University of Southern Queensland

Faculty of Health, Engineering and Sciences

Suitability Of Recycled Crushed Glass as a Replacement for Natural Sand in Concrete

A dissertation submitted by

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ABSTRACT

Research into recycled crushed glass (RCG) as a potential replacement for fine aggregates has attracted notable interest worldwide. This experimental study aims to build on existing literature (Guo et al. 2020) and progress further by testing the RCG percentage in the test specimens from 20% to 40% RCG in lieu of natural sand, thereby measuring the mechanical physical properties of the concrete samples.

The current published literature shows data inconsistencies that have affected consumer confidence.

This project aims to find the causes of inconsistent results for concrete samples with RCG, reach a consensus on the effects of recycled crushed glass in concrete, provide consistent experimental evidence that supports the use of recycled crushed glass in concrete, and determine the appropriate mix ratios of recycled crushed glass in concrete, that will give adequate compressive strength, flexural strength, split-tensile strength, slump values, durability, and appearance.

The development of an optimum mix design will provide consumer confidence in the RCG material as it ensures consistent physical and mechanical properties can be achieved with each mix when the correct mix design process is followed, as outlined in this report.

As recycled crushed glass is a more sustainable form of aggregate when compared to natural sand, reducing the depletion of natural sand deposits will provide significant environmental benefits worldwide. This report demonstrates that this alternative material can now be successfully utilised in some applications and at low RCG replacement percentages which allows for a more sustainable solution to be adopted.

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ABBREVIATIONS

RCG: Recycled Crushed Glass

CWG: Coarse Waste Glass

FWG: Fine Waste Glass

WHS: Work, Health, and Safety

PC: Pervious Concrete

WC: Water Content

CSC: Concrete Slump Chart

MPa: Megapascals

RMP: Risk Management Plan

QCP: Quality Control Plan

DIC: Digital Image Correlation

1. INTRODUCTION

1.1. Background

Concrete is one of the most conventional commonly used construction material in the world dating back many years ago and as the global human population grows, the demand for concrete continues to increase. Some of the uses of concrete include, but not limited to construction of roads, bridges, buildings, and pavements, it plays a pivotal role in first world development. Generally concrete constitutes of fine, medium, and coarse aggregates, cement, water, and additives if required. The most common fine aggregate that is used in concrete is natural sand and finely crushed rock, which has shown over long periods of time to deliver sufficient strength, durability and provides a desirable appearance when hardened.

Fine aggregates are obtained from the natural environment such as, on seashores and in rivers/streams or quarrying pits (Article 2017), and because of the growing demand for concrete all over the world, sourcing of these fine aggregates is becoming unsustainable and unfriendly to the natural environment. The unsustainability of natural fine aggregates presents a problem for the civil construction industry globally and as a result, there are several studies underway or recently undertaken to find a sustainable replacement for traditional fine aggregates currently used in concrete mixes.

Recently, research into recycled crushed glass (RCG) as a potential replacement for fine aggregates has attracted notable interest worldwide. Some of the literature that has been published on this matter reviewed the strength and durability of concrete after RCG was introduced incrementally in concrete mixtures (up to 40%). The findings have been inconsistent, with some finding that RCG improves the strength properties of concrete and others concluding that the introduction of RCG in concrete produced undesirable consequences on concrete strength properties (Guo et al. 2020). These inconsistent findings have resulted in the civil construction sector losing confident in adopting RCG as an alternative replacement for natural fine aggregates in concrete.

The objective of this experimental study is to build on existing research and progress further by increasing the RCG percentage in the test specimens from 40% to 100% RCG in lieu of natural fine aggregates and thereby testing the strength properties and workability of the concrete mixtures. The appearance of the concrete will be observed to ensure that the hardened concrete maintains preferable aesthetics as we have come to know about concrete.

None of the available published research papers has assessed the appearance of concrete with RCG added, therefore this research will also add to the library of available literature on this subject matter and expectantly increase the confidence of civil engineers in using RCG in concrete.

1.2. Idea Development and Motivation

The idea to conduct this research was recommended by Dr Sourish Banerjee, a senior lecturer for structural design at the University of Southern Queensland in Australia. The researcher then progressed by assessing the available literature to determine consistency and uniformity of results in published literature. The intent was to build on these discrepancies and attempt to achieve a consistent set of results that address the research gap.

The main drivers of this research are primarily to ensure that fine aggregates used in concrete are sustainable and reduce the sourcing of natural sand and fine crushed rock which directly presents a significant environmental problem.

The study of RCG in concrete, together with the primary drivers mentioned above, arise from the present-day problem that the world has in trying to dispose and recycle waste glass. RCG can be used as an alternative replacement for fine, medium, and coarse aggregate in concrete mixes, however this research will only concentrate on utilising RCG as a replacement for natural fine aggregates such as natural sand and finely crushed rock.

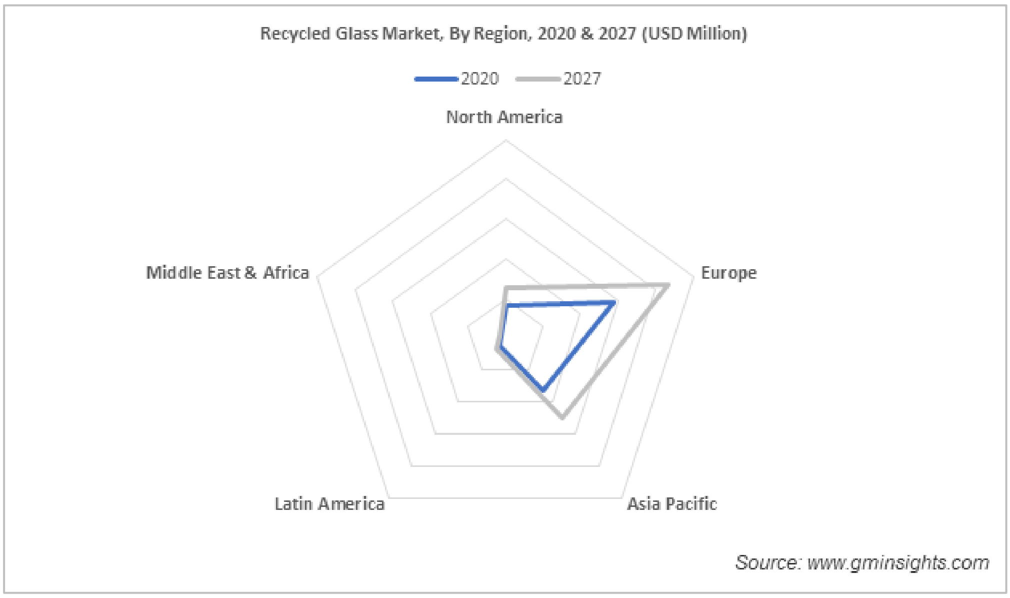


Figure 1: Recycled Glass Market by Region (Kiran Pulidindi 2021)

About 130 million tonnes of waste glass is generated annually worldwide and only a small fraction (approximately 35%) of waste glass is recycled (Dr.-Ing. Joachim Harder 2022). As shown in Figure 1, Europe possesses the largest share of the recycled glass market, therefore, this shows that there is significant growth potential if sustainable government policies are introduced and if the technology improves to support the recycling of waste glass. Most waste glass is disposed into landfill sites, however, landfill space in some regions around the world is becoming more and more difficult to obtain and due to the large volume of waste glass, it is almost impossible to reuse or remanufacture all waste glass into other glass products because the glass recycling industry has limited capacity (Ling, Poon & Wong 2013). There is need to identify/discover alternative methods of recycling waste glass. This research will provide an alternative method of recycling this large amount of waste glass.

Figure 2: Turning a Waste Problem Into a Green Solution (Sand 2019)

Figure 2 is from an innovative business which specialises in producing processed sands and powders from 100% recycled glass. These businesses have begun to pave the way for RCG to be used on a bigger scale in concrete applications, which this study will be helping to support and encourage.

Some researchers have mainly concentrated their research on utilising RCG in concrete for several applications, listed below:

- ✓ Pavements
- ✓ Asphalt
- ✓ Precast concrete blocks

My experimental research will not focus on a specific application as has been done in other studies, but rather seek to determine the properties of the fresh and hardened concrete after RCG is introduced incrementally from 40% up to 100% in lieu of natural sand. Depending on the results of this research, other practical applications could be established, and further research can be undertaken to confirm if the proposed applications are viable options for this type of concrete.

Glass has good heat resistance capabilities and so further research can be undertaken to use RCG concrete in house construction and determine whether these heat resistance capabilities of glass can be of value and reduce energy consumption for homeowners (home insulation), including commercial buildings. Glass also presents negative properties such as it is easy to crack and it is very brittle, these may negatively impact the strength properties of concrete specimens. The experiment within this study will help confirm whether these negative properties are true when glass is in its finest form, in a concrete mix, and determine to what magnitude the negative properties of RCG will impact the concrete strength properties.

2. LITERATURE REVIEW

2.1. Past Research

Several research studies have been undertaken for using recycled crushed glass in concrete, however, most of it has been concentrated on specific applications such as, pavements and in asphalt concrete. From the multiple research papers that were reviewed, some of the experimental papers investigated the cementitious nature of finely ground glass and its potential to be utilised as cement in Portland Cement concrete mixes because it possessed pozzolanic properties. However, this particular research pointed out the negative consequences of using crushed glass in concrete due to concerns of the concrete cracking as the glass expands (Shi & Zheng 2007).

The study of crushed glass in concrete mixes dates back to the 1960's, which found that, at that time, all hardened concrete containing crushed glass aggregates cracked (Shi & Zheng 2007). Glass tends to expand under certain heating conditions, which leads to cracking. This property of glass was found to be responsible for cracking concrete specimens. However, no benchmarking was completed at the time, to compare compressive strength of crushed glass concrete to traditional concrete mixes.

One of the other experimental study projects conducted, concentrated on replacing not only fine aggregates with recycled crushed glass, but also coarse aggregates with coarse waste glass (CWG) simultaneously. This paper focused mainly on the properties of this type of concrete made with RCG at elevated temperatures of up to 700 degrees Celsius. The findings demonstrated that the compressive strength of concrete made with recycled crushed glass at 10% for fine crushed glass and 10% for coarse crushed glass had better properties overall when subjected or exposed to high temperatures. This research paper was one of the most cited articles, which could imply that the study that had been conducted was trusted by many researchers (Terro 2006).

In 2019, research was undertaken to assess the strength in concrete footpaths when recycled plastic waste (RPW) and recycled crushed glass were used as aggregates. The research paper discussed the replacement of traditional natural aggregates with RPW and RCG from 0 to 50 percent at 10 percent increments. It was undertaken to find other methods of recycling waste glass which is causing negative environmental consequences when disposed in landfill sites not fit for purpose, and if successful RCG in concrete will become an innovative solution to resolving this crisis. The outcomes from this research concluded that at low percentages of up to 30%, RCG and RPW were viable aggregate replacement options for concrete footpaths (Mohammadinia et al. 2019).

Another interesting study looked at the permeability of recycled crushed glass for pavements porous concrete. The high void ratio needed in this type of concrete would aid in the decline of rainwater run-off and increase infiltration of rainwater and boost vegetation growth. There were remarkable benefits identified in this research, including, noticeable increment in the permeability coefficient, overall reduction in concrete production costs and the research concluded that the integration of waste glass into porous concrete (PC) was favourable and preferred for roads and public areas (Toghroli et al. 2018).

Another group of researchers reviewed and compared various experimental articles and findings from other researchers and set-out to draw a conclusion on how confident the civil construction industry is with recycled crushed glass in concrete mixes. One looked to reach consensus on the effects of using recycled crushed glass in concrete, but concluded that the inconsistencies in the available results had hindered the acceptance of recycled crushed glass in concrete across the world (Guo et al. 2020).

The tables below contain a summary of results from online literature. The results are for concrete samples that contain RCG up to 40% replacement. The intent of this summary is to identify any discrepancies and check the consistency of published results. This dissertation will aim to build on this existing information and addressing these discrepancies.

28 Days Compressive Strength (M20 Grade)

% RCG	Compressive Strength 1	Compressive Strength 2	Compressive Strength 3
0	40 MPa	32 MPa	27.05 MPa
10	40 MPa	32 MPa	30 MPa
20	40 MPa	36 MPa	33.5 MPa
30	35 MPa	40 MPa	24 MPa
40	32 MPa	42 MPa	19 MPa

Table 1: Compressive Strength of Concrete Cylinders with RCG from Literature Review (Mageswari & Vidivelli 2010; Vijayakumar, Vishaliny & Govindarajulu 2013; Raju & Kumar 2014)

The 28-day compressive strength results table above shows some inconsistencies with the strength properties of the hardened concrete samples with RCG added.

The first column shows that as the RCG percentage increases from 10% to 40%, the compressive strength properties of the samples decreased slightly from the control sample. For 10% and 20% RCG in the concrete samples in column 1(Mageswari & Vidivelli 2010), they maintained the same strength properties as the control sample, however as the RCG percentage increase above 20%, the samples experienced a decline in strength. The literature reports that "at 10% the strength of the concrete is more than that of conventional concrete", which is quite encouraging to see, however, further investigations are required to determine why the sudden decrease in strength occurs beyond 20% replacement.

On the other hand, the second column (Vijayakumar, Vishaliny & Govindarajulu 2013) displayed an increase in strength as the RCG percentage in the concrete increased from 10% to 40%. This is contradictory to the previous literature (1st column), which showed a decrease in strength with increasing RCG percentage. These inconsistencies badly affect consumer confidence.

The third column shows that the compressive strength increases up to 20% RCG replacement and decreases thereafter up to 40% RCG replacement. The pattern and trend of these results can be likened to the 1st column samples; however, the strength values are significantly lower than the other 2 columns across the entire sample range. In theory, we expect that at some stage the RCG in the concrete will cause a reduction in strength and so these experimental results are not consistent with the theoretical results.

These discrepancies demonstrate that even with the same grade and sample mix designs with RCG added at various percentages, there is still no uniformity in the results and the published literature above is evidence to that. Thereby, showing how consumer confidence is being negatively affected as was pointed out in one of the other research papers. (Guo et al. 2020)

28 Days Flexural Strength (M20 Grade)

% RCG	Flexural Strength 1	Flexural Strength 2	Flexural Strength 3
0	7 MPa	3 MPa	3.5 MPa
10	7 MPa	4 MPa	3.78 MPa
20	6.5 MPa	6 MPa	4.17 MPa
30	6 MPa	6.5 MPa	3.90 MPa
40	5 MPa	6.5 MPa	3.41 MPa

Table 2: Flexural Strength of Concrete Beams with RCG from Literature Review (Mageswari & Vidivelli 2010; Vijayakumar, Vishaliny & Govindarajulu 2013; Raju & Kumar 2014)

The 28-day flexural strength of concrete beams shown in the table above displays some inconsistencies with the flexural strength properties of the hardened concrete samples with RCG added similar to what was observed in the compressive strength values.

The results in all 3 references are not uniform and create difficulties in drawing reasonable conclusions in how RCG affected the flexural strength in the beams. It only helps to affirm the reasons why reaching consensus has been difficult in the use of RCG in concrete.

28 Days Split Tensile Strength (M20 Grade)

% RCG	Tensile Strength 1	Tensile Strength 2	Tensile Strength 3
0	9 MPa	9 MPa	2.68 MPa
10	9 MPa	6 MPa	2.4 MPa
20	8 MPa	7 MPa	2.2 MPa
30	7 MPa	7 MPa	2.12 MPa
40	6 MPa	6.5 MPa	2 MPa

Table 3: Split Tensile Strength of Concrete with RCG from Literature Review (Mageswari & Vidivelli 2010; Vijayakumar, Vishaliny & Govindarajulu 2013; Kavyateja, Reddy & Mohan 2016)

The 28-day split tensile strength (STS) of the concrete with RCG paint a slightly different picture to that displayed for compressive and flexural strength properties above.

The trend that can be seen from the STS results is that tensile strength decreases as RCG in concrete increases from 10% to 40%. This is true across the 3 columns of results from different researchers. However, the third column has produced significantly lower tensile strength results compared to the first 2 researchers in the first 2 columns.

2.2. Research Gap

As demonstrated in the concrete properties tables in the section above, the past research has not been conclusive in providing the industry with sufficient data to back the use of RCG in concrete and in some cases the data has been very inconsistent with theoretical norms. The majority of research papers have investigated the use of recycled crushed glass in concrete for specific applications such as, asphalt and concrete pavements, and at elevated temperatures and only up to approximately 40% replacement in concrete mixes for M20 concrete grade.

In this research, M32 concrete grade will be tested because researchers have already exhausted M20 grades as shown in the literature review above.

This paper will not only address the compressive, flexural, and split-tensile strength properties of concrete when recycled crushed glass is introduced as a fine aggregate from 40% to 100% replacement proportions but will also focus on the workability and appearance of the concrete mixes. Little research has been previously conducted on the workability and appearance of concrete when RCG is added. This research study will also seek to assist in drawing definitive conclusions and reaching consensus on the effects of recycled crushed glass in concrete. The success of this research will greatly benefit the construction industry, by helping to increase the amount of waste glass that can be recycled into concrete applications rather than placed in landfill sites, subsequently reducing the environmental consequences that sourcing natural fine aggregates presents.

Concrete properties like appearance, will be impacted when different colours of recycled crushed glass are used, the expectation is that it will modify the finish of the hardened concrete and may sow coloured fragments (depending on mix proportions with the recycled crushed glass and colour of crushed glass used in the mixture) on the surface of the hardened concrete. The results could be aesthetically desirable for applications where these types of finishes are required.

A small portion of the experimental research will seek to assess the safety aspects of handling recycled crushed glass. Glass poses a major hazard to workers and so how this will be managed in its fine form will be briefly discussed to assist workers in selecting appropriate PPE that is suitable when handling recycled crushed glass. The effects of breathing dust from recycled crushed glass will also be briefly discussed in this research paper but will not be the primary aim of this research. Further research can be undertaken using these findings on personnel safety to generate more research tailored to the work health and safety (WHS) aspects of crushed glass.

3. PROJECT PLANNING

3.1. Project Timeframe

The project was projected to take a maximum of 2 semesters, which spanned from February 2023 to October 2023. The proposed project activities were listed in the table below, however, the some of the activities were altered due to delays in acquiring resources for completing experiments. A summary of each activity can be found below.

Time	**2023**								
Proposed Activities	F	M	A	M	J	J	A	S	O
Literature review	■	■	■	■	■	■	■		
Resource acquisition		■	■						
Sample preparation				■	■				
Concrete testing					■	■			
Analysis and interpretation of data						■	■		
Draft conclusions							■	■	■
Final submission									■

Table 4: Project Timeframe Gantt Chart (Queensland 2022a)

Literature Review – Conduct initial literature reviews to identify the research gaps. Determine consistency and uniformity of properties/results from currently available literature and identify any discrepancies in published literature. Literature review was continuous and occurred for quite some time during the project.

Resource procurement – the purchasing of resources was completed as part of this activity. Recycled crushed glass, coarse aggregates, cement, concrete mixing tools and concrete testing tools were all purchased and delivered at the University of Southern Queensland laboratory, ready for sample preparation and testing.

Sample preparation – In this step, the RCG concrete samples were created. Mixing of samples and preparation of samples for compressive test and slump test was all undertaken as part of this activity.

Concrete testing – Compressive strength tests, slump tests, flexural strength tests and split tensile strength were conducted on all samples. There was an overlap between concrete testing and sample preparation, this is mainly because the slump test was completed at the same time as the samples were being prepared. Slump test is conducted on fresh concrete, hence the overlapping of activities.

Analysis and interpretation of data – Once all the samples have been tested and associated data has been collected, the researchers began to analyse the data and compare results with the traditional concrete results to draw conclusions.

Draft conclusions – Concise conclusions were drawn and drafted into the project report. The outcome of the research was assessed against the expectations that were set out in the research proposal to assess if they align or if the research gap is still present.

Final Submission – the research is now complete. A final review was undertaken by the research project supervisor on the paper to ensure all comments and values are accurate. The dissertation will thereby be submitted via the USQ online submission link.

3.2. Risk Assessment

Managing safety when undertaking experiments was pivotal to the experiment's success. Any injuries could cause serious implications for the project outcomes and affect the project objectives.

For this research a Risk Management Plans (RMP) was completed to control the risks associated with the concrete sample preparation and all the laboratory work detailed in this paper under the methodology section. The formal RMP has been created using USQ's Online Risk Management System, **RMP ID: 2449**.

Refer to **Appendix B** for completed Risk Assessment.

4. METHODOLOGY

4.1. Research Classification

The type of study will be classified as experimental research. Experimental research is research undertaken with a scientific approach, which will compare the differences between two sets of variables i.e., the control sample or theoretical predictions and the experimental samples. This allows adequate testing of the idea before it can be taken to the construction industry and produced on a larger scale. It will provide an ideal starting point and a platform for researchers to build more ideas and undertake further research (QuestionPro 2022).

4.1.1. Control Sample

The control sample will have no RCG added (0% RCG replacement) i.e., when traditional aggregates are used e.g., natural sands and crushed rock aggregates. The 28-day compressive strength values of this type of concrete will be used as the baseline in this experimental research.

Other properties that will be derived from the control sample include slump values for workability, flexural strength and split-tensile strength, and the appearance of the concrete. In this experiment one or two samples will be required to set the baseline for the experiment.

4.1.2. Experimental Plan

The experimental samples will produce differing results due to the varying inputs used to create the specimens. In this research, this will be a set of results garnered when recycled crushed glass is introduced into concrete mixtures from 20% to 40% in lieu of traditional fine aggregates. The 28-day compressive strength, flexural strength and split-tensile strength values will then be compared against the control sample to establish a relationship and draw conclusions on the effects of recycled crushed glass in concrete.

The chosen starting point of 20% RCG in the concrete mix is based on the current literature which has already shown that RCG replacement of up to 40% is already being used by different researchers, but producing inconsistent results, therefore, this paper will build on existing research and aim to investigate the source of these inconsistencies and test to see how the properties of the hardened concrete will be affected.

Samples will be created for 0% (control sample), 20% and 40% RCG replacement in concrete in place of natural sand.

A particle size distribution test was undertaken to minimize the effect of grading.

The 28-day compressive, split-tensile, and flexural strength and workability tests will then be conducted on the samples as per section 3.3 ‘Concrete Testing’.

4.2. Sample Preparation

4.2.1. Particle Size Distribution

To ensure that we minimise the effects of grading, numerous sieve analysis tests were performed on Sand and RCG material.

The first sieve analysis test was conducted on natural sand (USQ sand sample) to determine its grading curve when plotted on a sieve size (mm) against percent mass passing sieve (%) chart. The following plot was produced:

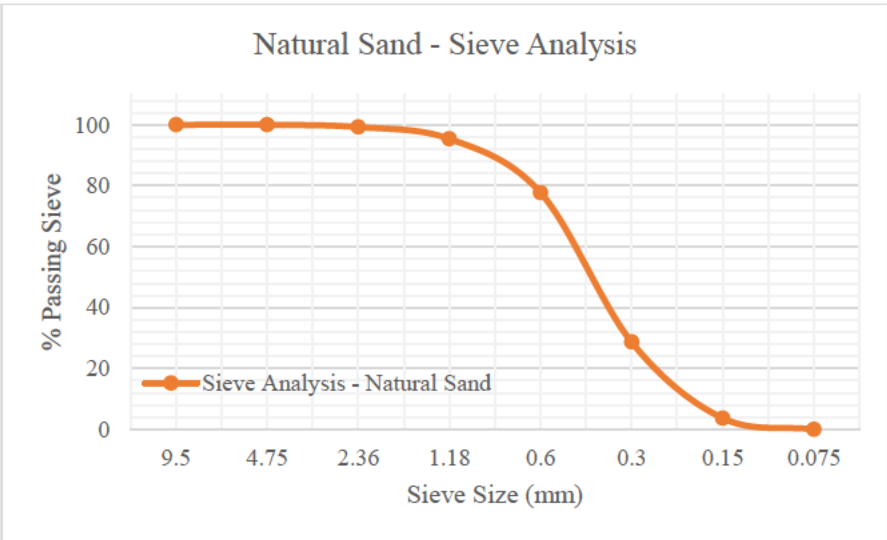


Chart 1: Natural Sand Grading - Sieve Analysis Chart

As shown on Chart 1, natural sand follows a smooth grading curve. The graph begins to trend downwards after sieve size 1.18mm and begins to flatten after sieve 0.15mm showing that most of the sand particles in the USQ natural sand, range between 0.15mm and 1.18mm.

Therefore, to minimise the effects of grading, it is essential that the RCG sample follows as close as possible the natural sand grading curve shown on Chart 1. Additionally, both the USQ natural sand and RCG grading curves should plot within the recommended natural fine aggregate lower and upper bounds as stipulated in Table B2 of Australian Standard 2758.1-2014 (Figure 3).

TABLE B2

FINE AGGREGATE—RECOMMENDED GRADINGS

Sieve aperture mm	Mass of sample passing, percent	
	Natural fine aggregate	Manufactured fine aggregate
9.50	100	100
4.75	90 to 100	90 to 100
2.36	60 to 100	60 to 100
1.18	30 to 100	30 to 100
0.6	15 to 100	15 to 80
0.3	5 to 50	5 to 40
0.15	0 to 20	0 to 25
0.075*	0 to 5	0 to 20

* Consideration may be given to the use of a manufactured fine aggregate with greater than 20% passing the 0.075 mm size, provided tit is used in combination with another fine aggregate where the total percentage passing 0.075 mm of the fine aggregate blend does not exceed 15% and provided the fine aggregate components meet the deviation limits in all respects.

Figure 3: Fine Aggregate – Recommended Gradings (Standard 2014)

Due to manufacturer constraints at the time of conducting this experiment, the RCG material was only available in 3 different sizes. These were as follows:

Size 1:

Range – 1.5 to 3mm

Colour – clear glass

Shape – Angular, Round (observed under microscope)

Figure 4: Size 1 - RCG

Size 2:

Range – 0.4 to 0.8mm

Colour – clear glass

Shape – Angular, Round

(observed under microscope)

Figure 5: Size 2 - RCG

Size 3:

Range – 0.2 to 0.6mm

Colour – clear glass

Shape – Angular, Round

(observed under microscope)

Figure 6: Size 3 - RCG

The 3 RCG sizes had to be blended in different proportions and numerous sieve analysis tests conducted until a suitable blend grading was achieved. That which complies with the recommended fine aggregate gradings in AS2758.1-2014 and the USQ natural sand grading curve.

5 RCG sieve analysis trials were conducted. The first 4 unsuccessful trials had the following proportions:

	RCG Mix Proportions (Ratio)		
Sample Size (mm)	**1.5 – 3.0mm**	**0.4 – 0.8mm**	**0.2 – 0.6mm**
Trial 1	0.7	0.15	0.15
Trial 2	0.3	0.4	0.3
Trial 3	0.2	0.3	0.5
Trial 4	0.15	0.25	0.6

Table 5: RCG Sieve Analysis Mix Proportions

The final trial, which proved to provide the closest grading to the recommended curve had the following proportions:

	RCG Mix Proportions (Ratio)		
Sample Size (mm)	**1.5 – 3.0mm**	**0.4 – 0.8mm**	**0.2 – 0.6mm**
Trial 5	0.1	0.2	0.7

Table 6: RCG Sieve Analysis Mix Proportions for Trial 5

The recommended fine aggregate grading curve could have been fully achieved if the RCG material had more finer particles available for blending. However, the analysis discovered that most of the mass was being retained in sieve size 0.3mm because most of the fine particles ranged above this size. Therefore, it wasn't possible to increase only the finer particles due to this constraint.

Below are the tables for the RCG and natural sand sieve analysis results that were then plotted on Chart 2 for comparison.

Size (mm)	**Mass of container (g)**	**Mass of container + RCG (g)**	**Mass retained on sieve (g)**	**Mass passing sieve**	**% passing sieve**
9.5	411.3	411.3	0	1000.36	100
4.75	410.6	410.6	0	1000.36	100
2.36	399.2	421.2	22	978.36	98
1.18	402.2	479.4	77.2	901.16	90
0.6	308.38	622.5	314.12	587.04	59
0.3	275.44	818.1	542.66	44.38	4
0.15	270.6	314.5	43.9	0.48	0
0.075	253.12	253.6	0.48	0	0
		Total	**1000.36**		

Table 7: RCG – Sieve Analysis Data

Size (mm)	**Mass of container (g)**	**Mass of container + sand (g)**	**Mass retained on sieve (g)**	**Mass passing sieve**	**% passing sieve**
9.5	411.3	411.3	0	1489.26	100
4.75	410.6	410.6	0	1489.26	100
2.36	399.2	410.2	11	1478.26	99
1.18	402.2	459.8	57.6	1420.66	95
0.6	308.38	571.2	262.82	1157.84	78
0.3	275.44	1006.4	730.96	426.88	29
0.15	270.6	642.5	371.9	54.98	4
0.075	253.12	308.1	54.98	0	0
		Total	**1489.26**		

Table 8: USQ Natural Sand – Sieve Analysis Data

The resulting Particle Size Distribution plot for trial 5 can be seen in Chart 2 below:

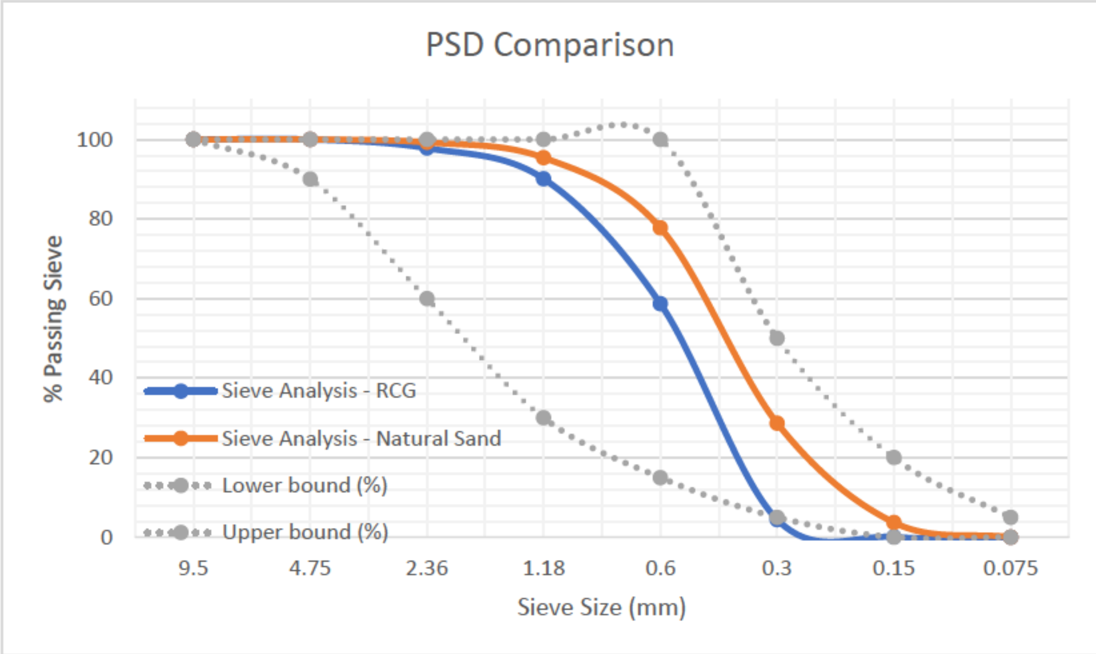


Chart 2: Particle Size Distribution - Sieve Analysis Chart

The chart shows that the RCG grading curve is within the recommended grading bounds and is as close as possible to the natural sand grading. Trial 5 blend grading was chosen as the most successful blend proportions for RCG.

The aggregates in the concrete will be made up of fine aggregates and coarse aggregates. Both these aggregates (fine and coarse) will need to be to produce a preliminary concrete mix design with suitable workability.

The following 3 standard aggregate tests were conducted on the sample aggregate materials:

- The grading of each individual coarse and fine aggregate as well as the combined grading of the blends of coarse and fine aggregates.
- Particle water absorption and moisture content of each of the individual coarse and fine aggregates.
- The bulk density of oven dry aggregate.

The grading of the fine aggregates has already been documented above, and below is the grading of coarse aggregates individually and combined grading of blends of coarse and fine aggregates.

Typically, the most common nominal size for coarse aggregates used in concrete is 20mm. This design adopted 20mm as the largest size aggregate in the mix, combined with 10mm and 7mm coarse aggregate plus natural sand as a fine aggregate to fill in the gaps and provide adequate strength and workability to the concrete mix. (Hilton 2020)

The British 'Road Note No.4' method was used to blend the solid volume of aggregates to achieve a target grading of the combined coarse and fine aggregates based on a series of 4 preferred grading curves.

The target grading curves for 20mm maximum size aggregate are shown below:

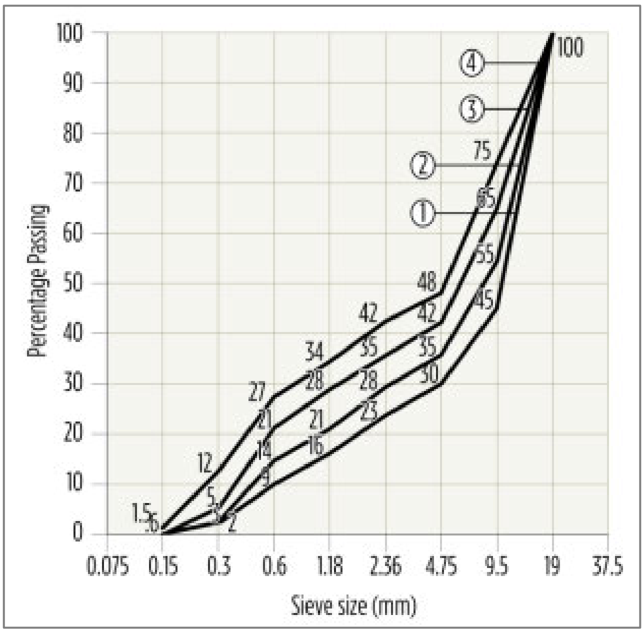


Figure 7: Road Note No. 4 – Target Grading for 20mm Maximum Size Aggregate

The fine and coarse aggregates were blended to target a best fit of the following blend:

- 22.5% volume of coarse aggregate – 20mm
- 31.9% volume of coarse aggregate – 10mm and 7mm combined (50:50)
- 45.6% volume of fine aggregate – USQ natural sand and RCG blended as per Table 5

The blend was adopted from Cement Concrete & Aggregates Australia (CCAA) after they conducted numerous iterations to achieve the best fit grading versus target grading (curve 4).(Australia 2020)

These blending proportions were tested in a sieve analysis test with materials that were to be used in the preparation of the concrete mix to determine if they would still achieve a best fit with the target curve (curve 4).

Figure 8: Sieve Analysis Apparatus

The resulting Particle Size Distribution plot for this combined blend can be seen in Chart 3 below:

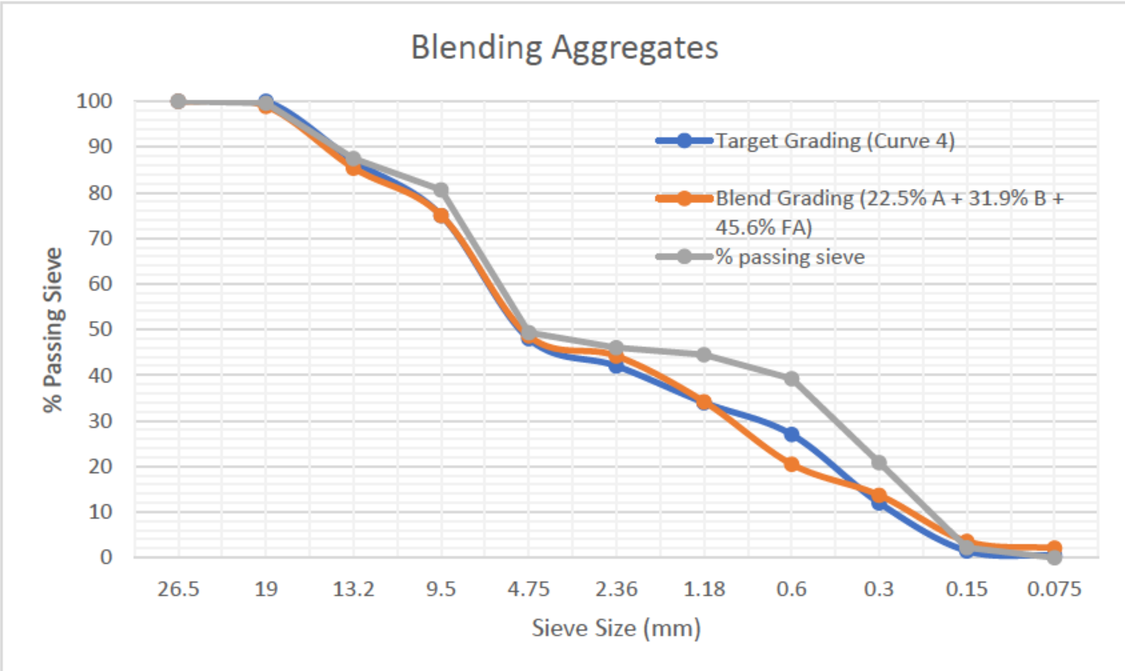


Chart 3: Particle Size Distribution – Blending Aggregates

Chart 3 shows that the blend grading proportions that were chosen and tested produced a line of best fit that closely follows the target grading (curve 4) and the blend grading ratios adopted from CCAA.

As a result, for the concrete mix design, the fine and coarse aggregates will be blended as per the CCAA blend grading of 22.5% A + 31.9% B + 45.6% FA.

4.2.2. Concrete Mix Design

After selection of all suitable materials for the samples, the concrete mix design can now be completed.

For this research, N32 concrete grade will be tested because previous research has already been conducted for other concrete grades as identified in the research gap above. This corresponds to a 28-day compressive strength of 32 MPa. To achieve N32 concrete grade, the following mix design was adopted based on the Australian Standard concrete mix design guidelines.(Constructor 2021)

Concrete Mix	Cylinder Strength (MPa)
N20	20
N25	25
N32	32
N40	40
N50	50
N65	65
N80	80
N100	100

Table 9: Australian Standard Concrete Grades (Floor 2018)

Target strength > F'c + (k × SD) (Australia 2020)

k = 1.65 (AS 3600 and AS 1379)(Australia 2020)

SD (Standard Deviation) = 3.6 (Australia 2020)

f'_c = 32 MPa

Target Strength = 32 + (1.65 x 3.6) = **37.94 MPa**

6-cylinder test specimens will be created for each percentage mix (3 for compressive strength and 3 for split-tensile strength) plus 2 beam samples each percentage mix to achieve the required statistical average of results.

Based on the sample creation data above, a total of 9 samples will be required for the compressive strength and 9 samples for split tensile strength, and 6 beam samples for flexural strength testing – **Total: 25 samples**

Compressive Strength:

- 9 samples

- Concrete cylinder dimensions (Ø 100mm x 200mm high) in accordance with AS1012.8.1-2014 Section 5.
- Volume needed for compressive strength samples =
  - 9 dia 100 cylinders = 9 x ($\pi(0.05)^2$ x 0.2) = **0.014 m^3**

Flexural Strength of Beams:

- 6 samples
- The nominal maximum size aggregate in the concrete = 20mm, therefore the concrete beam mould for flexure test will be 150mm x 150mm x 500mm in accordance with AS1012.8.2-2014 section 5.2(b).
- Volume needed for flexural strength samples =
  - 6 beams = 6 x (0.15 x 0.15 x 0.50) = **0.0675 m^3**

Split-Tensile Strength:

- 9 samples
- Concrete cylinder dimensions (Ø 100mm x 200mm high) in accordance with AS1012.8.1-2014 Section 5.
- Volume needed for split-tensile strength samples =
  - 9 dia 100 cylinders = 7 x ($\pi(0.05)^2$ x 0.2) = **0.014 m^3**

Assumed waste concrete (10%) = 0.00958 m^3

Total volume needed including waste = 0.1054 m^3

Assumed fresh concrete unit weight = 2400 kg/m^3

Total mass of fresh concrete = 2400 x 0.1054 = **252.8 kg (25 specimens)**

252.8/3 ≈ 85 kg fresh concrete needed per each RCG mix percentage (8 specimens).

85 kg for each RCG mix percentage will create 8 specimens for testing e.g., 3 x Split-Tensile Strength Specimens at 0%, 3 x Compressive Strength Specimen at 0% and 2 x Flexural Strength Beam Specimen at 0% up to 40% RCG replacement in the concrete.

A Water/Cement ratio of 0.48 that was chosen was based on numerous trial and error concrete batches that were created and failed to provide adequate (slump > 150m).

The fine aggregate/coarse aggregate ratio was determined in section 3.2.1 above from the blending of aggregates. The coarse aggregates contribute 22.5%+31.9% = 54.4% of the total aggregates, which leaves 45.6% allocated for fine aggregates. Therefore, the ratio of fine aggregate to coarse aggregates will be 45.6/54.4 = 0.84.

The aggregate/cement ratio was taken from Table 10 of the British method as follows:

20 mm aggregate																								
	Aggregate/cement ratio by weight																							
Degree of workability slump (mm)	Rounded gravel								Irregular gravel								Crushed rock							
	'Medium' 25–50				'High' 50–120				'Medium' 25–50				'High' 50–120				'Medium' 25–50				'High' 50–120			
Grading no. (Figure 3.3)	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Total water/cement ratio by weight 0.40	4.2	4.2	3.9	3.6	3.7	3.8	3.6	3.3	3.3	3.4	3.4	3.2	3.1	3.2	3.2	2.9								
0.45	5.3	5.3	5.0	4.6	4.6	4.8	4.5	4.1	4.0	4.1	4.1	3.9	S	3.8	3.8	3.5	3.7	3.7	3.4	3.3	3.5	3.5	3.2	3.1
0.50	6.3	6.3	6.0	5.5	5.5	5.7	5.4	4.8	4.6	4.8	4.8	4.5		4.4	4.4	4.1	4.2	4.2	3.9	3.8	S	3.9	3.8	3.5
0.55	7.3	7.3	7.0	6.3	6.3	6.5	6.1	5.5	S	5.4	5.3	5.1		4.9	4.9	4.7	4.7	4.7	4.5	4.3		S	4.3	4.0
0.60			8.0	7.1	S	7.2	6.8	6.1		6.0	5.9	5.6		S	5.4	5.2	S	5.2	4.9	4.8			4.7	4.5
0.65				7.8		7.7	7.4	6.6		S	6.4	6.1			5.8	5.7		5.7	5.4	5.2			5.2	4.9
0.70							7.9	7.1			6.8	6.6			6.2	6.1		6.2	5.8	5.7			5.5	5.3
0.75								7.6			7.2	7.0			6.6	6.5		S	6.2	6.1			5.8	5.7
0.80											7.5	7.4			S	7.0			6.6	6.5			6.1	6.0

Table 10: British Method

Method of interpolation was used to get the aggregate/cement ratio as shown above when the water/cement ratio is 0.48. All the inputs to the table have been highlighted in red.

Water/cement ratio	0.48
Aggregate/cement ratio	4.26
Fine aggregate/coarse aggregate ratio	0.84
Total concrete units	5.74

Table 11: Concrete Mix Design Ratios (Queensland 2022b)

Based on the ratios above, the final mix ratio that was used (in units) is:

Cement	Sand/RCG	Aggregate
1	1.92	2.35

Table 12: Mix Ratio

The ratio is a product of the contribution of fine aggregates and coarse aggregates (45.6% and 54.4% respectively) by the aggregate/cement ratio individually.

The USQ sand that was used was wet and so to accurately calculate the amount of water to add to the concrete mix, a moisture content test was undertaken for the sand. The coarse aggregates were dried in the oven overnight and so moisture content was not adjusted for coarse aggregates.

A sample of the sand was placed in the oven for 24 hours and then weighed.

Moisture Content of sand	
Mass of container (g)	70.5
Mass of container + wet soil (g)	240.4
Mass of wet soil (g)	169.9
Mass of container + dry soil (g)	231.7
Mass of dry soil (g)	161.2
Moisture Content	5.1%

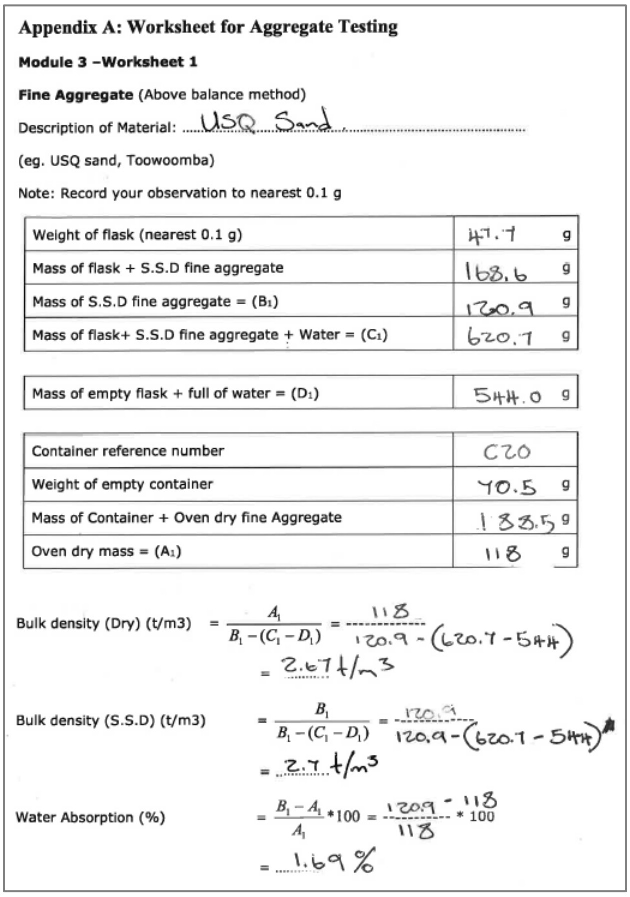
Table 13: USQ Natural Sand Moisture Content

To adjust for sand moisture the following formula will be used:

$$\text{Qty of free water} = \left[\left(\frac{\text{m/c} + 100}{\text{w/a} + 100}\right) * \text{SSD mass}\right] - \text{SSD mass}$$

m/c – Moisture Content; w/a – Water Absorption; SSD – Saturated Surface Dry

The water absorption data for USQ sand was derived from a previous experiment during the CIV3906 course which utilised the same materials.



Appendix A: Worksheet for Aggregate Testing

Module 3 –Worksheet 1

Fine Aggregate (Above balance method)

Description of Material: USQ Sand

(eg. USQ sand, Toowoomba)

Note: Record your observation to nearest 0.1 g

Weight of flask (nearest 0.1 g)	47.7	g
Mass of flask + S.S.D fine aggregate	168.6	g
Mass of S.S.D fine aggregate = (B_1)	120.9	g
Mass of flask+ S.S.D fine aggregate + Water = (C_1)	620.7	g
Mass of empty flask + full of water = (D_1)	544.0	g
Container reference number	C20	
Weight of empty container	70.5	g
Mass of Container + Oven dry fine Aggregate	188.5	g
Oven dry mass = (A_1)	118	g

Bulk density (Dry) (t/m3) $= \frac{A_1}{B_1-(C_1-D_1)} = \frac{118}{120.9-(620.7-544)}$ $= 2.67\ t/m^3$

Bulk density (S.S.D) (t/m3) $= \frac{B_1}{B_1-(C_1-D_1)} = \frac{120.9}{120.9-(620.7-544)}$ $= 2.7\ t/m^3$

Water Absorption (%) $= \frac{B_1-A_1}{A_1} * 100 = \frac{120.9-118}{118} * 100$ $= 1.69\ \%$

Figure 9: USQ Natural Sand Water Absorption Testing Results

Quantity of free water in USQ sand = **0.953 kg**

Calculation of mix components:

Sample Mix Components

Table 10 below shows the concrete mix quantities before the moisture content was adjusted for the USQ sand.

Proportion (kg) – no m/c adjustment			
Component	**0%**	**20%**	**40%**
Water	7.11	7.11	7.11
Cement	14.8	14.8	14.8
Aggregate – Sand	28.4	22.7	11.4
Aggregate – RCG	0	5.68	17
Aggregate – 20mm	14.5	14.5	14.5
Aggregate – 10mm	10.1	10.1	10.1
Aggregate – 7mm	10.1	10.1	10.1
Total	85.1	85.0	85.0

Table 14: Mix Quantities without Moisture Content Adjustments

Table 11 below shows the concrete mix quantities after the moisture content was adjusted for USQ sand. To adjust for sand moisture, the free water will be deducted from the water quantity in the mix and the sand mass will be increase by the same.

Proportion (kg) – m/c adjusted			
Component	**0%**	**20%**	**40%**
Water	6.17	6.17	6.17
Cement	14.8	14.8	14.8
Aggregate – Sand	29.4	23.5	17.6
Aggregate – RCG	0	5.88	11.8
Aggregate – 20mm	14.5	14.5	14.5
Aggregate – 10mm	10.1	10.1	10.1
Aggregate – 7mm	10.1	10.1	10.1
Total	85.1	85.0	85.1

Table 15: Mix Quantities with Moisture Content Adjustments

Although quantities of ingredients are adjusted for moisture content, the total mass for the concrete mix remains the same.

Total Quantities Used

Component	Total components required (kg)
Water	18.5
Cement	44.4
Aggregate – Sand	70.5
Aggregate – RCG	17.7
Aggregate – 10mm	30.3
Aggregate – 7mm	30.3

Table 16: Total Quantity of Materials Used

A spreadsheet was developed for the concrete mix design to allow for various iterations to be perfomed until the optimum mix design is achieved. Below is a screenshot showing the concrete mix design excel sheet:

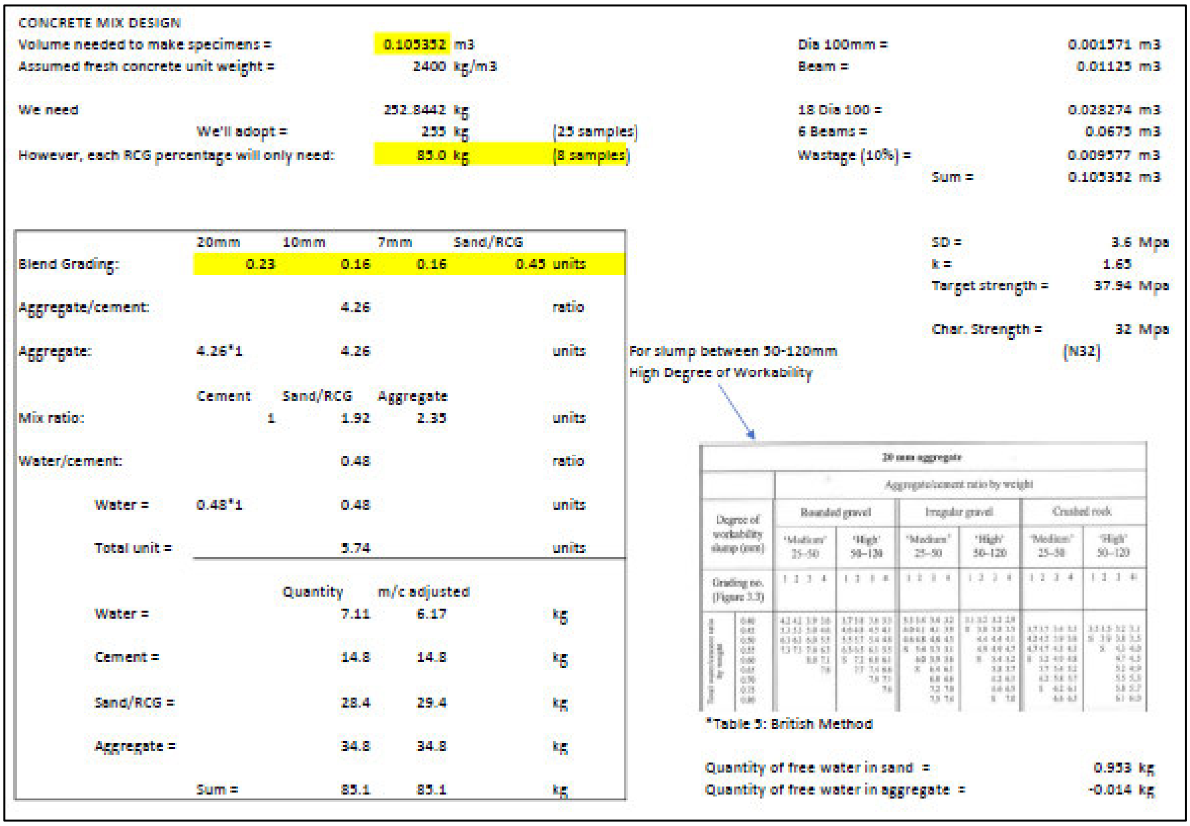


Figure 10: Concrete Mix Design Spreadsheet

The concrete batches were mixed using a shovel and electric concrete mixer until an even mix of the cement, water and aggregates was achieved. Sample creation was conducted in a controlled environment at the University of Southern Queensland laboratory under supervision by university lab technicians and frequent inspections by the project supervisor, Dr Sourish Banerjee.

4.2.3. Slump Test

As reported before, a couple of the initial control sample batches failed to provide minimum slump results. The slump was too high, and the mixture was too wet, therefore, the mix design was amended until a satisfactory slump was achieved. The high slump would negatively affect the final strength properties of the concrete because it would be susceptible to segregation.

To determine the workability of the fresh concrete mixes for all 3 mixes, the Slump Test was conducted. Workability indicates how simple and easy fresh concrete can be mixed, placed, handled, and compacted (Australia 2010).

Slump, in (mm)	Degree of Workability	Application
0-1 (0-25)	Very low	Very dry mixes used in paving machines with high-powered vibration
1-2 (25-50)	Low	Low-workability mixes used for foundations with light reinforcement; Pavements consolidated by hand-operated vibrators
2-4 (50-100)	Medium	Medium workability mixes; manually consolidated flat slabs. Normal reinforced concrete manually placed; heavily reinforced sections with mechanical vibration
4-7 (100-175)	High	High workability concrete for sections with congested reinforcement; May not respond well to vibration

Figure 11: Concrete Slump Chart (Backus 2022)

For this experiment, a low to medium slump was targeted and classified according to the Concrete Slump Chart (CSC) above.

The standard slump test procedure was followed as detailed below:

<u>Apparatus</u>

i. Standard slump cone
ii. Small scoop
iii. Bullet-nosed rod
iv. Ruler
v. Slump steel plate

<u>Method</u>

i. Ensure that the cone is clean. Dampen with water and place on the steel slump plate, the larger diameter will be at the bottom. Ensure that the steel slump plate is clear of any residue, firm, on a level surface and non-pervious.

ii. Collect the sample from the fresh concrete batch. Ensure you collect from various locations of the concrete mix to get a sample with even properties that are representative of the concrete batch.
iii. Place feet on slump plate foot pieces and fill a 1/3 of the volume of the slump cone with the fresh concrete sample. Compact the concrete by pushing the steel rod in and out of the concrete 25 times. Ensure you rod all areas of the concrete.
iv. Fill 2/3 of the slump cone volume and repeat step 3 for compacting the concrete.
v. Fill the slump cone until its full and repeat step 3 to compact the concrete sample. Top up the cone until its overflowing.
vi. Level off the surface by rolling the steel rod over the top of the slump cone. Ensure there is no concrete spillage around the base and top of cone. Push the slump cone down by grabbing the handles and step off the foot pieces.
vii. Slowly lift the cone vertically upwards, whilst making sure the sample does not move.
viii. Turn the empty slump cone upside down and place it next to the concrete sample. Place the steel rod across the upturned cone.
ix. Measure and record the average distance to the top of the concrete sample.
x. Classify the degree of workability of the sample by comparing the obtained slump values against table 3. (Australia 2010)

Figure 12: Slump Test – Batch 3

After conducting the slump test as shown in Figure 11 above, the following results were found:

- Batch 1: Control Sample – 70mm
- Batch 2 – 20% Sample – 45mm
- Batch 3 – 40% Sample – 28.3mm

The slump was all within an acceptable range and classified between low and medium. The slump was trending down with each batch, partly because the moisture that was initially corrected in the USQ natural sand was potentially drying up with time and so the mixture was getting dryer and dryer with time as well. However, this was not of a major concern as all the values were still within an acceptable range and workability was enough for casting into cylinder and beam moulds.

4.2.4. Concrete Beam Casting

The concrete beam moulds used in the experiment were 150mm x 150mm x 500mm in accordance with AS 1012.8.2-2014.

The beam samples were reinforced longitudinally with 10mm bars and 6mm stirrups @ 100mm spacing for shear reinforcement.

A minimum of 25mm cover all around was allowed as per AS3600 requirements.

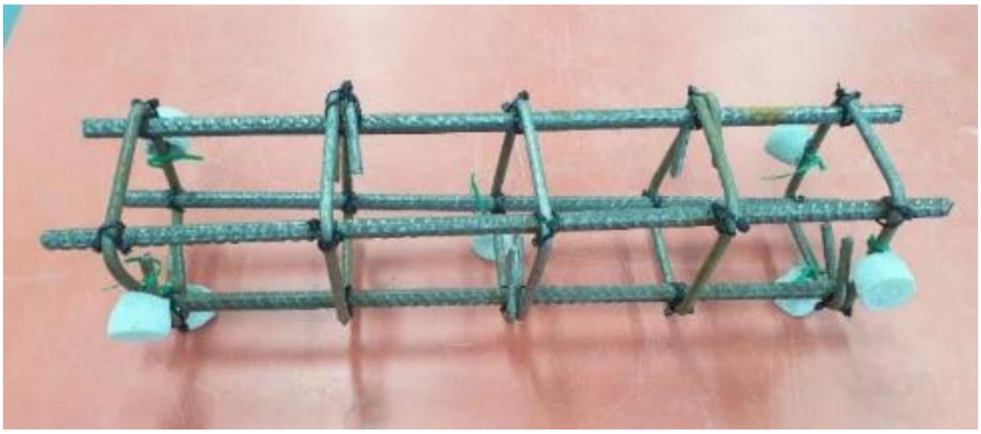


Figure 13: Concrete Beam Reinforcement

25mm high concrete blocks were created to ensure that the reinforcement is placed correctly in the beam moulds and to maintain 25mm cover all around as shown in Figure 13 below.

Figure 14: Concrete Beam Reinforcement in Mould

After conducting slump test the concrete was then placed into the beam moulds and a handheld vibrator poker was used to eliminate air bubbles and ensure that the concrete filled all the gaps around the reinforcement.

A hand float was then used to finish and smooth the top of the concrete beam.

Figure 15: Concrete Beam Soon After Casting

After 24 hours the concrete beams were removed from the moulds and the marked (date and sample information) with either a marker or writing into the concrete with a piece of wire as shown in Figure 15 and then samples were stored in the USQ curing room until 28 days have passed.

A total of 6 beams were cast namely 2 for the control sample, 2 for 20% samples and 2 for 40% samples.

Figure 16: Marked Concrete Beam Samples

4.2.5. Concrete Cylinder Casting

A total of 18 (Ø 100mm x 200mm high) concrete cylinders were cast for split-tensile testing and compressive strength testing.

Each batch of concrete had 3 concrete cylinders cast i.e., 3 for control sample, 3 for 20% and 3 for 40%. The average results will be recorded when the final testing is conducted on the hardened concrete samples.

The following standard casting procedure for concrete cylinders was followed in accordance with AS 1012.8.2-2014:

Apparatus

i. Concrete cylinders (Ø 100mm x 200mm high)
ii. Small scoop
iii. Bullet-nosed rod
iv. Steel float
v. Steel baseplate

Method

i. Ensure the cylinder mould is clean and coat the inside of the cylinder lightly with form oil. Place on the steel plate which should be clean, flat, and firm.
ii. Collect the sample from the fresh concrete batch. Ensure you collect from various locations of the concrete mix to get a sample with even properties that are representative of the concrete batch.
iii. Fill ½ the volume of the cylinder with fresh concrete and compact 25 times by using the steel rod. A vibration table can also be used for compaction.
iv. Fill the cylinder until its overflowing and rod 25 times using the steel rod and top up the sample until its overflowing.
v. Level off the surface by rolling the steel rod over the top of the cylinder. Ensure there is no concrete spillage around the base and top of cylinder.
vi. Install cylinder cap and clearly tag the cylinders for easy identification. Place in a cool dry place and allow the concrete to set for 24 hours.
vii. After setting for 24 hrs, remove cylinder mould and cure concrete sample for 28 days.

After removing the cylinder mould, the concrete samples were placed in a curing room in the USQ lab for 28 days in preparation for the compressive and split-tensile tests.

Figure 17: Marked Concrete Cylinder Samples

4.3. Hardened Concrete Testing Methodology

4 tests are to be conducted on the 7 samples created in section 5.2. These tests will be:

i. The Compression Test
ii. Flexural Strength of Beams
iii. Split-Tensile Strength Test
iv. Visual Appearance Check

4.3.1. The Compression Test

To determine the compressive strength of the 7 concrete samples, the compression test will be completed. This test will test the compressive strength of hardened concrete. Compressive strength is measured in megapascals (MPa) and is normally specified as the characteristic strength of concrete measured after 28 days after mixing. Compressive strength of concrete is a measure of the hardened concrete's ability to resist crush loads.

After successful curing, crush test the concrete sample to obtain compressive strength.

4.3.2. Flexural Strength of Beams

After 28 days, the 7 concrete beam samples flexural strength will be tested in accordance with AS 1012.8.2-2014.

4.3.3. Split-Tensile Strength Test

After 28 days, the 7 concrete cylinder samples split-tensile strength will be tested using the indirect method in accordance with AS 1012.8.1-2014.

Method:

i. Place the cylinder sideways between the platens of the compression test machine.
ii. Set the loading rate as per testing standard and proceed loading.
iii. Record the failure load (in kN)
iv. Calculate the tensile strength (in MPa)

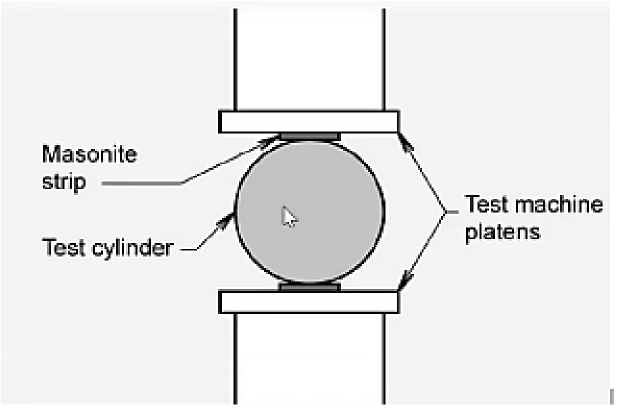


Figure 18: Tensile Strength – Indirect Method (USQ 2022)

The following measurements will need to be taken:

1. Weight of the concrete sample in kilograms
2. Height (L) in meters
3. Diameter (D) in meters
4. Maximum load at failure (P) in kilonewtons

The tensile strength in MPa will be calculated using the following expression:

Tensile Strength (MPa) = $\frac{2P}{1000\pi LD}$

4.3.4. Visual Appearance Check

The surface finish of concrete contributes to the aesthetic look infrastructure. The introduction of organic and inorganic pigments, natural stone and consciously chosen coarse aggregates has created various desirable surface finishes for concrete (Heinemann 2017).

In this research, the final appearance of each of the 7 samples will be briefly reported and compared against other finishes available in the concrete market. However, because appearance is subjective, no conclusions will be drawn from this but rather the results will be documented to assist consumers when attempting to reproduce a similar concrete finish in various applications.

Traditional concrete finishes to be compared include, but not limited to:

i. Coloured concrete
ii. Exposed aggregate concrete
iii. Textured finish or decorative concrete
iv. Plain concrete

4.4. Expected Outcomes

The project will aim to assist in drawing definitive conclusions and reaching consensus on the effects of recycled crushed glass in concrete. The experimental data produced by this research can be used to standardise RCG concrete within the construction industry.

Some of the expected outcomes of this research include:

i. Help draw definitive conclusions and reaching consensus on the effects of recycled crushed glass in concrete.
ii. Provide consistent experimental evidence that supports the use of recycled crushed glass in concrete.
iii. Determine the appropriate mix ratios of recycled crushed glass in concrete, that will give adequate compressive strength, flexural strength, split-tensile strength, slump values, durability, and appearance.
iv. The success of this research will largely benefit the waste glass recycling industry and the environment. Recycled crushed glass is a more sustainable form of aggregate when compared to natural sand, therefore reducing the depletion of natural sand deposits will provide environmental benefits on a global scale.

5. CONSEQUENCES AND ETHICS

The project methodology, experimentation and reporting complies with the values and principles set out in the Engineers Australia Code of Ethics (Australia 2022) to ensure that the researchers act in a way that is keeping with the nationally recognised engineering ethical standards. which stipulate that a Professional Engineer shall:

1. Demonstrate integrity – this will be demonstrated through reporting the objective outcomes accurately without bias, regardless of the consequences of the outcomes. As engineers in this project, we are committed to be trustworthy and honest to ensure that we can accurately develop a sustainable engineering solution for the civil construction industry. Researchers will ensure that all sources of information utilised in the development of this research paper are cited and referenced in accordance with Harvard AGPS referencing style.
2. Practise competently – the engineers and technical personnel involved in the completion of this research project commit to act on the premise of adequate and well-informed knowledge. The experiment will be conducted in the presence of well skilled and competent technicians who will ensure that the outcomes achieved are as accurate as possible. The researcher will seek expert review and advise from the project supervisor on an ongoing basis, on the content of this report to ensure that an accurate and professional standard of work is upheld.
3. Exercise leadership – researchers will actively champion the ethical issues in undertaking of this research project. All issues arising from the project will be communicated clearly and in a timely manner to all affected parties. One of the unwritten expectations of this project is to maintain a reputation and integrity of the engineering practice and this will be addressed by exercising leadership and advocating for all parties involved to act in an ethical manner in keeping with the Engineers Australia Code of Ethics.
4. Promote sustainability – the principle of sustainable engineering is well addressed by the objectives of this research project. One of the main objectives of this report which is to move away from natural sand and reuse recycled crushed glass in concrete is triggered by the need for engineering activities to incorporate environmental and economic considerations, including balancing the needs of the future population with that of the current. This is wholly a sustainability objective and complies with one of the four ethical guidelines set out by the Engineers Australia Code of Ethics. This

project will accurately report on all the potential consequences that are likely to be encountered because of the actions that are experimented in this research project.

The ethical standards will be directly monitored by the owner of the research project, and they shall lead the entire project team in accordance with these ethical guidelines. This transparency will ensure that the trustworthiness of the engineering practice is upheld. (Australia 2022)

Consequences as a result of the actions undertaken in developing this report are both positive and negative. Some of the consequences that are expected as part of this research include:

- Sustainability issues
- Safety related consequences
- Ethical issues

5.1. Sustainability Issues

As briefly discussed under section 4, the main objective of this research is to promote environmentally sustainable use of construction materials and so by reducing the need to depend on natural sand this will have a desirable impact on the environment.

To ensure the project achieves its sustainability goals, these extra steps will also be taken:

- The materials used in the creation of samples will be sustainably sourced from reputable sustainable vendors.
- Only the required quantities will be sourced to reduce wastage of concrete material.
- Concrete specimens will then be crushed and reused as recycled crushed concrete for various applications including, base material for pavements or can be disposed to recycling plants where it can be resold as recycled crushed concrete.

5.2. Safety Related Consequences

All safety related consequences associated with the preparation and testing of concrete samples with recycled crushed glass have been adequately assessed and controlled through a Risk Management Plan.

The risk management plan can be found in Appendix B. Also refer to section 5.2 for further risk related information.

5.3. Ethical Issues

Ethical guidelines set out in the Engineers Australia Code of Ethics will guide the research team and ensure that the team commits to abiding by these principles. This will be managed by the leader of the research paper and the consequences of not complying could include engineers losing their membership if they're found to be negligent. (Australia 2022)

A full detailed analysis of how ethical responsibility will be managed throughout the research project is provided at the beginning of section 4 of this research paper.

6. RESULTS AND DISCUSSION

The following tests were conducted on the concrete samples as discussed in section 3 "Hardened Concrete Testing Methodology":

- Compressive strength test
- Split-tensile strength test
- Flexural strength of beams

Figure 19: Hardened concrete samples prior to testing

The garnered results are discussed in the section below.

6.1. Slump test

The slump test was undertaken in accordance with relevant Australian Standards and the procedures mentioned in section 3.2.3. Some of the results have been discussed in section 3.2.3 above.

The resulting slump data is illustrated in 'chart 4' below:

- Batch 1: Control Sample – 70mm
- Batch 2: 20% Sample – 45mm
- Batch 3: 40% Sample – 28.3mm

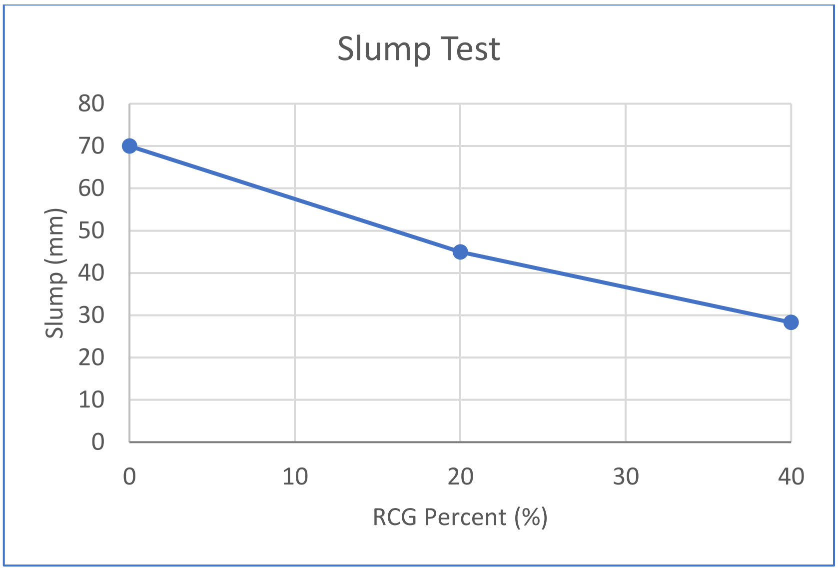


Chart 4: Slump vs RCG Percentage Graph

The slump was all within an acceptable range and classified between low and medium. The slump was trending down with each batch, partly because the moisture that was initially corrected in the USQ natural sand was potentially drying up with time and so the mixture was getting dryer and dryer with time as well. However, this was not of a major concern as all the values were still within an acceptable range and workability was enough for casting into cylinder and beam moulds.

As reported before, a couple of the initial control sample batches failed to provide minimum slump results. The slump was too high, and the mixture was too wet, therefore, the mix design was amended until a satisfactory slump was achieved. These amendments to the mix design based on the slump provide a good guide to researchers on how to prepare the concrete mix design and what slump values to expect.

However, it is recommended to ensure aggregates are dry prior to mixing of concrete with RCG because this has shown to affect workability.

6.2. Compressive Strength Test

After 28 days, the compressive strength of the concrete cylinders was tested in accordance with AS 1012.8.2-2014.

6.2.1. Control Sample

3 control samples were tested, and the average was taken.

The control sample contained 0% of RCG and was made using traditional concrete material. These results will be used a benchmark for the 20% and 40% samples, to gauge the performance of the samples as RCG is incrementally increased to 40%.

The average weight, average height and diameter of the samples was measured and reported in table 17.

Figure 20: Measuring of cylinders

Figure 21: Crush test machine

The compressive strength and failure load of each of the samples was reported in table 17.

	C1	**C2**	**C3**	**Average**
Weight	3.75kg	3.75kg	3.75kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	200mm	
Failure Load	372.9	354	346.3	**357.73**
Compressive Strength	47.5	45.1	44.1	**45.57**

Table 17: Compressive Strength Results – Control Sample

The cylinders achieved a much higher compressive strength that what was targeted (37.94 Mpa), which indicates that the control samples were satisfactory. This is expected and shows that the concrete when prepared correctly will yield a much higher compressive strength capacity and thus make structures safer than their designed for.

The data had a standard error of **±1.75 Mpa** which shows that deviation was minimal and insignificant to affect the overall confidence in the data.

These trends and findings will be checked in the upcoming samples which contained RCG.

The failure modes can be observed in figure 22 and 23 below.

Figure 22: Failure mode C1

Figure 23: Failure mode C2

The samples sheared at a 45-degree angle from the top to the centre of the cylinder and behaved consistent with theoretical expectations for traditional concrete specimens. However, even though the specimen sheared at this angle, it did not completely shatter into small pieces which some of the following samples with RCG will demonstrate.

6.2.2. 20% RCG Samples

Like the control sample, 3 20% samples were tested, and the average was taken.

The 20% sample had 20% replacement of sand with RCG.

The average weight, average height, diameter, compressive strength and failure load of the samples was measured and reported in table 18.

	20% (1)	**20% (2)**	**20% (3)**	**Average**
Weight	3.75kg	3.75kg	3.75kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	202mm	
Failure Load	334.7	319.9	322.3	**325.63**
Compressive Strength	42.6	40.75	41.1	**41.48**

Table 18: Compressive Strength Results – 20% RCG Samples

The data had a standard error of **±0.98 Mpa** which shows that deviation was minimal and insignificant to affect the overall confidence in the data.

There was a slight drop in strength of approximately 4.09Mpa from the control sample (45.57Mpa) to the 20% RCG sample (41.48Mpa). However, the average compressive strength of the 20% samples was still 3.54Mpa higher than the target strength of the mix design (37.94Mpa), this shows that if the mix design is done properly and adjustments for the water/cement ratio are made as shown in this research paper, the 20% RCG concrete samples would produce adequate mechanical and physical properties.

The failure mode can be observed in figure 24 below.

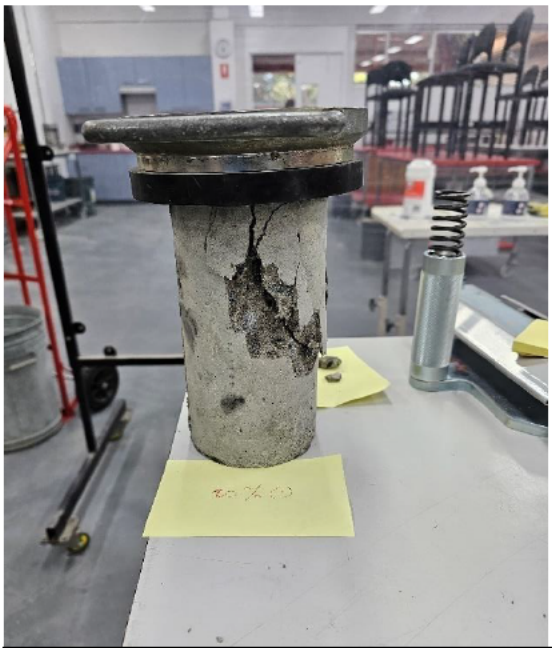


Figure 24: Failure mode: 20% Sample

Consistent with the control samples, the 20% RCG samples sheared at a 45-degree angle from the top to the centre of the cylinder and behaved consistent with theoretical expectations for traditional concrete specimens. This is expected because the compressive strength results were only 8.95% lower than the control samples and 8.5% higher than the target strength.

6.2.3. 40% RCG Samples

Like the control sample, 3 40% samples were tested, and the average was taken.

The 40% sample had 40% replacement of sand with RCG.

The average weight, average height, diameter, compressive strength, and failure load of the samples was measured and reported in table 19.

	40% (1)	40% (2)	40% (3)	Average
Weight	3.70kg	3.70kg	3.70kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	200mm	
Failure Load	246.5	244	301.4	**263.97**
Compressive Strength	31.4	31.1	38.4	**33.63**

Table 19: Compressive Strength Results – 40% RCG Samples

The data had a standard error of **±4.93 Mpa** which shows that deviation was much higher when compared to the control sample and 20% RCG sample standard deviation of **±1.75 and ±0.98** respectively. This large error was due to the last sample producing a compressive strength of 38.4Mpa which was approx.. 7Mpa higher than the first 2 samples. As a result the deviation is large and affected the confidence in the data.

Additionally, the average compressive strength was 11.4Mpa lower than the target strength which is unsatisfactory. Therefore, this coupled by the large standard error demonstrates that when 40% RCG is added into concrete, inconsistent and inconclusive results are to be expected. This finding discourages the use of RCG at this percentage until further evidence can be garnered to improve the consistency of the concrete properties at 40% RCG replacement of sand.

The failure modes can be observed in figure 25 and 26 below:

Figure 25: Failure mode:40%(a)

Figure 26: Failure mode:40%(b)

Unlike the control sample and the 20% RCG samples, the 40% RCG samples completely shattered under much less compressive loading. The failure mode shown above shows how weak the concrete samples had become at 40% RCG replacement under compressive load.

6.2.4. Comparison and Discussion

	Control	**20%**	**40%**
Weight (kg)	3.75	3.75	3.75
Dia (mm)	100	100	100
Height (mm)	200	200	200
Compressive Strength (Mpa)	45.57 ± 1.75	41.48 ± 0.98	33.63 ± 4.93
Tensile Strength (Mpa)	2.51 ± 0.26	2.07 ± 0.30	2.55 ± 0.33

Table 20: Compressive Strength Results – All samples

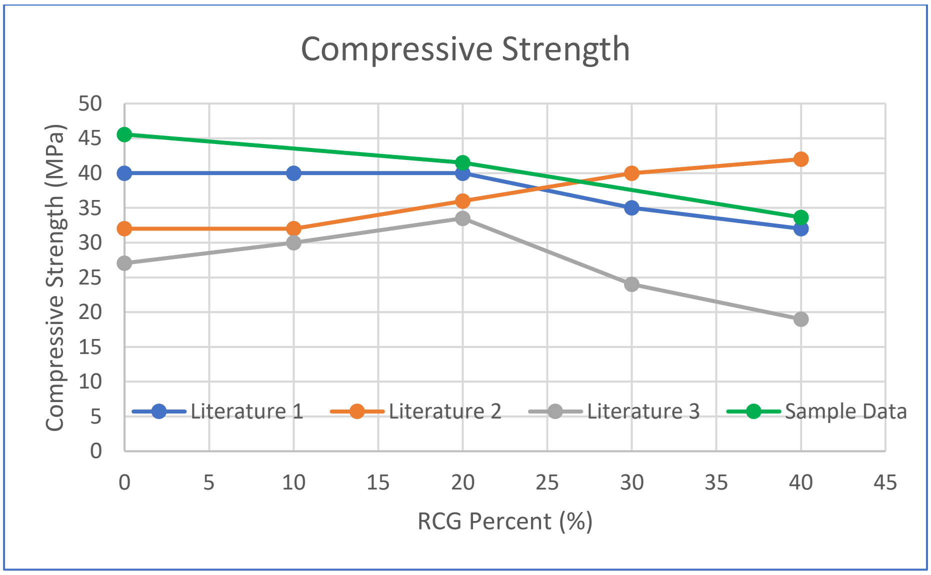


Chart 5: Comparison of Compressive Strength Results

- Literature 1: *(Mageswari & Vidivelli 2010)*
- Literature 2: *(Vijayakumar, Vishaliny & Govindarajulu 2013)*
- Literature 3: *(Raju & Kumar 2014)*

As shown in chart 5 above, as the RCG percentage increased the compressive strength of the cylinders reduced for the sample data, literature 1 and literature 3. However, literature 2 has shown the opposite effect which is now proving to be incorrect based the findings of this report supported by the trend of lit 1 and lit 3.

Some of the reasons contributing to the reduction in strength have been summarised to be following:

i. An aggregate crushing value (ACV) test was not undertaken which would have provided a measure of the resistance of the glass material when a compressive load is applied. However, the results from the cylinder compressive strength have demonstrated that the ACV value for glass is much lower than natural sand hence the reduction in strength. The findings are consistent with this analogy. Future research can be undertaken to ascertain the ACV for RCG and confirm the findings within this report.
ii. The clear glass used in the experiment was processed to a high degree which is evidenced by the lack of random colours in the glass material. Randomisation of the glass material would allow for grading of strength properties to be optimised and improved.

The results for 20% RCG concrete are encouraging and there is mounting evidence to support the use of RCG in concrete at percentages less than or equal to 20% as it achieves a compressive strength that is 8% higher than the target strength.

6.3. Split-Tensile Strength Test

After 28 days, the split-tensile strength of the concrete cylinders was tested in accordance with AS 1012.8.2-2014 and as per the procedure stated in section 3.3.3.

Figure 27: Split-Tensile Test Setup

6.3.1. Control Sample

3 control samples were tested, and the average was taken.

The average weight, average height, diameter, compressive strength, and failure load of the samples was measured and reported in table 21.

	C1	**C2**	**C3**	**Average**
Weight	3.75kg	3.70kg	3.80kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	200mm	
Failure Load	86.7	70.3	79.9	**78.97**
Tensile Strength	2.76	2.24	2.54	**2.51**

Table 21: Split-Tensile Strength Results –Control Samples

The data had a standard error of **±0.26 Mpa** which shows that deviation was minimal and insignificant to affect the overall confidence in the data.

AS3600 clause 3.1.1.3 stipulates that at 28 days the uniaxial tensile strength can be calculated using $0.36\sqrt{f'_c}$.

This formula produces a theoretical 28-day tensile strength of $0.36\sqrt{32}$ = 2.04 Mpa.

In comparison to the theoretical understanding in AS3600, the control sample was 23% higher. This is consistent with the compressive strength findings of having much higher strength properties than the target.

The failure modes can be observed in figure 26 below:

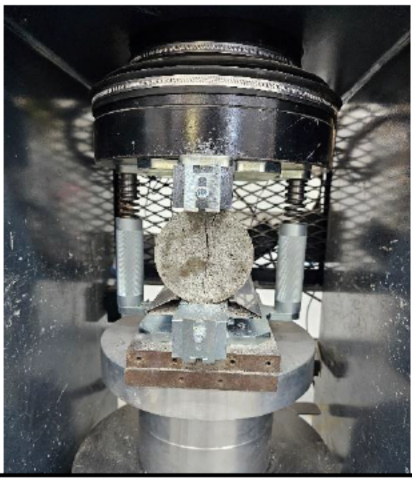


Figure 28: Split-Tensile Failure Mode: Control Sample

The failure mode for all split-tensile samples (control, 20% RCG and 40% RCG) produced the same crack pattern. The sample sheared vertically as shown in figure 28. However, the tensile strength values were different as will be shown in upcoming sections of this report.

6.3.2. 20% RCG Sample

3 control samples were tested, and the average was taken.

The average weight, average height, diameter, compressive strength, and failure load of the samples was measured and reported in table 22.

	20% (1)	**20% (2)**	**20% (3)**	**Average**
Weight	3.70kg	3.70kg	3.75kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	202mm	
Failure Load	75.5	62.1	57.2	**64.93**
Tensile Strength	2.4	1.98	1.82	**2.07**

Table 22: Split-Tensile Strength Results –20% RCG Samples

The data had a standard error of **±0.30 Mpa** which shows that deviation was minimal and insignificant to affect the overall confidence in the data.

The average tensile strength results when compared to AS3600 theoretical formula is 1.5% higher. However, the difference between the control sample and the 20% tensile strength is quite large and inconclusive. Further discussions will be made after the 40% results are reported below.

As discussed in section 5.3.1, the failure mode for the 20% RCG sample was the same as the control sample (Figure 25).

6.3.3. 40% RCG Sample

3 control samples were tested, and the average was taken.

The average weight, average height, diameter, compressive strength, and failure load of the samples was measured and reported in table 23.

	40% (1)	40% (2)	40% (3)	Average
Weight	3.70kg	3.70kg	3.70kg	
Dia	100mm	100mm	100mm	
Height	200mm	200mm	200mm	
Failure Load	91.7	76	71.8	**79.83**
Tensile Strength	2.92	2.43	2.29	**2.55**

Table 23: Split-Tensile Strength Results –40% RCG Samples

The data had a standard error of **±0.33 Mpa** which shows that deviation was minimal and insignificant to affect the overall confidence in the data.

The average tensile strength results when compared to AS3600 theoretical formula is 25% higher. These results are very inconsistent as they do not display any particular trend. The 40% RCG sample had the highest split-tensile strength of all the tested samples, including the control sample. The up and down nature of the results could be due to an error in the testing setup when the 20% RCG sample was loaded. However, all results were above the AS3600 theoretical expectation for tensile strength.

This proves that the samples maintained satisfactory tensile strength properties as the RCG percentage increased.

As discussed in section 5.3.1, the failure mode for the 40% RCG sample was the same as the control sample (Figure 25).

6.3.4. Comparison and Discussion

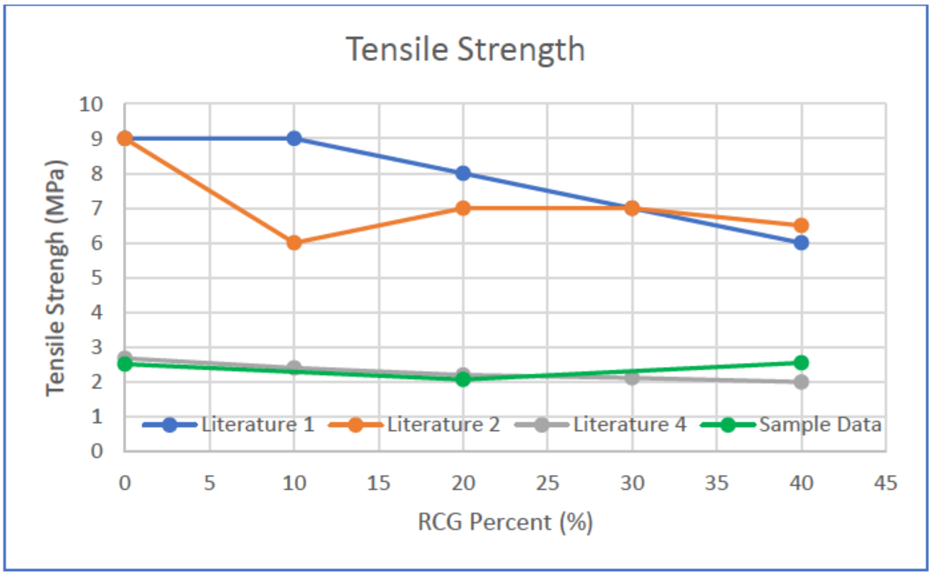


Chart 6: Comparison of Split-Tensile Strength Results

- Literature 1: *(Mageswari & Vidivelli 2010)*
- Literature 2: *(Vijayakumar, Vishaliny & Govindarajulu 2013)*
- Literature 4: *(Kavyateja, Reddy & Mohan 2016)*

As shown in chart 6, the tensile strength of the concrete cylinders reduced at 20% and increased at 40% RCG replacement when compared to the control sample. However, all results were above the AS3600 theoretical expectation for tensile strength, which proves that the samples maintained satisfactory tensile strength properties as the RCG percentage increased.

Some of the reasons that may have contributed to the inconsistent results include:

i. The shape of the glass was not tested and thus this could mean that if the glass material contained angular particles more than sand, it would bond better with the concrete and produce a higher split-tensile strength. Future research can focus on aggregate shape testing to ensure that this can be confirmed.

ii. Since the 20% sample data is the only one that varied greatly from the control sample (40% RCG sample data was only 1.5% higher than the control sample), it would suggest that the sample may have been incorrectly prepared and therefore the results should be approximately similar to the control sample and 40% RCG sample. It should be noted that this sample was prepared by a colleague that was not part of the initial sample preparation and may have altered the procedure.

Additionally, the results are closely relatable to lit 4, plus lit 2 also shows a dip at 10% and then an increase thereafter, this could be simply because tensile strength increases with increase to RCG.

Further work will need to be undertaken on the tensile strength behaviour of concrete with RCG.

Lastly, it’s still important to highlight that regardless of these inconsistencies of the tensile strength data, the samples maintained satisfactory tensile strength properties as the RCG percentage increased and all results were above the AS3600 theoretical result.

6.4. Flexural Strength of Beams

After 28 days, the flexural strength of the concrete beams was tested in accordance with AS 1012.8.2-2014.

A 25mm x 25mm grid was drawn on the concrete beam face to measure the crack propagation as the concrete beams are loaded (figure 26).

The 4-point test rig was used, and the force was applied at 10kN increments and after each increment the beams were inspected to mark and trace the cracks, which would help establish some knowledge on the failure mode of beams with RCG.

The distance between the top loading points was **150mm** whilst the distance between the bottom supports was **450mm**.

Figure 29: Concrete Beam with Grid on 4-Point Test Rig

The beam deflection and failure load were measured.

The first 3 samples of different RCG proportions were tested using the 4-point test machine and grid system and the other 3 samples were tested using the 4 -point test machine with Digital Image Correlation (DIC) scanning so to compare the two methods.

The camera scans the points marked on the face of the beam and then measures the deflection of that point when loading is applied. The grid was setup as shown Figure 30 below:

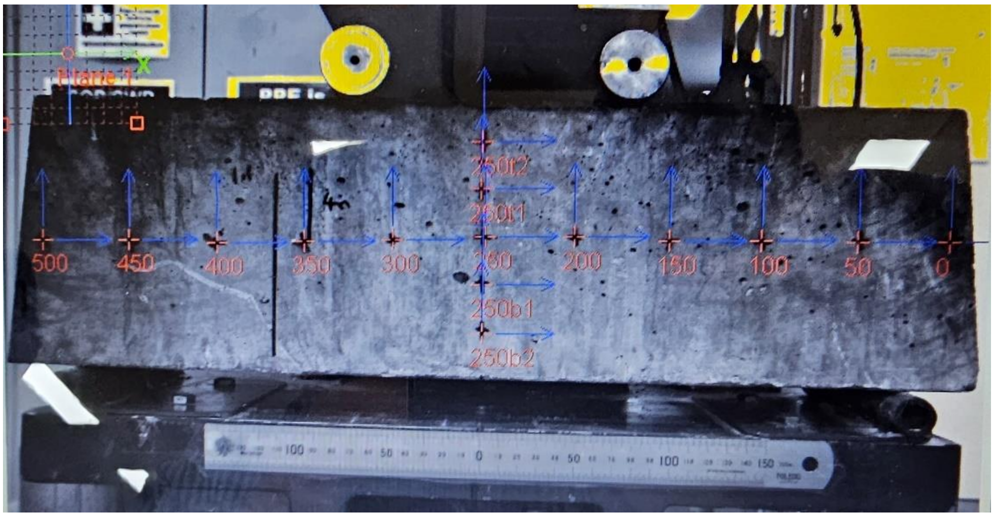


Figure 30: DIC Grid Configuration on Beam

Figure 31: DIC equipment setup

6.4.1. Control Sample

The first control sample was tested with the grid system and produced the following figure:

Figure 32: Control sample 1 at failure

The grid on the beam helped show the crack propagation which was then marked with a red marker and the load at which the crack formed was recorded next to the cracks.

The second control sample was tested with the DIC scanning technology and produced the following figure:

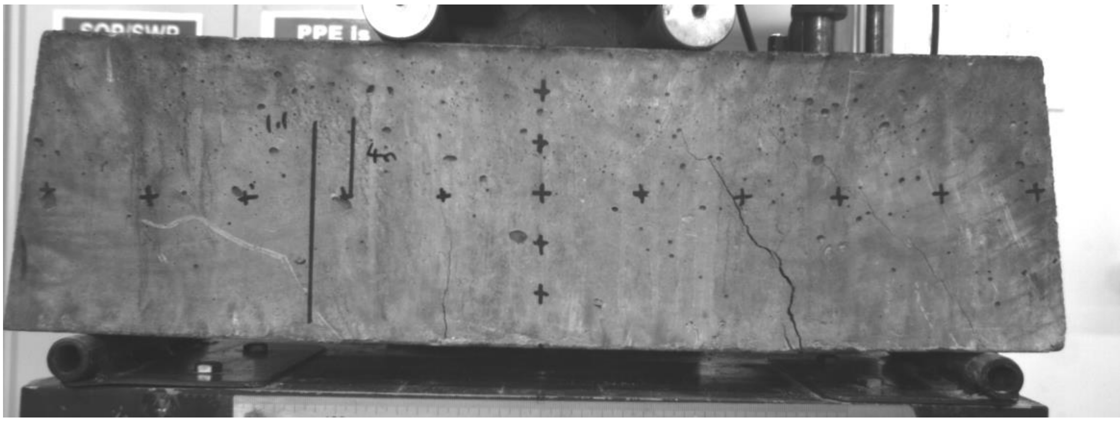


Figure 33: Control sample 2 at failure

The average failure load and deflection were plotted in the chart below:

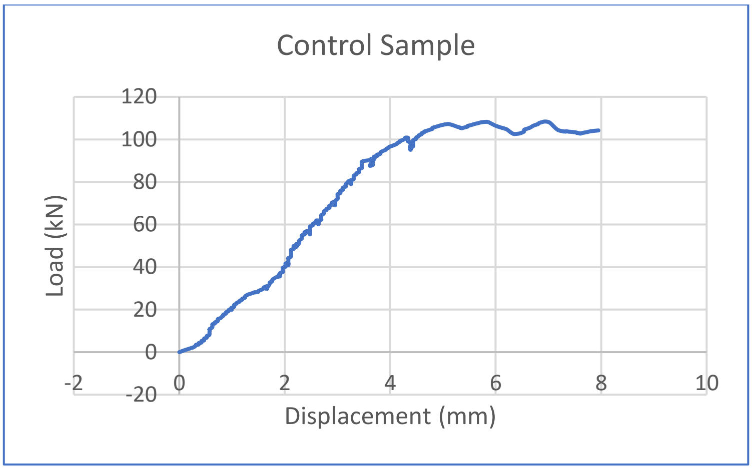


Chart 7: Average flexural strength of control sample

6.4.2. 20% RCG Sample

Similar to the control sample, the first 20% RCG sample was tested with the grid system and produced the following figure:

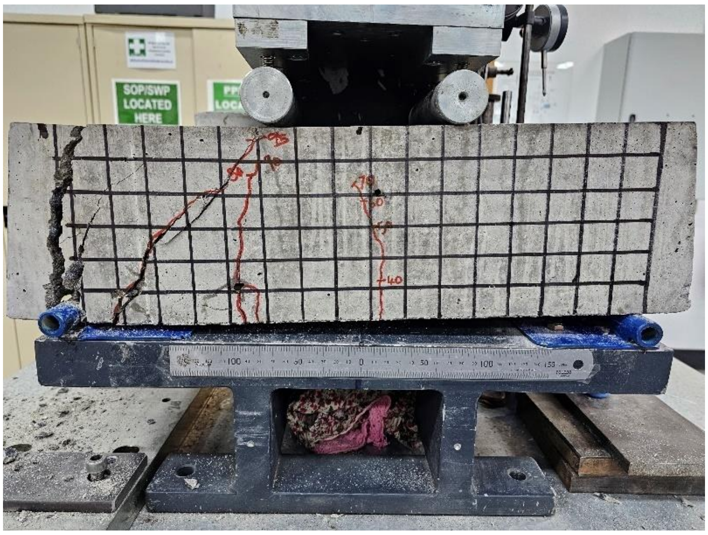


Figure 34: 20% RCG sample 1 at failure

The second 20% RCG sample was tested with the DIC scanning technology and produced the following figure:

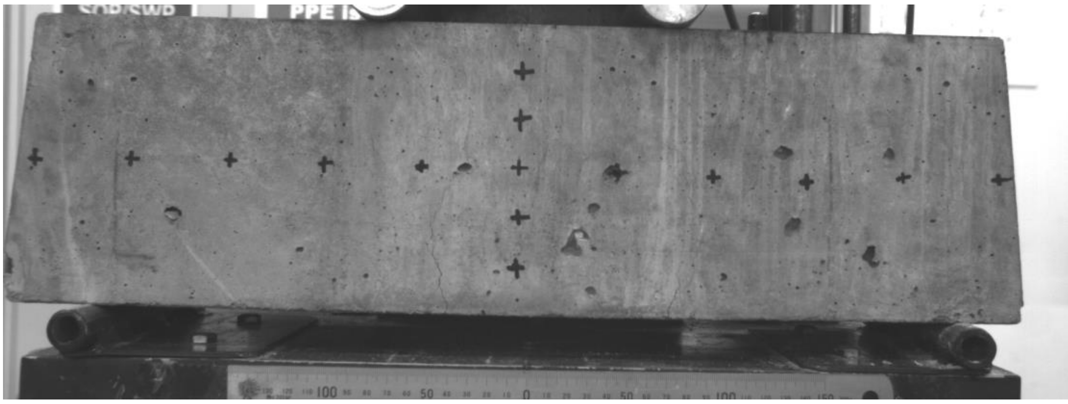


Figure 35: 20% RCG sample 2 at failure

The average failure load and deflection were plotted in the chart below:

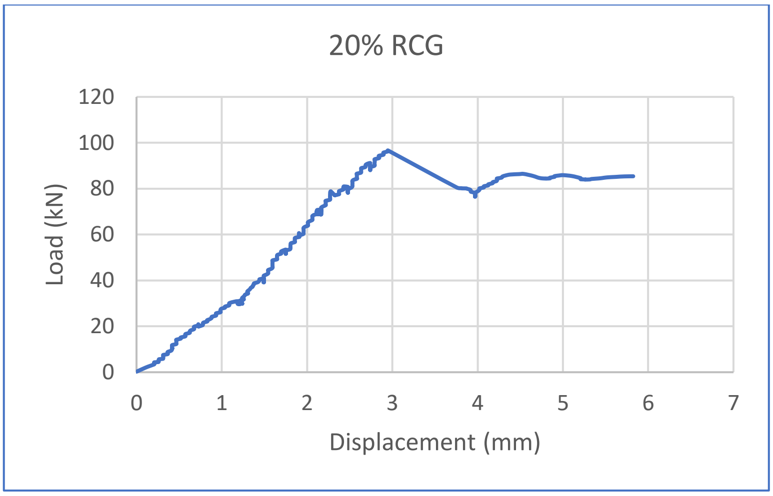


Chart 8: Average flexural strength of control sample

6.4.3. 40% RCG Sample

Similar to the control sample, the first 40% RCG sample was tested with the grid system and produced the following figure:

Figure 36: 40% RCG sample 1 at failure

The second 40% RCG sample was tested with the DIC scanning technology and produced the following figure:

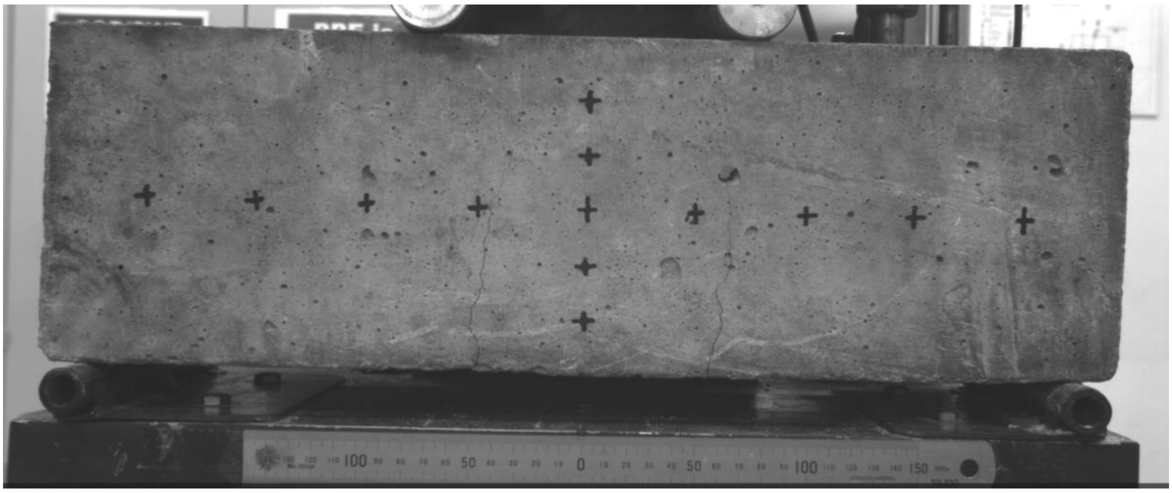


Figure 37: 40% RCG sample 1 at failure

The average failure load and deflection were plotted in the chart below:

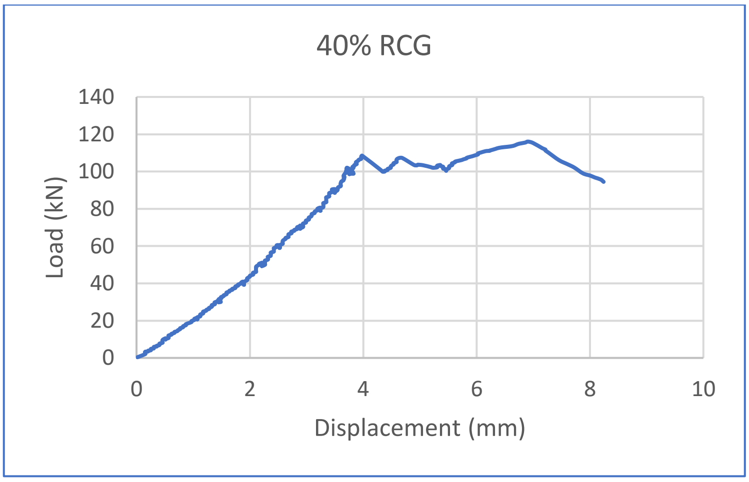


Chart 9: Average flexural strength of control sample

6.4.4. Comparison and Discussion

Unfortunately, due to time and software constraints, the DIC analysis could not be undertaken and so only the data from the 4-point bending machine was used in this report.

In all 3 beams, a similar pattern of failure and cracking was observed. The first crack was observed at the bottom centre of the beams at approx. 30kN. The beams would continue to crack along the centre up to about 70kN and then the centre crack would stop forming. The beams would then continue to take more load and then eventually a 45-degree shear crack would form. This shear crack ran from the top loading point to the bottom support.

At this point, the beam would start yielding up until failure.

All the charts above for the 3 beams, show that the beams would gradually take the load up to a point and then yield for some time before complete failure.

This is consistent with the theoretical understanding of reinforced concrete, because initially as the beam bends, the highest bending moment is expected to be at the bottom centre of the beam and because concrete is weak under tension, this caused the beams to start cracking. However, due to the steel reinforcement (longitudinal and shear), the beams would then be able to resist any further cracking as the steel reo would begin to resist the bending of the beams.

Additionally, the centre crack would stop propagating as well due to the compressive capability of concrete at the top of the beam, which is the region in which compression occurs when a beam is in bending.

In relation to the effects of RCG in the beams, 2 aspects were reported:

i. **Crack propagation:**
    a. The control sample and the 20% RCG sample behaved similarly i.e., the initial crack at 30kN travelled the same distance along the grid which demonstrates that good mechanical properties are maintained after replacing 20% of sand with RCG in concrete, for concrete beam applications. However, the 40% beam initial crack travelled twice the distance when compared to the first 2 samples, this demonstrated a significant drop in concrete strength because at these low loads the concrete would have been carrying most of the tensile load before the steel reo was engaged.

ii. **Flexural Strength:**
    a. The flexural strength for all beams was very high and because the beams were reinforced it is assumed that the steel reinforcement ensured that the beams would carry similar maximum loads. However, the data varies slightly between batches:

    Average maximum flexural strength before yielding:

    Control Sample = 106 kN

    20% RCG Sample = 96 kN

    40% RCG Sample = 106 kN

Considering these results, the beams were relatively similar in their capacity to withstand flexural bending when reinforced with steel (longitudinal bars and shear stirrups). The slight drop in the 20% sample could not be analysed due to the time and software constraints presented by the DIC scanning process. Future research can be undertaken to determine what the effects of RCG in concrete would be if the beams are not reinforced.

7. KEY OUTCOMES AND CONCLUSION

7.1. Key Outcomes

The project set out to:

- Provide an alternative material that provides sufficient strength and durability. Recycled crushed glass is a more sustainable form of aggregate when compared to natural sand, therefore reducing the depletion of natural sand deposits will provide significant environmental benefits on a global scale.
- Help draw definitive conclusions and reach a consensus on the effects of RCG in concrete and increase consumer confidence in the use of RCG, which has been reduced by inconsistent findings in previous studies.
- Determine the appropriate mix ratios that will give adequate physical and mechanical properties.
- Measure various physical and mechanical properties of concrete made with RCG replacing natural sand.

When assessing the success of this study against the project objectives summarised above, the following key outcomes have been realised:

Concrete Mix Design

The research was able to assess the mix design ratios that were used in the other research studies and found that there was no uniformity:

Mix Ratios:

- Literature 1 *(Mageswari & Vidivelli 2010)* – 1:1.66:3.61 @ 0.48 w/c
- Literature 2 *(Vijayakumar, Vishaliny & Govindarajulu 2013)* – 1:2.33:3.6 @ 0.53 w/c
- Literature 3 *(Raju & Kumar 2014)* – 1:2.35:4.47 @ 0.5 w/c
- Literature 4 *(Kavyateja, Reddy & Mohan 2016)* – 1:1.5:3 @ 0.5 w/c

By adjusting the water/cement ratio based on numerous trial and error concrete batches, the concrete mix design was then adjusted accordingly to ensure that adequate slump was achieved.

By doing this, the study was able to achieve an optimum mix design, which if followed, ensures that consistent physical and mechanical properties are achieved.

This then builds on existing research and provides confidence to the construction sector on what to expect when using RCG in concrete and following a consistent mix design process as demonstrated in this research report.

Concrete Physical and Mechanical Properties

The compressive strength results for 20% RCG concrete are encouraging and there is reasonable evidence to support the use of RCG in concrete at percentages less than or equal to 20% as it achieves a compressive strength that is 8% higher than the target strength.

The tensile strength of the concrete cylinders reduced at 20% and increased at 40% RCG replacement when compared to the control sample. However, all results were above the AS3600 theoretical expectation for tensile strength, which proves that the samples maintained satisfactory tensile strength properties as the RCG percentage increased.

The flexural strength of the beams was relatively similar in their capacity to withstand flexural bending when reinforced with steel (longitudinal bars and shear stirrups), this proves that in reinforced concrete beam applications, the use of RCG in concrete does not result in a significant decline in strength when compared with traditional concrete mixes.

All the above evidence supports the use of RCG in concrete at percentages less than or equal to 20%.

Cost and Availability Analysis

Due to manufacturer constraints at the time of conducting this experiment, the RCG material was only available in 3 different sizes.

The RCG was not available from our usual vendor in QLD, instead it was purchased from Victoria, resulting in shipping delays.

The cost of the glass was extremely high when compared to natural sand, at about $85 per 20kg bag of RCG.

Therefore, it is important to note that this dilemma (cost and availability) needs to improve, to encourage contractors to actively utilise RCG in their various concrete applications.

7.2. Future Research

Below is a short summary of the areas in which future research can build from this dissertation.

- Environmental impact of recycling waste glass vs. the current impacts.
- Safety aspects when handling RCG for workers and determining appropriate construction procedures.
- Future research can be undertaken to ascertain the Aggregate Crushing Value (ACV) for RCG and confirm the findings within this report (increase in RCG resulted in decrease in strength properties).
- Future research can focus on aggregate shape testing to ascertain the relationship between RCG shape and split-tensile strength.

7.3. Conclusion

Finding the causes of inconsistent results for samples with RCG is a key success of this report as it will support the uptake of this sustainable material as a fine aggregate in concrete mixes.

Additionally, the development of an optimum mix design will provide consumer confidence in the RCG material as it ensures consistent physical and mechanical properties can be achieved with each mix when the correct mix design process is followed, as outlined in this report.

Recycled crushed glass is a more sustainable form of aggregate when compared to natural sand, therefore reducing the depletion of natural sand deposits will provide significant environmental benefits on a global scale. This report demonstrates that this alternative material can now be successfully utilised in some applications which allows for a more sustainable solution to be adopted.

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9. APPENDICES

9.1. Appendix A: Project Specification

ENG4111/4112 Research Project

Project Specification

For:	Mordecai Murerwa
Title:	Suitability of recycled crushed glass as a replacement for natural sand in concrete
Major:	Civil Engineering
Supervisors:	Dr. Sourish Banerjee
Enrollment:	ENG4111 – EXT S1, 2023 ENG4112 – EXT S2, 2023
Project Aim:	To help draw definitive conclusions and reaching consensus on the effects of recycled crushed glass (RCG) in concrete, an experimental study will be undertaken to measure various physical and mechanical properties of concrete made with RCG replacing natural sand. The outcomes would benefit the construction industry, waste glass recycling industry and more importantly, the environment.

Programme: Version 1, 15th March 2023

1. Conduct initial literature reviews to identify the research gaps. Determine consistency and uniformity of properties/results from currently available literature and identify any discrepancies in published literature.
2. Specify and procure all relevant materials required for creating RCG concrete samples.
3. Make several concrete samples using various percentages of recycled crushed glass (RCG) as replacement for natural sand.
4. Conduct slump tests on all fresh concrete samples and record workability results.
5. Measure compressive strength and split tensile strength on RCG samples. Simultaneously check the appearance of hardened concrete samples to see if any desirable finishes can be seen.
6. Conduct flexural strength test of beam samples.
7. Compare results with control samples and theoretical predictions as applicable.
8. Draw conclusions and write an acceptable dissertation.

If time and resource permit:

9. Conduct Alkali Silica Reaction test.
10. Shed light and discuss the safety aspects of using recycled crushed glass i.e., specify appropriate PPE required and safety risks of handling RCG.

9.2. Appendix B: Risk Assessment

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
2499	Preparing and testing concrete samples with recycled crushed glass		Medium	Medium

DOCUMENTS REFERENCED
Slump test procedure; Compressive strength test procedure; Flexural strength test procedure; Split-tensile strength test procedure; AS1012:2018

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Mordecai Murerwa	25/05/2023	26/05/2023	26/11/2023

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE DATE
Falling tools and equipment: Foot injury from falling tools or concrete specimens.	**Control:** Steel capped boots **Control:** Not standing under loose objects and equipment	**No Control:**		
A back injury can occur when lifting concrete samples, cement bags, or equipment	**Control:** Assistance from technical lab supervisor when lifting heavy loads	**Control:** Undertake manual handling awareness training **Control:** Use trolleys to move heavy loads		30/06/2023 31/05/2023
The concrete mixture can leave the surface wet and lead to slips and falls. Untidy equipment can result in trips and falls	**Control:** Safety boots with sufficient grip	**No Control:**		

	Control: Lab induction to ensure all people involved are familiar with the workplace **Control:** Ensure work area is tidy	
Operator errors, pinch points and malfunctioning machinery can cause injury. Bruises, cut and serious injury can occur.	**Control:** Trained personnel are to operate machinery **Control:** Relevant manufacturers manuals and guidance procedures to be available	**Control:** Ensure all electrical equipment is tested and tagged prior to the experiment 30/06/2023
Inhalation of cement dust and rcg dust can be hazardous to operator health. Cement dust carries silica which is harmful when inhaled.	**Control:** Dust face masks **Control:** Relevant safety data sheets will be available **Control:** Sufficient air circulation in the lab	**No Control:**
When mixing concrete, the natural sand can splash into the eyes when water is introduced and cause eye injury.	**Control:** wear eye protection i.e., safety glasses	**No Control:**