of cement content on UCS values at both 7-day and 28-day curing. Similar to the data from Year 1, the UCS values of the recycled materials increased with the increase in the cement content. However, the degree of improvement varied between each blend.

Figure 5.6: Effect of cement content on UCS (Year 2)



5.5.2 Performance Feasibility

The UCS test results of the cement stabilised materials for the 7-day and 28-day curing conditions are presented in Figure 5.7 and Figure 5.8, respectively. It should be noted that Material 1 (100% RCC) was treated with 0.8%, 1.5% and 2.5% cement contents as opposed to the 1%, 2% and 3% used for all the other recycled blends. The full data containing the results of the UCS test for each tested blend are presented in Appendix F.

Generally, materials treated with 1% to below 2.5% cement content complied with the 7-day UCS requirement for lightly bound improved layer from TMR MRTS10 (2022c), with some exceptions. For example, 100% RCC (Material 3) with 2% cement exceeded the maximum 7-day strength requirement of 2.0 MPa. Also, the 40% RCC blend with 1% cement did not meet the minimum criteria.

Like the 7-day result, recycled materials treated with 1% cement achieved the 28-day strength requirements for lightly bound base/subbase, with the exception of Material 3 (100% RCC) which showed slightly higher UCS than the maximum limit.

All tested materials stabilised with 2% cement or more exceeded the 28-day UCS requirement. As such, the recycled blends tested in the second year of this project stabilised with a cement content greater than 2% generally cannot be considered as lightly bound cemented materials according to the 28-day requirement for lightly bound base/subbase materials.

Overall, the recycled blends in Year 2 treated with 1% cement generally met the available 7-day and 28-day UCS requirements for lightly bound materials, with limited exceptions. This result is contrary to the findings in Year 1 of the project where a higher percentage of cement content was required for the recycled blends to be able to meet the current criteria. This highlights the importance of undertaking individual laboratory assessments and mix designs for each recycled material obtained from specific suppliers, while considering their specific gradations.

Figure 5.7: 7-day UCS test results (Year 2)

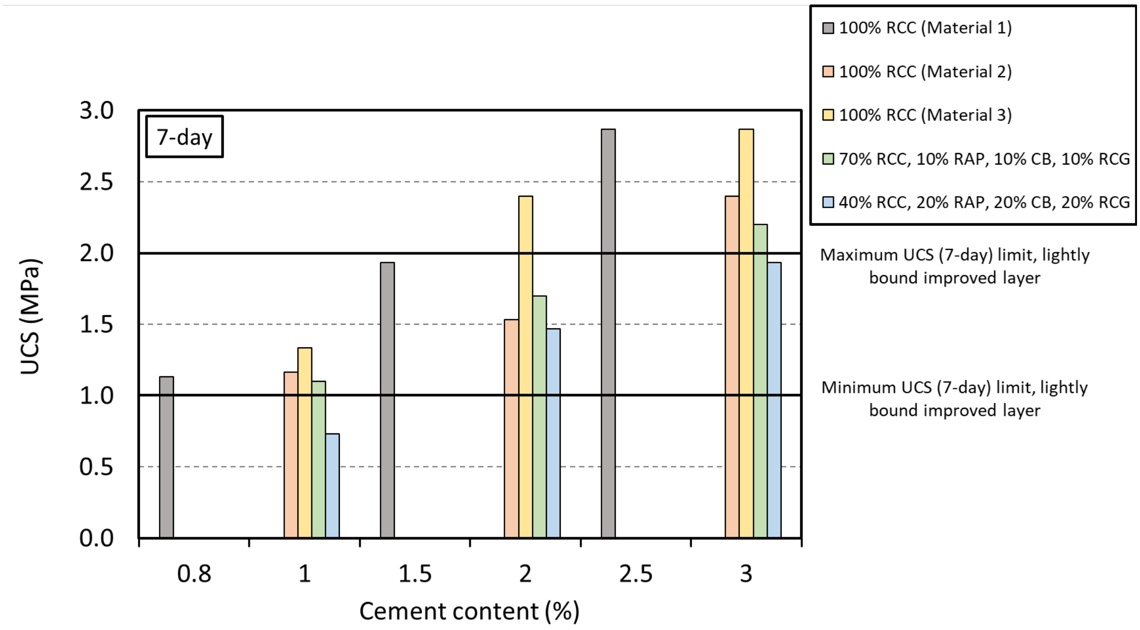
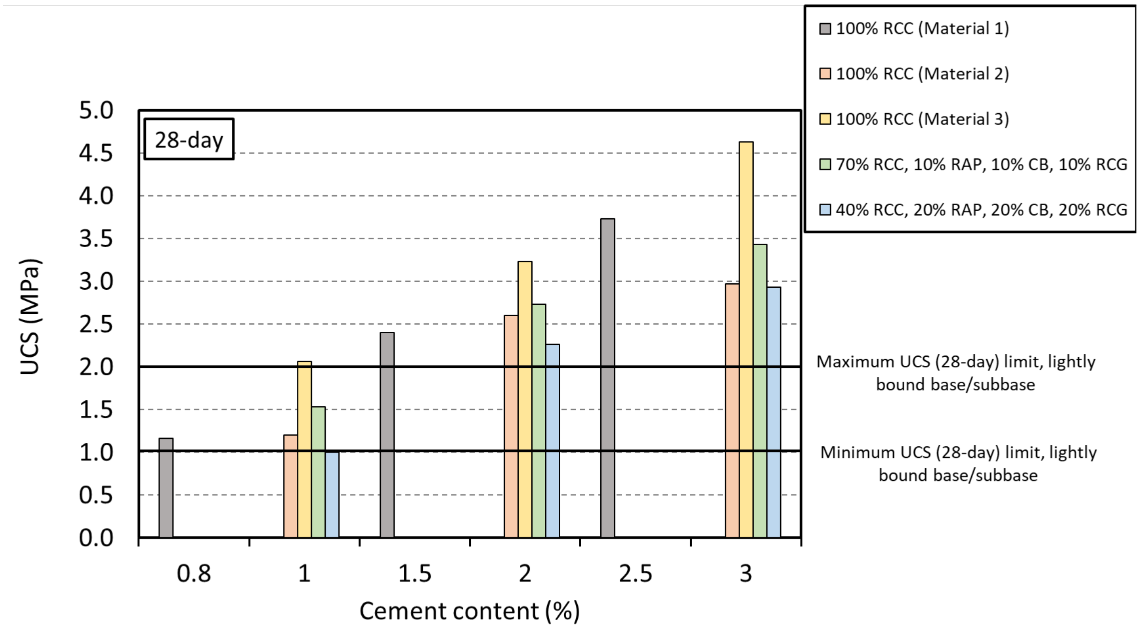


Figure 5.8: 28-day UCS test results (Year 2)



5.5.3 Effect of Curing on UCS

The effect of curing time on the UCS test results for cement contents of 1%, 2% and 3% are presented in Figure 5.9, Figure 5.10, Figure 5.11, respectively. All the relative performance compared to the 40% RCC blend are included in the figures by the arrows. Table 5.10 summaries the UCS results, with the numbers presented in red font indicating non-compliance with TMR MRTS10 (2022c).

As expected, the UCS results showed an increase with curing. The 28-day/7-day UCS ratios varied between 1.03 and 1.70 for different recycled materials with no specific trend observed. It appears that the trend of strength gain is highly dependent on the selection of the specific 100% RCC material used as the reference.

The values shown on the arrows indicate the relative performance of the recycled material blends. For example, for 1% cement content, Material 2, Material 3 and the 70% RCC blend exhibited about 60%, 80% and 50% higher 7-day UCS than 40% RCC blend, respectively. Also, at 28-days, these values were around 20%, 105% and 55%, respectively (again for 1% cement content).

Unlike the UCS results presented for the materials tested in Year 1, a reduction in RCC proportion generally resulted in a decrease in the UCS strength of materials. It is interesting to note that it appears that as cement content increased from 1% to 3%, the reduction in the material's UCS as the result of the replacement of 100% RCC with other recycled blends (i.e. 100% RCC vs 40% RCC) generally decreased.

The allowable working time of the cement stabilised blends are also summarised in Table 5.11.

Figure 5.9: **Effect of curing on the UCS of recycled material blends containing 1% cement (Year 2)**

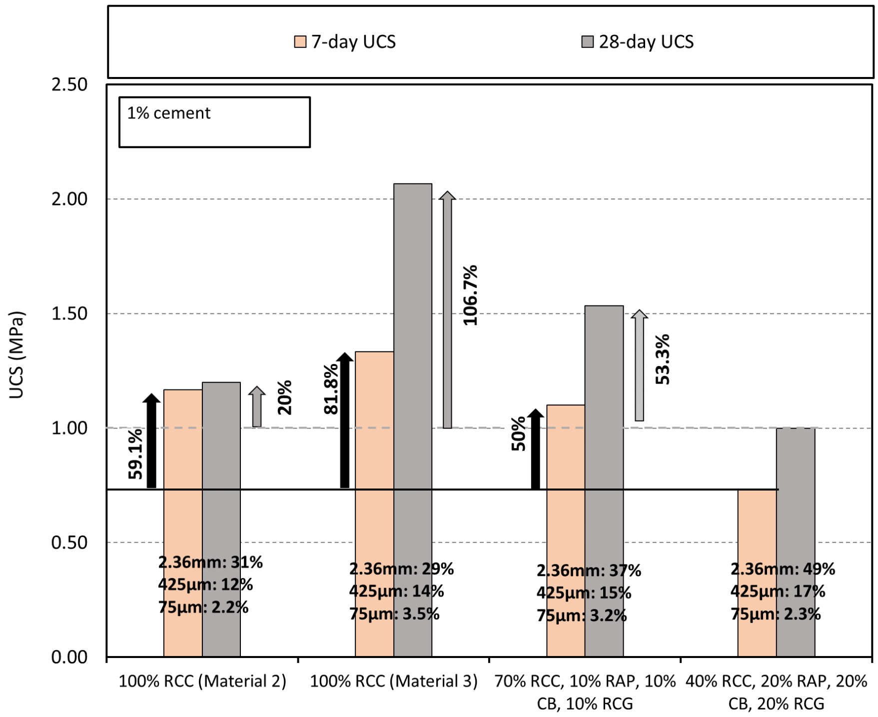


Figure 5.10: Effect of curing on the UCS of recycled material blends containing 2% cement (Year 2)

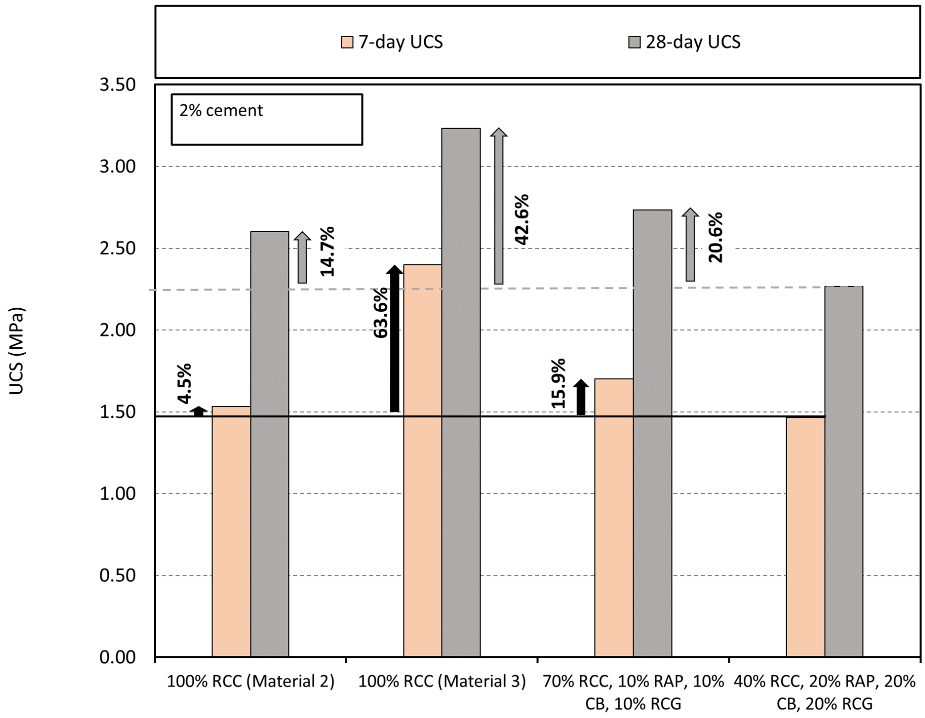


Figure 5.11: Effect of curing on the UCS of recycled material blends containing 3% cement (Year 2)

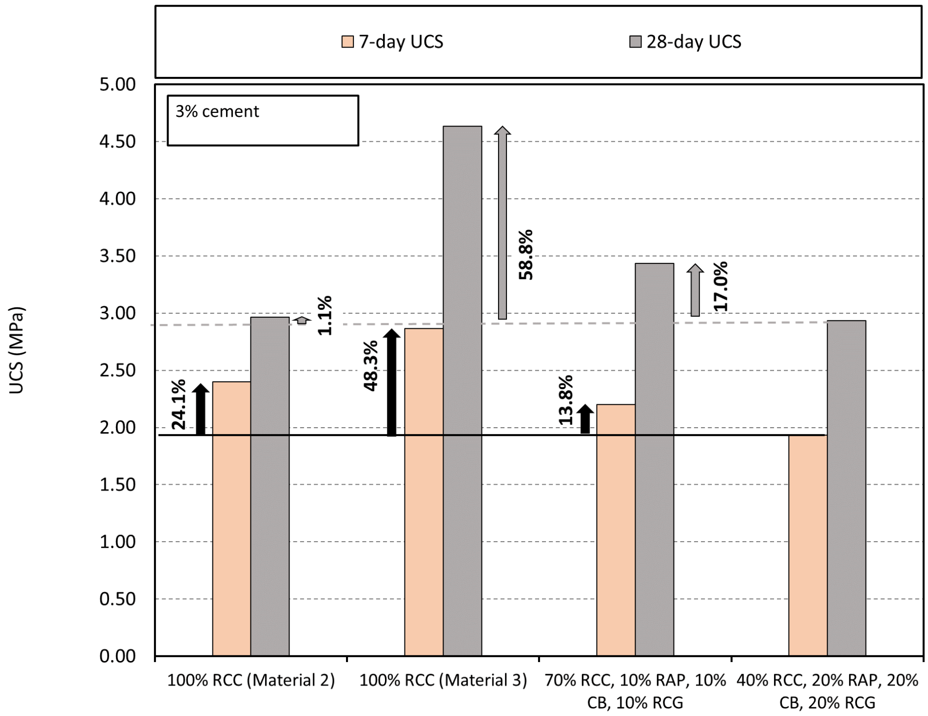


Table 5.10: Summary of the UCS test results (Year 2)

Material	Cement content (%)	Average 7-day UCS (MPa)	Average 28-day UCS (MPa)	28-day/7-day UCS ratio
100% RCC (Material 1)	0.80	1.13	1.17	1.03
	1.50	1.93	2.40	1.24
	2.50	2.87	3.73	1.30
100% RCC (Material 2)	1	1.17	1.20	1.03
	2	1.53	2.60	1.70
	3	2.40	2.97	1.24
100% RCC (Material 3)	1	1.33	2.07	1.55
	2	2.40	3.23	1.35
	3	2.87	4.63	1.62
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	1	1.10	1.53	1.39
	2	1.70	2.73	1.61
	3	2.20	3.43	1.56
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	1	0.73	1.00	1.36
	2	1.47	2.27	1.55
	3	1.93	2.93	1.52

Table 5.11: The allowable working time of the cement stabilised blends (Year 2)

Parameter	100% RCC (Material 1)	100% RCC (Material 2)	100% RCC (Material 3)	70% RCC, 10% RAP, 10% CB, 10% RCG	40% RCC, 20% RAP, 20% CB, 20% RCG
Cement content (%)	1	1.2	1.2	1.2	1.2
Dry density allowable working time (h)	11	5.5	75.5	139.5	10.5
UCS allowable working time (h)	2	2	4.5	2.5	2.5
Allowable working time (h)	2	2	4.5	2.5	2.5

5.6 Mix Design Assessment for Plant-mixed Blends

Similar processes to those detailed in Section 4.4 for the mix design assessment process for plant-mixed blends were undertaken for the materials tested in Year 2.

Figure 5.12 to Figure 5.15 show the acceptable target content range of stabilising agent for different tested materials. These are the results derived from the adopted mix design process.

Figure 5.12: Target contents of stabilising agent for 100% RCC (Material 1) (Year 2)

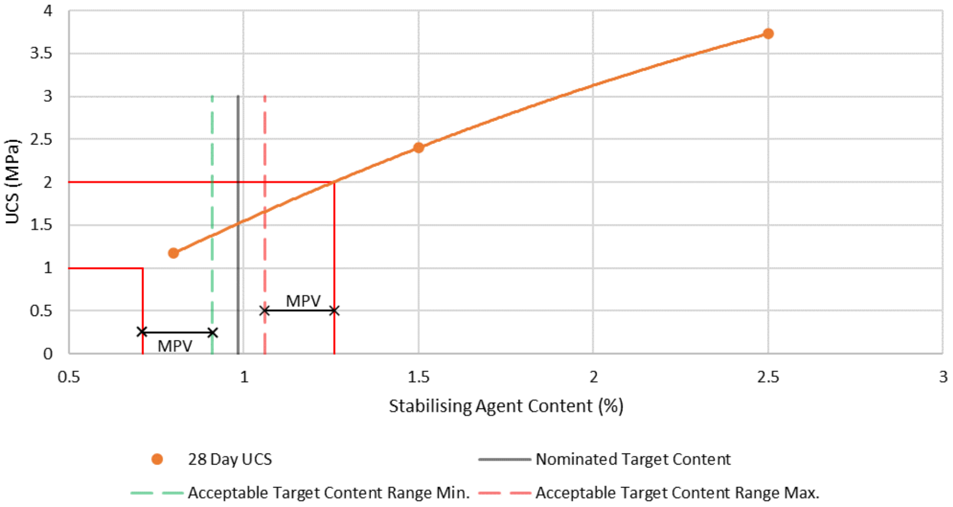


Figure 5.13: Target contents of stabilising agent for 100% RCC (Material 2) (Year 2)

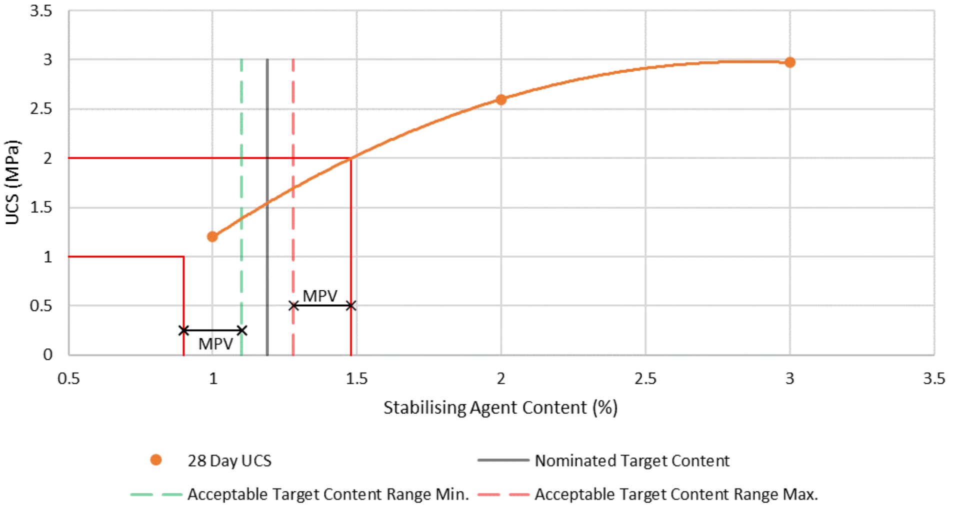


Figure 5.14: Target contents of stabilising agent for 70% RCC blend (Year 2)

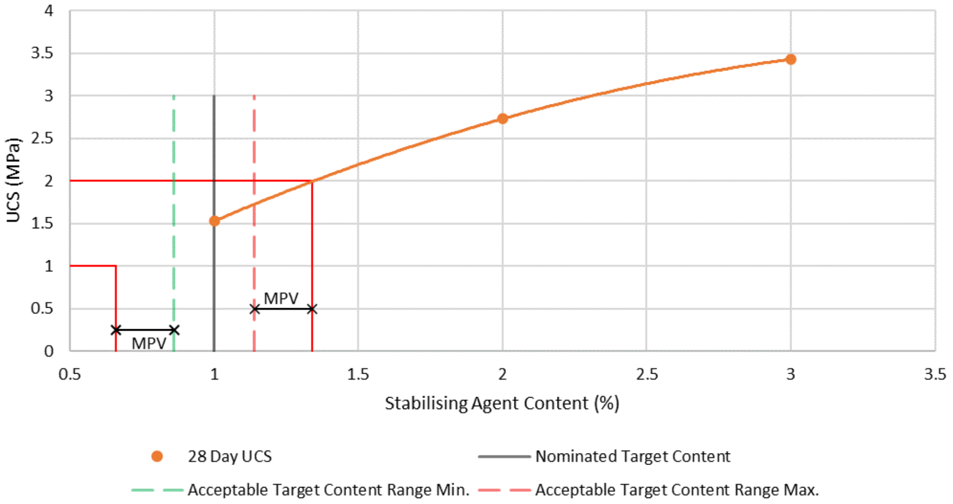
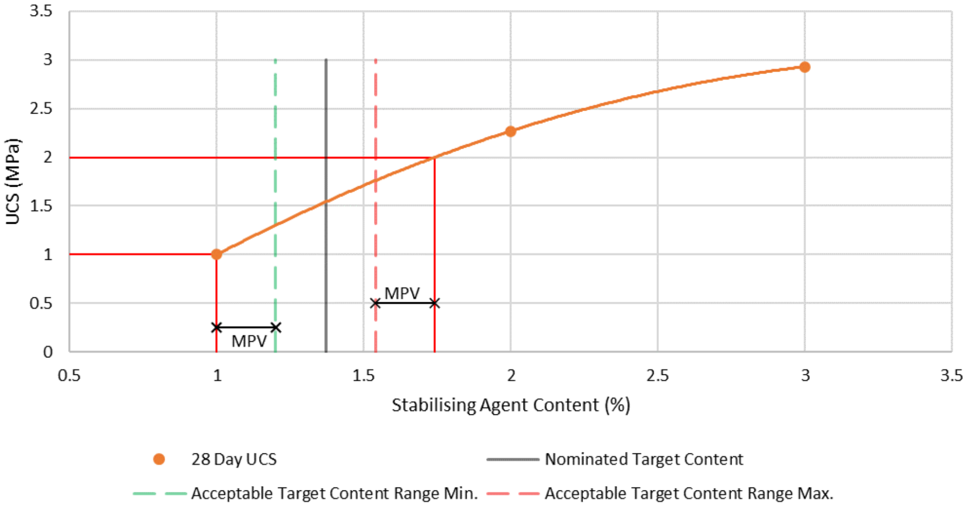


Figure 5.15: Target contents of stabilising agent for 40% RCC blend (Year 2)



6. Summary and Recommendations

This project assessed the performance of recycled material blends stabilised with foamed bitumen and cement through an extensive laboratory testing program. Several laboratory tests were undertaken to characterise the physical, engineering and mechanical properties of the stabilised blends. The blends were assessed to see if they will meet current TMR specification requirements.

Eight recycled material blends were evaluated as part of this project over 2 years (2021–22 and 2022–23). The recycled blends were supplied by 3 different suppliers as already blended materials. Three materials were tested in Year 1 and 5 materials were tested in Year 2. The materials used for laboratory characterisation were recycled crushed concrete (RCC), recycled crushed brick (CB), reclaimed asphalt pavement (RAP) and recycled crushed glass (RCG). The selected recycled blend types for the laboratory investigation included:

- recycled material blend: 100% RCC
- recycled minimum blend: 70% RCC, 10% RAP, 10% CB and 10% RCG
- recycled maximum blend: 40% RCC, 20% RAP, 20% CB and 20% RCG.

For the foamed bitumen stabilised blends, the indirect tensile modulus (ITM) test was carried out to investigate the resilient modulus of the materials. Additionally, in the second year of the project (2022–23), the recycled blends stabilised with foamed bitumen were also tested for indirect tensile cracking/strength (ITS) and unconfined compressive strength (UCS). To assess the strength properties of the cement stabilised recycled blends, the unconfined compressive strength (UCS) test was conducted. These tests were accompanied by a range of initial physical characteristics of the selected materials.

6.1 Key Findings

It was found that stabilised recycled material blends generally satisfied the current TMR specification mix design testing requirements for lightly bound and foamed bitumen stabilised materials. To assure conformance, care must be taken with project specific mix design and selection of constituent /blends.

This is consistent with TMR specification requirements based on which mix design testing is required for any candidate stabilised material, to assess if the material is suitable for stabilisation and to determine the optimal additive(s) type and amount for the candidate material.

6.2 Detailed Findings

The following detailed conclusions can be made based on the experimental investigations:

PSD of the recycled materials

- In Year 1 (2021–22):
  - The PSD of the 40% RCC blend almost fell within the specified limits of TMR MRTS05 (2022a) for recycled material blends, while the PSD of the 70% RCC blend was marginally below the lower limit. The 100% RCC material did not meet the PSD requirement.
  - The most noticeable gradation deficiency was the limited portion of fines content for the 100% RCC and 70% RCC blend, which could significantly affect the modulus and strength properties.
- In Year 2 (2022–23):
  - The PSD of the 70% RCC blend conformed to all TMR MRTS05 (2022a) grading requirements. The 40% RCC blend almost fell within the specified limits.
  - The three 100% RCC materials almost met the TMR MRTS05 (2022a) grading requirements with slight non-conformance for Materials 2 and 3 for one sieve size.

Foamed bitumen stabilised recycled blends

- The ITM testing results indicated that generally, the ITM increased with partial replacement of the RCC with RAP, CB and RCG. This could be primarily attributed to the improvement of the gradation of the blends in terms of the portion of fines and sand-sized aggregates, which in turn enhanced the mechanical properties of the mixes. Additionally, a better performance in the blends including RAP might be due to the contribution of the aged bitumen from the RAP in those mixes. It should be noted that the increase in ITM from the 100% RCC to 40% RCC blend was more significant in Year 1 materials. This could be attributed to the fact that the 100% RCC (in Year 1) had some gradation deficiency, and its grading did not meet the PSD requirement.
- Among the tested blends in Year 1, the 40% RCC blend was the only material that met the requirements of the 3-day dry and soaked ITM for ESA < 100 and ESA = 100–3,000, specified by TMR MRTS09 (2021a). The 70% RCC blend met the requirements for only ESA < 100, while the 100% RCC failed to comply with any of the ITM requirements.
  However, all the recycled blends evaluated in Year 2 met the requirements of the 3-day dry ITM for ESA = 100–3,000. Two of the 100% RCC materials did not meet the soaked ITM requirement for traffic greater than 100 ESA. Nonetheless, all investigated blends met the retained modulus requirement.
  It was concluded that the performance of 100% RCC may vary depending on the source of the recycled materials, their PSD, and other physical properties.
- The dry density of the compacted foamed bitumen specimens increased with the partial replacement of the RCC with RAP, CB and RCG. However, this was not observed in the recycled blends tested in Year 2, and it was again dependent on the source of the 100% RCC.
- As expected, the ITM of the FBS materials increased with the curing time for both dry and soaked conditions. The enhancement in ITM was generally more significant for the 40% RCC blend, particularly in dry condition, and was the least for the 100% RCC. This indicated that the partial replacement of RCC with RAP, CB and RCG generally improved the rate of modulus gain.

Cementitious stabilised recycled blends

- As expected, the UCS values increased with the increase in cement content. However, the rate of the strength gain was different between various mixes.
- Contrary findings were found for the 7-day UCS test results in terms of meeting the lightly bound materials requirements depending on the recycled material’s source and gradation. For example, based on the recycled blends tested in the first year of this project, the 7-day UCS test results showed that all blends with 4% cement met the TMR requirements for a lightly bound improved layer. Also, only 70% RCC and 40% RCC blends with 2.5% cement met the 7-day UCS requirements, and none of the blends with 1% cement met the requirements. While in Year 2, recycled blends treated with 1% to below 2.5% cement content generally complied with the TMR 7-day UCS requirement, with some exceptions.
- Like the 7-day UCS results, the materials tested in Years 1 and 2 showed different performance in terms of 28-day UCS. For example, in Year 1, the 40% RCC blend was the only material with 1% cement that just met the minimum requirement for 28-day UCS of lightly bound base/subbase. All 3 materials with 2.5% and 4% cement contents complied with the 28-day UCS requirements except the 40% RCC blend with 4% cement, which showed a higher UCS than the maximum limit. In contrast, the Year 2 materials treated with 1% cement generally achieved the 28-day strength requirements. Also, all tested materials stabilised with 2% cement or more exceeded the 28-day UCS requirement and cannot be considered lightly bound cemented materials.
- Overall, the above 2 findings about the UCS test results of cement stabilised materials concluded that the recycled blends in Year 2 treated with 1% cement generally met both 7-day and 28-day UCS requirements for lightly bound materials, with limited exceptions. This result was in contrast to the findings in Year 1 where a higher percentage of cement was required for the blends to meet the current criteria. This highlights the significance of undertaking individual laboratory assessments and mix designs for each recycled material obtained from specific suppliers to fully understand their performance and engineering characteristics based on their grading, fines content and potentially other physical characteristics.
- Unlike the UCS results of the materials tested in Year 1, in Year 2, a reduction in RCC proportion generally resulted in a decrease in the UCS of the materials.

- The 28-day/7-day UCS ratio varied between 1.03 and 1.70 for different recycled materials with no specific trend observed. It appears that the trend of strength gain is dependent on the selection of the specific 100% RCC material used as the reference.

Overall, the results indicated that foamed bitumen stabilisation and cement stabilisation are feasible and viable methods to improve the engineering properties of recycled material blends. The combined project findings from the 2 years assessing several different recycled blends from 3 different suppliers suggest that the recycled material blends treated with cement or foamed bitumen can generally satisfy the TMR specification requirements for lightly bound and FBS materials. However, the performance variations observed between different blends indicate that the mechanical characterisation of RCC blends is impacted by the combined effects of physical properties such as grading, Atterberg limits, materials structure, etc. as well as materials source. It was shown that RCC with poor gradations can be blended with other recycled materials (i.e. RCG) to adjust for grading deficiencies. Conducting individual laboratory assessments and mix designs for each recycled material was highlighted to accurately understand their mechanical performance relative to the current requirements. Although the cement and/or foamed bitumen stabilisation of recycled blends can improve the properties of recycled material blends for pavement applications, given the possible variability in the gradation and physical characteristics of these materials, further research in this area can improve confidence to use stabilised recycled materials in roads for pavement construction and maintenance.

This project will continue in 2023–24 to focus on possible field trials, as also supported by the findings from the laboratory testing phases, to assess and monitor the performance of stabilised recycled materials in an actual pavement structure. It is expected that the findings of this project will provide new insight into the suitability and optimisation of various recycled material blends for foamed bitumen and cement stabilisation.

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1. ITM Test Data (Year 1)

Table A.1: 3-day cured ITM data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	3-day cured ITM (MPa)				Retained modulus (%)	Average retained modulus (%)
			ITM (dry)	Average ITM (dry)	ITM (soaked)	Average ITM (soaked)		
100% RCC	65.8	152.5	3,017	2,306	1,573	1,321	52	59
	66	152.7	1,501		1,003		67	
	65.3	152.5	2,399		1,388		58	
70% RCC, 10% RAP, 10% CB, 10% RCG	67.3	152.5	3,239	2,920	1,774	1,703	55	58
	66.8	152.6	2,990		1,886		63	
	66.9	152.5	2,532		1,450		57	
40% RCC, 20% RAP, 20% CB, 20%RCG	69.2	152.5	3,819	3,956	2,126	2,275	56	57
	69.2	152.6	3,992		2,280		57	
	69.5	152.5	4,058		2,420		60	

Table A.2: 14-day cured ITM data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	14-day cured ITM (MPa)				Retained modulus (%)	Average retained modulus (%)
			ITM (dry)	Average ITM (dry)	ITM (soaked)	Average ITM (soaked)		
100% RCC	65.5	152.5	2,292	2,091	1,465	1,336	64	64.9
	66.1	152.4	1,604		1,174		73	
	65.6	152.7	2,376		1,370		58	
70% RCC, 10% RAP, 10% CB, 10% RCG	68.1	152.4	3,844	3,272	2,262	1,945	59	59.5
	67.7	152.6	3,047		1,765		58	
	67.4	152.4	2,926		1,808		62	
40% RCC, 20% RAP, 20% CB, 20% RCG	69.7	152.4	4,890	5,212	2,890	2,973	59	57.1
	70	152.5	5,045		2,782		55	
	70.2	152.3	5,701		3,247		57	

2. UCS Test Data (Year 1)

Table B.1: UCS test data of the tested recycled material blends

Material	Cement content (%)	7-day UCS (MPa)	Average 7-day UCS (MPa)	28-day UCS (MPa)	Average 28-day UCS (Mpa)	28-day/ 7-day UCS ratio	Average 28-day/ 7-day UCS ratio
100% RCC	1	0.40	0.40	0.60	0.57	1.50	1.42
		0.40		0.50		1.25	
		0.40		0.60		1.50	
	2.5	0.80	0.80	1.00	1.00	1.25	1.25
		0.80		1.00		1.25	
		0.80		1.00		1.25	
	4	1.00	1.00	1.40	1.40	1.40	1.40
		1.00		1.40		1.40	
		1.00		1.40		1.40	
70% RCC, 10% RAP, 10% CB, 10% RCG	1	0.60	0.60	0.80	0.77	1.33	1.28
		0.60		0.70		1.17	
		0.60		0.80		1.33	
	2.5	1.00	1.00	1.40	1.40	1.40	1.40
		1.00		1.40		1.40	
		1.00		1.40		1.40	
	4	1.20	1.33	1.80	1.83	1.50	1.38
		1.40		1.90		1.36	
		1.40		1.80		1.29	
40% RCC, 20% RAP, 20% CB, 20% RCG	1	0.80	0.70	1.00	1.00	1.25	1.45
		0.60		1.00		1.67	
		0.70		1.00		1.43	
	2.5	0.80	1.27	1.80	1.97	2.25	1.66
		1.50		2.20		1.47	
		1.50		1.90		1.27	
	4	2.00	1.90	2.60	2.63	1.30	1.39
		1.80		2.60		1.44	
		1.90		2.70		1.42	

3. ITM Test Data (Year 2)

Table C.1: 3-day cured ITM data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	3-day cured ITM (MPa)				Retained modulus (%)	Average retained modulus (%)
			ITM (dry)	Average ITM (dry)	ITM (soaked)	Average ITM (soaked)		
100% RCC (Material 1)	66.6	152.2	3,191	3,285	1,734	1,722	54	52
	67.3	152.2	3,347		1,746		52	
	67.4	152.2	3,317		1,685		51	
100% RCC (Material 2)	67.7	152.1	3,797	3,747	2,311	2,296	61	61
	67.8	152.1	3,223		1,984		62	
	67.7	152.1	4,220		2,592		61	
100% RCC (Material 3)	67.9	152.4	3,128	3,225	1,763	1,779	56	55
	68.4	152.3	2,976		1,667		56	
	68.6	152.2	3,570		1,906		53	
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	68.7	152.3	3,694	3,285	2,118	1,965	57	60
	68.7	152.4	3,128		1,920		61	
	69	152.3	3,033		1,857		61	
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	68.7	152.3	4,297	4,324	2,821	2,909	66	67
	68.7	152.3	4,113		2,811		68	
	69	152.2	4,561		3,094		68	

Table C.2: 14-day cured ITM data of the tested recycled material blends

			14-day cured ITM (MPa)					
Sample ID	Mean height (mm)	Mean diameter (mm)	ITM (dry)	Average ITM (dry)	ITM (soaked)	Average ITM (soaked)	Retained modulus (%)	Average retained modulus (%)
100% RCC (Material 1)	67.1	152	3,188	3,206	1,543	1,638	48	51
	67.4	152.1	3,251		1,678		52	
	67.1	152.2	3,180		1,694		53	
100% RCC (Material 2)	68.1	152.3	4,923	4,398	3,053	2,742	62	63
	68.4	152.2	3,574		2,329		65	
	67.8	152.3	4,696		2,845		61	
100% RCC (Material 3)	68.7	152.2	3,643	3,583	2,114	2,128	58	59
	68.4	152.1	3,816		2,373		62	
	68.4	152.1	3,290		1,896		58	
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	69	152.2	4,258	4,131	2,609	2,527	61	61
	68.4	152.2	4,036		2,476		61	
	68.7	152.3	4,100		2,497		61	
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	69.2	152.3	5,697	5,688	3,637	3,589	64	63
	69.3	152.3	5,315		3,458		65	
	69.3	152.2	6,053		3,671		61	

4. ITC Test Data (Year 2)

Table D.1: 3-day ITC data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	Peak load (N)	Displacement at l_{75} (mm)	Post peak slope (N/m)	Failure energy (Joules/m^2)	Work of failure (Joules)	Cracking tolerance (CT$_{index}$)
100% RCC (Material 1)	67.5	152.2	4,958	1.49	3,458,003	720	7.39	2.21
	67.5	152.1	5,246	1.51	3,192,147	805	8.26	2.73
	67.6	152.2	4,747	1.46	3,219,057	674	6.94	2.19
100% RCC (Material 2)	68.5	152.2	5,564	1.76	2,745,130	936	9.74	4.32
	68.5	152.2	5,377	1.9	2,186,417	1,065	11.11	6.7
	68.2	152.2	6,141	2.02	3,463,313	1,026	10.65	4.34
100% RCC (Material 3)	68.5	152.5	5,200	2.01	2,623,127	930	9.72	5.15
	67.8	152.2	5,847	1.9	3,037,465	1,051	10.84	4.71
	68.1	152.3	5,550	1.96	3,125,137	848	8.8	3.84
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	69.1	152.2	5,110	2.16	2,088,325	1,096	11.53	8.28
	68.6	152.3	5,381	2.13	2,296,072	1,081	11.29	7.29
	69.2	152.3	5,332	2.12	2,224,741	1,100	11.6	7.67
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	69.1	152.2	5,110	2.16	2,088,325	1,096	11.53	8.28
	68.6	152.3	5,381	2.13	2,296,072	1,081	11.29	7.29
	69.2	152.3	5,332	2.12	2,224,741	1,100	11.6	7.67

Table D.2: 3-day (soaked) ITC data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	Peak load (N)	Displacement at l75	Post peak slope (N/M)	Failure energy (Joules/m2)	Work of failure (Joules)	Cracking tolerance (CTindex)
100% RCC (Material 1)	67.2	152.2	2,472	1.37	1,564,087	360	3.68	2.25
	67.6	152.2	2,304	1.48	1,274,927	372	3.83	3.08
	67.2	152.1	2,271	1.46	1,379,061	325	3.32	2.44
100% RCC (Material 2)	68.3	152.3	3,568	1.41	2,142,694	575	5.98	2.74
	68.8	152.2	3,320	1.51	1,802,389	559	5.86	3.41
	67.8	152.2	3,697	1.48	1,837,474	616	6.36	3.58
100% RCC (Material 3)	68.7	152.2	2,722	1.89	1,433,731	493	5.15	4.73
	68.5	152.3	3,453	1.81	1,828,086	622	6.49	4.46
	68	152.2	3,057	1.61	1,942,790	480	4.97	2.87
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	68.6	152.3	3,539	1.89	1,604,633	672	7.02	5.74
	69.1	152.2	3,059	1.85	1,326,959	608	6.39	6.19
	68.4	152.3	3,646	1.96	1,607,887	735	7.65	6.48
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	69.1	152.3	3,831	2.21	1,294,439	856	9	10.67
	69.1	152.3	3,736	2.04	1,448,271	724	7.62	7.45
	69.1	152.3	3,840	1.93	1,584,983	764	8.05	6.81

Table D.3: 14-day ITC data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	Peak load (N)	Displacement at l75	Post peak slope (N/M)	Failure energy (Joules/m2)	Work of failure (Joules)	Cracking tolerance (CTindex)
100% RCC (Material 1)	67.7	152.2	5,864	1.48	3,987,870	787	8.11	2.09
	67.4	152.1	5,459	1.59	3,325,266	904	9.26	3.09
	67.5	152.1	5,718	1.54	3,919,666	913	9.37	2.57
100% RCC (Material 2)	68	152.2	6,798	1.76	5,127,317	770	7.97	1.9
	68.1	152.2	6,974	1.65	3,875,967	1,147	11.88	3.52
	68.1	152.3	7,607	1.92	4,510,963	1,124	11.66	3.46
100% RCC (Material 3)	68.3	152.1	7,176	1.81	3,521,047	1,213	12.61	4.51
	68.7	152.1	7,038	1.43	5,443,871	969	10.13	1.85
	68.2	152.2	6,902	1.82	4,318,355	1,069	11.09	3.25
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	69	152.2	6,553	1.86	4,436,299	963	10.11	2.95
	68.8	152.2	6,944	1.9	4,259,735	1,093	11.45	3.55
	69.2	152.2	6,806	1.63	3,976,904	994	10.47	2.98
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	69.1	152.2	7,063	1.55	3,937,439	1,107	11.65	3.19
	69.6	152.1	7,350	1.28	4,541,365	1,017	10.77	2.11
	69.2	152.1	7,480	1.58	4,581,308	1,272	13.39	3.23

Table D.4: 14-day (saoked) ITC data of the tested recycled material blends

Sample ID	Mean height (mm)	Mean diameter (mm)	Peak load (N)	Displacement at l75	Post peak slope (N/M)	Failure energy (Joules/m2)	Work of failure (Joules)	Cracking tolerance (CTindex)
100% RCC (Material 1)	67.4	152.2	3,088	1.43	2,023,305	379	3.88	1.91
	67.4	152.1	2,624	1.75	1,727,006	312	3.21	2.27
	67.5	152.1	2,831	1.37	2,051,177	365	3.75	1.74
100% RCC (Material 2)	68.2	152.2	4,854	2	2,295,429	934	9.7	5.87
	68.6	152.2	5,328	2.32	2,486,097	1,086	11.33	7.36
	68.6	152.2	4,659	1.52	2,969,638	630	6.57	2.34
100% RCC (Material 3)	68.3	152.1	4,447	1.73	2,564,177	702	7.29	3.42
	68.7	152.1	4,227	1.73	2,050,292	764	7.98	4.69
	68.5	152.2	4,545	1.83	2,538,577	820	8.54	4.3
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	68.5	152.2	4,812	1.82	2,351,077	882	9.19	4.95
	69	152.2	4,628	1.84	2,263,618	815	8.56	4.84
	69	152.3	4,784	1.93	2,170,380	876	9.2	5.69
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	69.4	152.1	5,547	1.77	2,579,562	986	10.4	4.97
	69.2	152.1	5,533	1.59	3,479,953	786	8.27	2.63
	69.3	152.1	5,480	1.94	2,755,747	927	9.77	4.78

5. UCS Test Data of FBS Materials (Year 2)

Table E.1: UCS test data of the tested recycled material blends (7-day)

Sample ID	Achieved density (t/m³)	Achieved moisture content (%)	UCS (MPa)	Mean UCS (MPa)
100% RCC (Material 1)	1.72	9.7	0.3	0.4
	1.72		0.4	
	1.72		0.4	
100% RCC (Material 2)	1.75	10.0	0.5	0.5
	1.73		0.4	
	1.72		0.5	
100% RCC (Material 3)	1.75	8.8	0.4	0.3
	1.74		0.2	
	1.74		0.3	
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	1.75	8.6	0.4	0.3
	1.74		0.2	
	1.74		0.3	
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	1.77	9.2	0.3	0.3
	1.78		0.3	
	1.77		0.3	

Table E.2: UCS test data of the tested recycled material blends (28-day)

Sample ID	Achieved density (t/m³)	Achieved moisture content (%)	UCS (MPa)	Mean UCS (MPa)	28-day/7-day UCS
100% RCC (Material 1)	1.73	9.6	0.5	0.5	1.4
	1.73		0.5		
	1.72		0.5		
100% RCC (Material 2)	1.72	10.4	0.8	0.8	1.7
	1.72		0.8		
	1.72		0.8		
100% RCC (Material 3)	1.75	8.8	0.6	0.6	2.1
	1.75		0.7		
	1.77		0.6		
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	1.73	8.5	0.4	0.5	1.7
	1.75		0.6		
	1.74		0.5		
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	1.78	9.0	0.5	0.5	1.8
	1.78		0.5		
	1.77		0.6		

6. UCS Test Data of Cement Stabilised Materials (Year 2)

Table F.1: UCS test data of the cement stabilised recycled material blends

Sample ID	Cement content (%)	7-day UCS (MPa)	Average 7-day UCS (MPa)	28-day UCS (MPa)	Average 28-day UCS (MPa)	28-day/ 7-day	Average 28-day/ 7-day ratio
100% RCC (Material 1)	0.8	1.2	1.13	1.2	1.17	1.0	1.03
		1.2		1.2		1.0	
		1		1.1		1.1	
	1.5	1.8	1.93	2.4	2.40	1.3	1.24
		2		2.4		1.2	
		2		2.4		1.2	
	2.5	2.8	2.87	3.6	3.73	1.3	1.30
		3		3.6		1.2	
		2.8		4		1.4	
100% RCC (Material 2)	1.0	1.3	1.17	1.2	1.20	0.9	1.03
		1		1.2		1.2	
		1.2		1.2		1.0	
	2.0	1.3	1.53	2.6	2.60	2.0	1.70
		1.7		2.7		1.6	
		1.6		2.5		1.6	
	3.0	2.7	2.40	3.4	2.97	1.3	1.24
		2.2		2.9		1.3	
		2.3		2.6		1.1	
100% RCC (Material 3)	1.0	1.2	1.33	2.1	2.07	1.8	1.55
		1.5		2		1.3	
		1.3		2.1		1.6	
	2.0	2.6	2.40	3.5	3.23	1.3	1.35
		2.3		3.2		1.4	
		2.3		3		1.3	
	3.0	2.8	2.87	4.6	4.63	1.6	1.62
		3		4.6		1.5	
		2.8		4.7		1.7	
70% RCC, 10% RAP, 10% brick, 10% glass (Min. blend)	1.0	1.1	1.10	1.3	1.53	1.2	1.39
		1.1		1.7		1.5	
		1.1		1.6		1.5	
	2.0	1.7	1.70	2.9	2.73	1.7	1.61
		1.8		2.6		1.4	
		1.6		2.7		1.7	
	3.0	2.1	2.20	3.4	3.43	1.6	1.56
		2.1		3.4		1.6	
		2.4		3.5		1.5	

Sample ID	Cement content (%)	7-day UCS (MPa)	Average 7-day UCS (MPa)	28-day UCS (MPa)	Average 28-day UCS (MPa)	28-day/ 7-day	Average 28-day/ 7-day ratio
40% RCC, 20% RAP, 20% brick, 20% glass (Max. blend)	1.0	0.8	0.73	1	1.00	1.3	1.36
		0.7		1		1.4	
		0.7		1		1.4	
	2.0	1.4	1.47	2.3	2.27	1.6	1.55
		1.5		2.3		1.5	
		1.5		2.2		1.5	
	3.0	1.9	1.93	3.1	2.93	1.6	1.52
		1.9		3		1.6	
		2		2.7		1.4	