University of Southern Queensland
Faculty of Health, Engineering and Sciences

PERFORMANCE OF CONCRETE MADE WITH RECYCLED CRUSHED GLASS

A dissertation submitted by

Jesse Hjort

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Abstract

According to Cao et al. (2022), sand is the second most extracted natural resource globally, with an annual consumption of about 15 billion tons. The construction industry is the major sand consumer, with concrete production alone accounting for approximately 10 billion tons of sand per year. The extensive use of sand has negative environmental implications such as habitat destruction, depletion of natural resources, and degradation. Therefore, the construction industry must explore sustainable building practices to reduce environmental impact.

The primary objective of this research was to investigate the feasibility of using recycled crushed glass (RCG) as a partial replacement for fine aggregate in concrete. The study involved a comprehensive review of relevant literature and various tests to determine the fresh and hardened concrete properties made with RCG. The literature review revealed conflicting results of multiple studies investigating the effects of RCG on concrete properties. However, most studies suggest an optimal RCG replacement level of 20%. Therefore, this project utilised three high strength mix designs, including the control, 20%, and 40%, where sand is replaced with RCG by weight. Three main tests, namely compression, crack mouth opening displacement (CMOD), and pull-out testing, were used to evaluate the RCG concrete's performance.

The results showed that the addition of RCG caused a significant decrease in workability, a slight decrease in hardened density, no loss in compressive strength at 20% RCG replacement, and an increase in flexural strength at 20% and 40% RCG replacement. The findings of this research align with multiple other studies, which concluded that 20% RCG is the optimum replacement level in a concrete mix.

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Jesse Hjort

Student Number: [redacted]

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Abbreviations/ Nomenclature

ASR: Alkali-silica reaction

CMOD: Crack mouth opening displacement

DIC: Digital image correlation

LVDT: Linear variable differential transducer

PET: Polyethylene terephthalate

PSD: Particle size distribution

RCG: Recycled crushed glass

SEM: Scanning electronic microscope

Chapter 1: Introduction

1.1 Background

Sand is the second most extracted natural resource, with 15 billion tons being consumed annually around the globe (Cao et al. 2022). The majority of this demand comes from the construction industry, where sand is a crucial component in the production of concrete. Concrete alone consumes approximately 10 billion tons of sand each year (Cao et al. 2022). The extensive use of sand has negative environmental consequences such as habitat destruction, degradation, and depletion of natural resources. Therefore, it is crucial that the construction industry explores more sustainable building practices to minimise the impact it has on the planet.

One possible solution is using recycled materials in concrete production. Incorporating recycled materials can have various benefits such as reducing the environmental impact of concrete production, reducing waste disposal costs, and conserving natural resources.

Recycled crushed glass (RCG) is one such material that has been extensively studied as a potential replacement for aggregates in concrete. By crushing and screening discarded glass bottles, jars, and other glass products to meet size specifications, RCG can be used as a substitute for aggregate in concrete. In 2018, Australia produced a total of 1.29 million tonnes of glass, of which only 46% was recycled (Allan 2019). The large amounts of waste glass provides a great opportunity for the construction industry to utilise this material in concrete production and reduce the amount of waste glass that would otherwise end up in landfills. This makes RCG a promising solution for both waste reduction and the conservation of natural resources.

The main objective of this project is to evaluate the performance of concrete that uses RCG as a substitute for fine aggregates. Various tests will be conducted, including compression tests and more unique tests, such as the crack mouth opening displacement (CMOD) and pull-out test.

The use of RCG as a substitute for traditional aggregates in concrete production has been extensively studied, but results have varied between studies. One of the primary concerns regarding RCG replacement is the possibility of alkali-silica reaction (ASR) between the cement and RCG, which can cause cracking and reduce the strength of the hardened concrete. However, other studies have found that the inclusion of RCG can lead to similar or even improved mechanical properties up to a certain level of replacement.

1.2 Aim, Objectives and Scope

This project aims to experimentally measure the mechanical properties of hardened concrete made with RCG as a fine aggregate replacement. The main objectives of the project are summarised as follows:

1. Measure the mechanical properties of hardened concrete made with RCG as a fine aggregate replacement using pull-out and CMOD tests.
2. Compare the results of RCG concrete specimens to those of concrete that uses sand as a fine aggregate, existing literature, and theoretical predictions.
3. Contribute to the development of more sustainable building practices in the construction industry by providing valuable data and insights into the performance of RCG as a substitute for traditional aggregates in concrete production.

The project will be limited to three mix designs: a control mix with sand as the fine aggregate, a 20% RCG replacement mix, and a 40% RCG replacement mix. These replacement levels have been chosen based on the available supply of glass and previous studies on RCG concrete.

To ensure the accuracy and reliability of the results, the concrete specimens will be produced in a controlled laboratory environment using consistent procedures and equipment. The testing program will consist of various mechanical tests, including compression tests, pull-out tests, and CMOD tests, to evaluate the strength and durability of the concrete. The project will also involve a thorough review of existing literature related to the use of RCG in concrete production to provide a comprehensive understanding of this material's potential benefits and limitations.

Due to the time and resource constraints of the project, the number of mix designs and testing methods will be limited. However, the results of this study will provide valuable insights into the potential of RCG as a sustainable alternative to traditional aggregates in concrete production.

1.3 Consequences and Ethics

The outcomes of this project have important implications for sustainable construction practices, waste reduction, and concrete performance. The potential benefits of using recycled crushed glass as a fine aggregate could have a significant impact on the construction industry. The following outlines the possible outcomes of this project:

- Sustainability: This project contributes to sustainable construction practices by reducing the use of natural resources and recycling glass waste.
- Environmental Impact: This project may reduce the amount of glass waste that ends up in landfills, reducing the environmental impact of waste disposal.
- Technical Advancements: This project may lead to the development of new concrete mix designs that can help create standards for using RCG in concrete.

The project was conducted in accordance with the code of ethics set out by Engineers Australia (2019), which highlights integrity, competency, leadership and sustainability. Following these codes of ethics throughout the project was important to ensure the safety and welfare of the public, promote professionalism and innovation, and uphold the reputation of the engineering profession. The following details how these codes of ethics were adhered to throughout the project:

- Health and safety were prioritised by ensuring that the testing process was safe for all involved, including myself, other researchers, and participants in the study.
- Sustainable construction practices were promoted by using recycled crushed glass as a fine aggregate replacement, reducing the amount of waste in landfills.
- Research was conducted fairly, and the results were presented in an unbiased and objective manner to ensure integrity and fairness.

This project has several potential consequences, including reduced environmental impact, cost savings, and improved understanding of RCG in concrete. The results of the project may contribute to the development of more sustainable and efficient construction practices, which can benefit the construction industry and society as a whole. Throughout the project, ethical considerations were taken into account, including safety, environmental impact and fairness. Following the Engineers Australia Code of Ethics was important in ensuring the project was conducted ethically and responsibly. Adhering to ethical guidelines also helped to promote professionalism and innovation while upholding the reputation of the engineering profession.

Chapter 2: Literature Review

Understanding how incorporating RCG in a concrete mix affects its properties is vital for adopting it as common practice. It is important to investigate the potential advantages and disadvantages of using RCG in concrete, such as its effects on workability and strength. Therefore, a comprehensive literature review is necessary to evaluate the existing studies on using RCG in concrete and identify any knowledge gaps or inconsistencies in the findings. This literature review will provide a better understanding of the potential RCG has as a substitute for sand in concrete production and guide future research in this area.

2.1 Alkali-Silica Reaction

Often referred to as "concrete cancer" (Bodin et al. 2022), ASR is a chemical reaction that can occur when the alkalis in the concrete react with silica materials. When alkali-silica reaction occurs, a gel-like substance is produced that can cause the concrete to expand and crack over time. This can lead to a reduction in the strength and durability of the concrete, as well as potential safety risks in structures such as bridges and buildings. Concrete made with recycled crushed glass will be more likely to experience ASR and its adverse effects due to the reactive silica minerals found in glass. The ASR expansion can drastically vary depending on the type, colour and size of the glass particles used. A study by Ke et al. (2018) on the mitigation effect of waste glass powders on ASR expansion in cementitious composite compared the effects different size glass particles have on ASR expansion. As seen in Figure 2.1, using glass powder finer than 300 μm can reduce the ASR expansion, whereas using glass powder greater than 300 μm can actually increase the ASR expansion compared to the control sample.

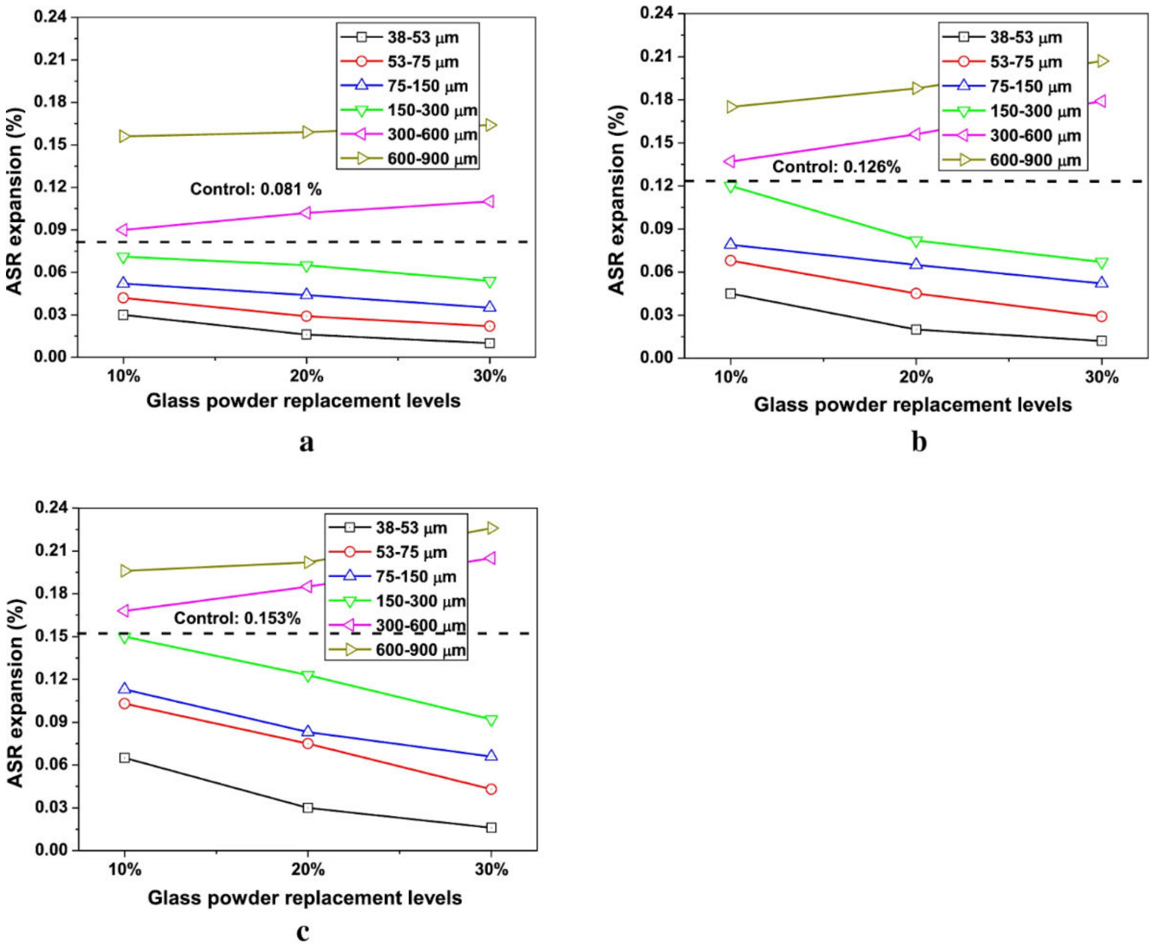

Figure 2.1: Effect of the content of waste glass powder on ASR expansion of cement mortar bars at different curing ages. A Curing age of 14 days, b curing age of 28 days, c curing age of 35 days. (Ke et al. 2018)

A similar study was done by Du & Tan (2014), where they tested the effects that recycled glass particle size has on ASR expansion but also the type of glass. Mortar made with green glass fine aggregates exhibited greater ASR expansion compared to mortar made with brown glass. Figure 2.2 shows that the mortar made with green glass particles significantly reduced ASR expansion when the glass particles were 600 μm in size and almost non-existent when the glass particles were 300 μm or less. As mentioned by Du & Tan (2014), Ke et al. (2018) and others, the reason smaller particles result in a lower ASR expansion may be due to higher pozzolanic activity. When glass is crushed into smaller particles, it has a larger surface area per unit volume, which increases the contact area between the glass particles and the cement paste. This results in a higher degree of pozzolanic activity, which can reduce the alkalinity of the pore solution within the concrete. The reduction in alkalinity inhibits the formation of ASR gel, which can cause expansion and cracking in the concrete.

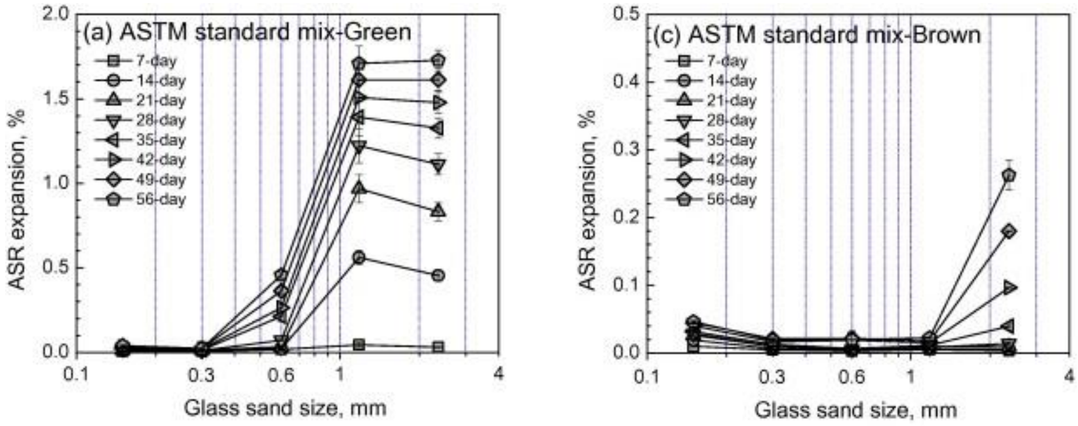

Figure 2.2: Effect of particle size on ASR expansion for brown and green glass. (Du & Tan 2014)

Using finer glass particles in RCG concrete can be an easy and effective way to reduce ASR expansion. However, other mitigation strategies can be used. Bodin et al. (2022) have highlighted several mitigation strategies for the effect of ASR in RCG concrete. These are: using admixtures such as metakaolin and fly ash, modifying or applying a protective coating to the glass and using a low-alkali cement. In their research, Liu et al. (2022) used carbonation curing to combat the effects of ASR expansion. Carbonation curing involves curing the concrete in a high-pressure atmosphere of pure CO2. Carbon curing managed to increase the compressive strength of the concrete by up to 40% and reduce ASR expansion by up to 85% (Liu et al. 2022). Another successful example of mitigating ASR effects is provided by Singh & Siddique (2022) in their research on self-compacting concrete made with RCG. In their research, they used metakaolin as a partial replacement for cement to mitigate the reaction caused by the glass, which improved the mechanical properties of the concrete at all levels of RCG mix designs. One other study to note is one by Taha & Nounu (2009), whose research purpose was to measure the expansion of ASR and how to mitigate it. By using a lithium compound admixture and replacing the cement with low calcium ashes, Taha & Nounu (2009) observed very little ASR expansion compared to the control sample.

2.2 RCG Concrete Properties

Although the use of recycled crushed glass has the potential to improve concrete's sustainability and environmental impact, the use of glass as a fine aggregate has a significant impact on the properties of concrete. While there have been many studies on the effects of fine glass aggregate on concrete properties, the results of these studies have been mixed and often contradictory. Minimal variance between results is expected due to different mix designs, human error and testing methods. However, the major difference in results between these studies can be attributed to the properties of the recycled crushed glass, indicating that the use of glass in concrete requires careful consideration and evaluation.

2.2.1 Strength

The incorporation of RCG has a significant impact on the strength of concrete. Incorporating glass in concrete can either improve or reduce its strength, depending on various factors such as the size, quality and amount of RCG used. Due to these factors, it can be challenging to determine the impact glass may have on the strength of the concrete. For example, Ali & Al-Tersawy (2012) and Singh & Siddique (2022) replaced their fine aggregates with RCG at increments of 10% up to 50%, and both found that the compressive strength of the concrete steadily decreased with an increase in RCG content. Whereas other studies, such as Arivalagan & Sethuraman (2021) and Bisht & Ramana (2022), report an increase in compressive strength up to 20% RCG replacement. Numerous studies appear to agree that 20% RCG replacement for natural sand is the optimum amount and provides the greatest compressive strength. However, some studies have shown compressive strength to increase with RCG content up to 30% (Shiva Srikanth & Lalitha 2022) and even 60% (Ho & Huynh 2022). A thorough investigation conducted by Lee et al. (2013) tested the performance of RCG concrete at varying levels of glass particle sizes at RCG replacement ratios of 25%, 50%, 75% and 100%. As shown in Figure 2.3, using an aggregate size of 600 µm or less resulted in an increase in compressive strength at all levels of RCG Replacement, whereas using anything above that particle size would impair the compressive strength of the concrete. As well as reducing the ASR expansion, the increased pozzolanic activity from the smaller glass particles also results in the formation of calcium silicate hydrate (C-S-H) gel, which can fill the pores in the concrete and increase its mechanical strength (Lee et al. 2013).

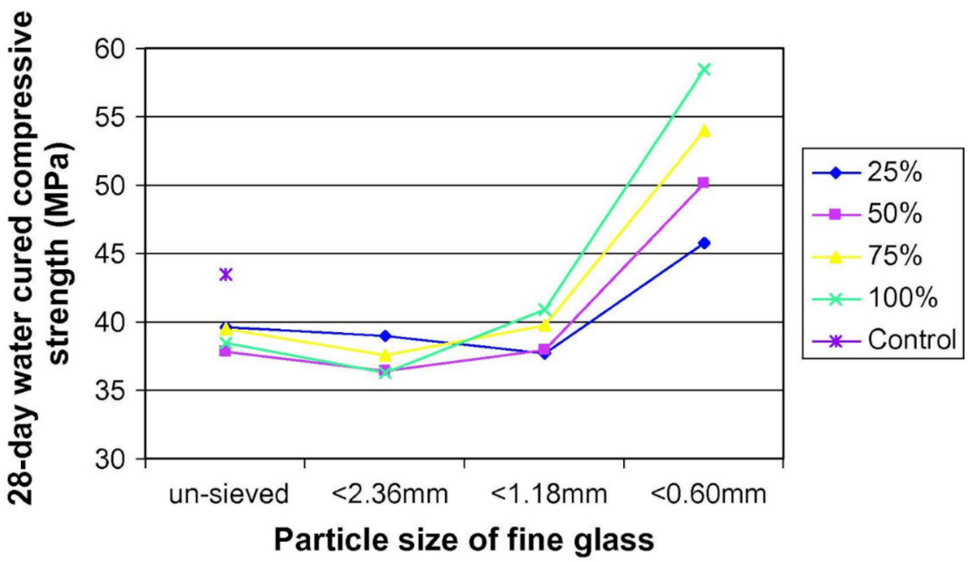

Figure 2.3: The 28-day water cured compressive strength of concrete blocks (effect of particle size) (Lee et al. 2013)

Similarly, to compressive strength, studies that tested flexural and tensile strength also have conflicting results. Ekop et al. (2022) and Ismail & Al-Hashmi (2009) found the flexural strength to increase with RCG in contrast to Singh & Siddique (2022) and Ali & Al-Tersawy (2012), who reported an opposite trend. Limited studies have tested the split tensile strength of RCG concrete. The results of Singh & Siddique (2022) and Ali & Al-Tersawy (2012) showed a decrease in split tensile strength with RCG content, and Arivalagan & Sethuraman (2021) results showed the split tensile strength remained constant up to 20% replacement but decreased thereafter. The use of crushed recycled glass as a fine aggregate in concrete has been studied with varying results reported in different studies. The mechanical properties of concrete, such as compressive strength, tensile strength, and flexural strength, were found to be influenced by the percentage of glass used, particle size, and curing conditions.

2.2.2 Workability

The use of fine glass aggregate can also affect the workability of concrete. Similarly, to concrete strength, the studies that tested the workability of fresh RCG concrete often had conflicting results. Ekop et al. (2022), Singh & Siddique (2022) and Ali & Al-Tersawy (2012) all reported that the workability of their fresh concrete increased with RCG content. These studies attribute the increase in workability to the low water absorption and smooth texture of the glass, which can reduce the friction between the aggregates and the cement paste, making the mix more fluid and easier to place. However, other studies such as Ismail & Al-Hashmi (2009), Bisht & Ramana (2022), and Arivalagan & Sethuraman (2021) reported a decrease in workability as the RCG content increased. The cause of this decrease in workability is theorised to be due to the sharp edges and angular shape of the glass particles causing the particles to interlock and making it more difficult to slide past each other.

2.2.3 Density

The majority of studies reviewed did not measure the density of concrete made with RCG. However, the few that did, reported a slight decrease in hardened concrete density with the addition of RCG. These studies include Ekop et al. (2022), Ismail & Al-Hashmi (2009), and Lee et al. (2013). The reduction in density is attributed to the lower specific gravity of the RCG compared to the replaced sand and the potential voids created by the poor workability of the concrete when RCG is added.

2.2.4 Summary

Table 2.1 provides a summary of studies and their reported influence of RCG on concrete properties. Despite the contradictory results, most studies have revealed a common trend regarding the optimum RCG replacement level, which is 20%. For instance, while Ekop et al. (2022) reported an overall decrease in compressive strength with the addition of RCG content, they still identified 20% as the optimum RCG replacement level. Similarly, other studies such as Arivalagan & Sethuraman (2021) and Bisht & Ramana (2022) also reported an optimum RCG replacement of 20%, which resulted in an increase in strength compared to their control samples.

Table 2.1: Summary of concrete properties made with RCG

Author	RCG (%)	Workability	Density	Compressive Strength	Flexural Strength
Ekop et al. 2022	0, 5, 10, 15, 20, 25	Increased	Slight decrease	Decreased overall Optimum 20% RCG	Steady increase with RCG %.
Ho & Huynh 2022	0, 20, 40, 60, 80, 100	N/A	N/A	Increased strength up to 60%.	N/A
Arivalagan & Sethuraman 2021	0, 10, 20, 30	Decreased	N/A	Increased strength up to 20%.	Increased strength up to 20%.
Bisht & Ramana 2022	0, 18, 19, 20, 21, 22, 23, 24	Decreased	N/A	Increased strength up to 20%	N/A
Singh & Siddique 2022	0, 10, 20, 30, 40, 50	Increased	N/A	Decreased strength with RCG %	Decreased strength with RCG %
Liu et al. 2022	20, 40	N/A	N/A	Optimum 20% RCG	N/A
Ismail & Al-Hashmi 2009	0, 10, 15, 20	Decreased	Slight decrease	Increased strength at 20% RCG	Steady increase with RCG %.
Lee et al. 2013	0, 25, 50, 75, 100	N/A	Slight decrease	strength increase with particle sizes < 0.6 mm	N/A
Ali & Al-Tersawy 2012	0, 10, 20, 30, 40, 50	Increased	N/A	Decrease strength with RCG %	Decrease strength with RCG %

2.3 Alternative Concrete Testing Methods

Aside from the commonly used compression and flexural tests, there are alternative ways to assess concrete properties that provide valuable insights into specific aspects of concrete behaviour and properties. These alternative methods have their own advantages and contribute to a more complete evaluation of concrete, particularly when recycled materials are incorporated. Two such alternative methods include the Crack Mouth Opening Displacement test and the Pull-Out test. The following section will discuss their applications, benefits, and how they contribute to our understanding of concrete performance.

2.3.1 Crack Mouth Opening Displacement (CMOD)

The CMOD test is a less conventional method used to evaluate the properties of concrete. As highlighted in AS 3600:2018, this test is typically performed on fiber-reinforced concrete and involves measuring the displacement of a crack in a concrete specimen under flexural loads. The data recorded in this test can be used to determine the residual flexural tensile strength of the concrete. Calculating the residual flexural tensile strength helps determine the concrete's capacity to withstand bending or flexural loads when cracks are present and provides a better understanding of the concrete's suitability for applications involving bending.

The literature review showed many studies had performed the CMOD test on concrete made with glass fibres. However, no specific studies were found that investigated the CMOD test on concrete incorporating RCG as a fine aggregate. This lack of research is primarily due to the fact that the CMOD test is commonly performed to evaluate the behaviour of fibre-reinforced concrete. While the literature review did not find studies directly addressing the CMOD test on concrete with RCG, the results of their control samples without reinforcement provide a basis for comparison and reference in this study.

Studies by Arslan (2016) and Ahmed & Lim (2023) focused on fibre-reinforced concrete, where the CMOD test was carried out to evaluate the behaviour of the specimens. In their experiments, both studies had a span of 400 mm for their test specimens but had different cross-sectional areas and mix designs. Interestingly, the use of this span length led to a common trend observed in the CMOD test results across both the control samples and the fibre-reinforced samples. Specifically, the maximum load achieved corresponded to a CMOD of approximately 0.04 mm to 0.06 mm. This finding suggests a consistent response in terms of crack opening behaviour and load-displacement relationship for the tested specimens, despite variations in the concrete composition and presence of fibres.

In a study conducted by Kangavar et al. (2022), the concrete specimens did not incorporate any fibre reinforcement. Instead, they replaced the fine aggregate with recycled polyethylene terephthalate granules at various levels. In this study, all of the mix designs reached their maximum load at the same CMOD of 0.5 mm. The maximum loads observed in Kangavar et al. (2022) occurred at a significantly higher CMOD compared to the findings of Arslan (2016) and Ahmed & Lim (2023). One possible explanation for this discrepancy is the difference in the span length of the concrete specimens where Kangavar et al. (2022) had a longer span of 500 mm.

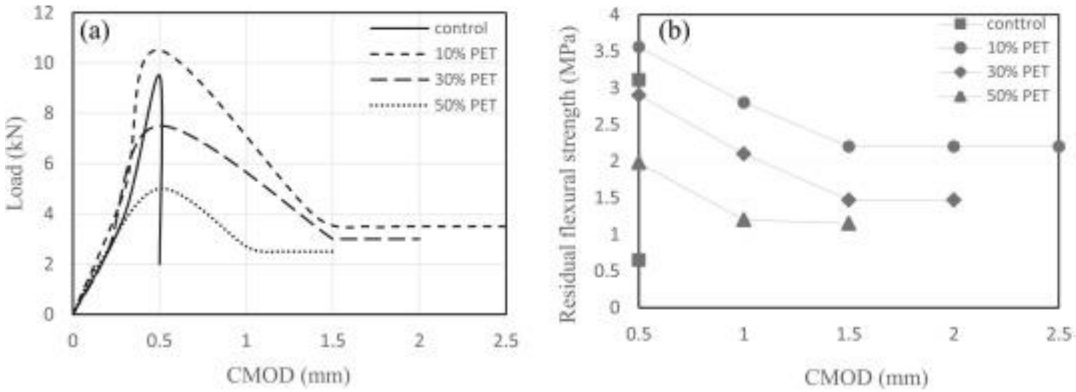

Figure 2.4: Effect of PET granules on CMOD and residual flexural tensile strength of concrete Kangavar et al. (2022).

The study by Kangavar et al. (2022) observed an increase in residual flexural tensile strength with the addition of polyethylene terephthalate (PET) granules. This improvement was attributed to the flexible nature and bridging effect of the PET granules. Unlike sand, which typically consists of quartz and has a crystalline structure, glass is an amorphous material with an irregular atomic pattern. The absence of a regular atomic pattern in an amorphous material allows for greater freedom of movement and deformation, resulting in increased flexibility. Therefore, the incorporation of glass particles has the potential to increase the residual flexural strength of the concrete, although the results may be insignificant compared to the addition of PET granules by Kangavar et al. (2022).

2.3.2 Pull-out Test

The pull-out test is a method to evaluate the bond strength between concrete and steel reinforcement. This measurement determines how effectively the hardened concrete mixture binds to the reinforcement, which is essential for the structural stability of concrete by transferring loads and resisting deformation.

The literature review reveals that previous studies have conducted pull-out tests on concrete containing recycled aggregates such as polyethylene terephthalate (PET) (Kangavar et al. 2023) and wood chips (Dias et al. 2023). However, no studies have yet examined the bond strength of concrete made with recycled glass aggregates using the pull-out test method.

While standards such as BS EN 10080 provide specifications for conducting the pull-out test, methods and dimensions used in different studies tend to vary significantly. Despite these variations, the methods used are all valid in determining the bond strength of concrete. As seen in Figure 2.5(a), BS EN 10080 depicts a rebar running throughout the length of a concrete cube with a pipe covering half of the embedded rebar, creating an unbonded zone. This unbonded sone helps control the failure mode of the pull-out sample, preventing a cone of concrete from being pulled out with the rebar or the concrete from splitting open, which can affect test results. In contrast, studies such as Chu & Kwan (2018), have the rebar running 2/3 of the way into the concrete, with a PVC pipe covering half of the rebar inside the concrete, as illustrated in Figure 2.5(b). Meanwhile, Huang et al. (2016) have the rebar running through the entire concrete sample, similar to BS EN 10080, but two PVC pipes are used to cover the top and bottom portions of the rebar in the concrete, ensuring that only a small section of the rebar is bonded to the concrete in the centre as detailed in Figure 2.5(c).

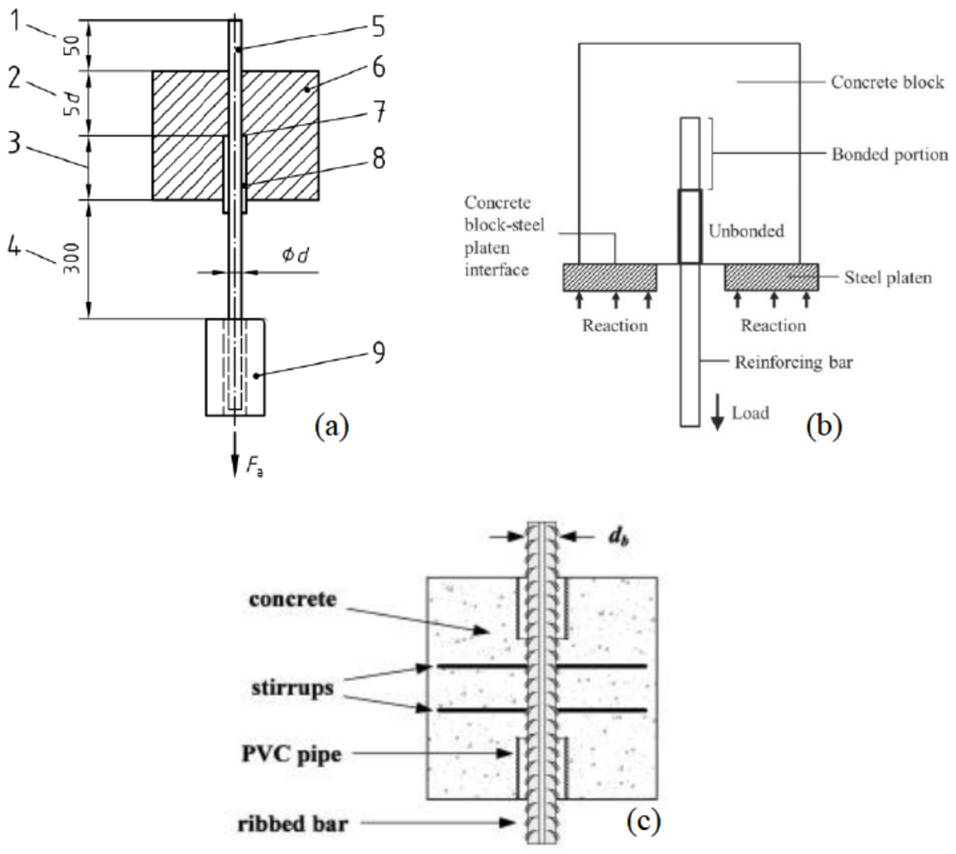

Figure 2.5: Different pull-out sample designs (a) BS EN 10080 (b) Chu & Kwan (2018) (c) Huang et al. (2016)

2.5 Research Gap

Using recycled crushed glass is a promising solution for reducing waste and promoting sustainability in the construction industry. Despite the existing studies on substituting natural sand with RCG in concrete production, the results have been inconsistent. Therefore, it is important to conduct further research to fully comprehend the benefits and drawbacks of using RCG in concrete production.

This project aims to reaffirm the results of similar studies and contribute new data by conducting pull-out and CMOD testing on concrete made with fine glass aggregate, which is yet to be explored by any other research. The results of these tests can help identify the effect of RCG on the bond strength of concrete and its fracture mechanics. By providing the industry with more comprehensive and reliable data, this research could inform policies and practices related to sustainability in construction.

Chapter 3: Methodology

3.1 Materials

This section will discuss the various materials used to create the concrete specimens. The selection of materials is crucial as they significantly impact the strength and performance of the concrete. It is also important that the materials being used align with the requirements set out by Australian Standards to ensure compliance and quality.

3.1.1 General Purpose Cement

The general-purpose cement used in this project is shown in Figure 3.1. Cement is the most important component as it is the binding agent that holds all the materials together. General purpose cement contains Portland cement that may contain up to 5% of mineral additions as set out by AS 3972.

Portland cements are composed of calcium carbonate, alumina, silica, and iron oxide. These raw materials, including limestone, clay, shale, silica, alumina, and iron ore, are grounded together, and burnt in rotary kilns at high temperatures to create clinker. Clinkers are hard ceramic-like balls that are crushed up with gypsum, which is needed to regulate the rate of hydration when water is added to the cement (The New Zealand Guide to Concrete Construction).

Figure 3.1: General purpose cement

3.1.2 Natural Fine Aggregate

The most commonly used material for fine aggregates in concrete is natural river sand, the sand used in this project is shown in Figure 3.2. Fine aggregate is an essential component that fills the spaces between coarse aggregates, cement, and other constituents. To properly fill these spaces, it is important to have a suitable particle size distribution. Poorly graded fine aggregates can lead to reduced workability and strength. Therefore, the sand must have a grading curve within the limits set out by AS 2758.1 to ensure the quality of the concrete samples.

Figure 3.2: Natural River sand

3.1.3 Gravel/ Crushed Stone

Coarse aggregates in concrete typically consist of gravel, crushed stone or a combination of both. Coarse aggregates should be angular in shape to provide more surface area for better bonding and interlocking within the concrete. The compressive strength of concrete increases with larger coarse aggregate particle sizes, typically ranging from 5 to 40 mm in diameter. For this mix design, 10 and 20 mm nominal-sized coarse aggregates are used and are shown in Figure 3.3.

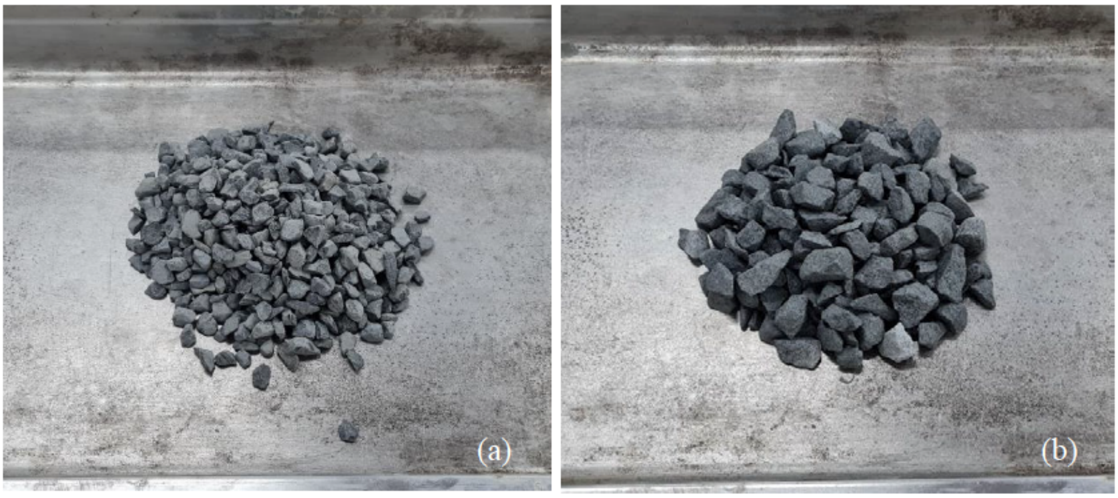

Figure 3.3: Coarse aggregates (a) 10 mm (b) 20 mm

3.1.4 Recycled Crushed Glass

The glass used in this project was sourced from Schneppa Glass in Victoria, specialising in recycled glass products. Although their glass is typically used for decorative purposes such as exposed aggregate concrete flooring and benchtops, they have a selection of clear glass that ranges from 0.2 mm to 3 mm, suitable for this project.

The glass arrived in four different size gradings, 0.2-0.6mm, 0.4-0.8mm, 0.8-1.5mm and 1.5-3.0mm. To ensure the glass had a similar size grading to the sand being used in the project, it was separated into different sizes by using the sieves needed for a sieve analysis. When the sieve analysis for the sand was complete, the different size glass particles were added together in specific quantities in an attempt to recreate a similar grading curve as the sand.

Figure 3.4: Clear recycled crushed glass

3.2 Mix Designs

The focus of this study is to ascertain as to whether glass is a suitable replacement for sand in a concrete composite to be used within the construction industry. Therefore, this project will use a mix design for high-strength concrete, which is used in projects that experience greater loads, such as high-rise buildings and bridges. Three mix designs are used for this project, including the control mix containing 0% RCG, a 20% mix and 40% RCG mix design where sand is replaced with RCG by weight. The specific proportions for these three mix designs are detailed in Table 3.1.

Table 3.1: Mix designs for concrete specimens (kg/m³)

Mix	Cement	Water	20 mm	10 mm	Sand	Glass
Control	466	158	564	564	581	0
20%	466	158	564	564	465	116
40%	466	158	564	564	349	232

3.3 Sample Preparation

The measurement and mixing of materials were conducted in accordance with AS 1012.2:2014. Mixing was achieved using a motor-driven cement mixer, the batch sizes for each mix were 20% greater than required to ensure there was enough material to create the specimens. The casting of the concrete specimens was conducted in accordance with AS 1012.8. The moulds were cleaned of any debris and lubricated with form oil to ensure they could easily be demoulded once the concrete had set.

3.3.1 Compression Samples

The moulds used for casting compression concrete cylinders are depicted in Figure 3.5. The dimensions of the concrete cylinder samples are 100 × 200 mm. A set of three concrete cylinders were cast for each mix design to ensure quality of test results. Therefore, a total of nine cylinders were cast for compression testing.

Figure 3.5: Concrete cylinder moulds for compression test

3.3.2 CMOD Samples

Figure 3.8 provides a detailed overview of the dimensions of the CMOD samples. The beam is 150 x 150 x 510 mm and features a 25 mm deep notch cut in the centre. It is set up in a 4-point bending configuration where the loading span is 1/3 the length of the support span. Due to limitations in RCG material, only two samples were cast for each mix design, resulting in a total of six CMOD samples.

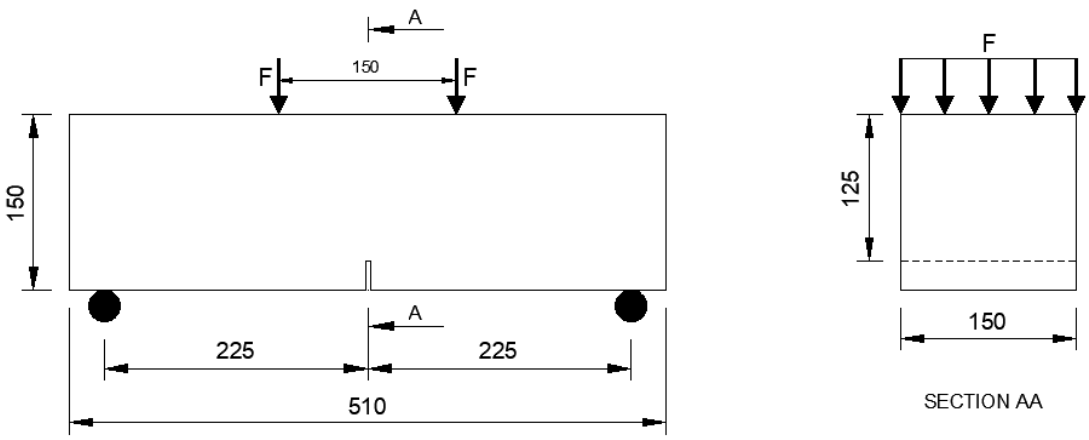

Figure 3.6: Illustration of CMOD test specimen dimensions

3.3.3 Pull-out Samples

The moulds for the pull-out samples had to be constructed. As illustrated in Figure 3.6, a 12 mm diameter rebar had to extend through a 150 x 150 mm concrete cylinder with an aluminium pipe covering the entry and exit point of the rebar. This pipe was to limit the bonded length of rebar to a length of 50 mm in the centre of the concrete cylinder. Limiting the bonded rebar section to the centre of the concrete cylinder ensures the surface conditions of the concrete do not affect the pull-out testing results. This also helps prevent a splitting-type failure of the concrete.

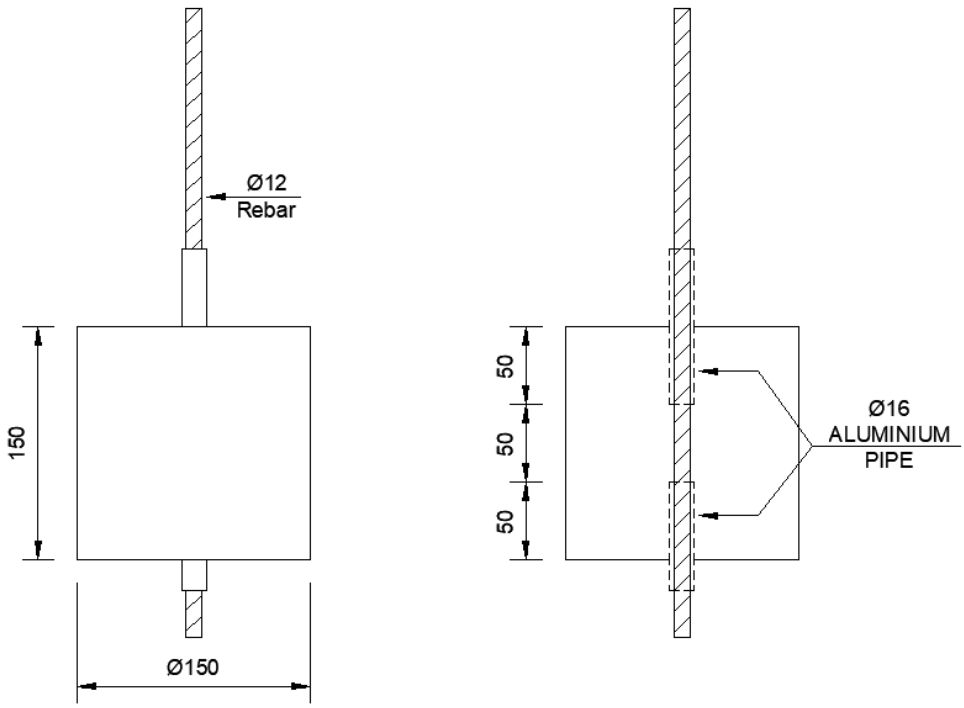

Figure 3.7: Illustration of pull-out test sample dimensions

As depicted in Figure 3.7, the moulds were constructed using 150 mm diameter PVC pipe with end caps. A hole was drilled through the end cap so the aluminium pipe and rebar could pass through it. The rebar and pipe covering were held in place with duct tape to create the 50 mm exposed rebar in the centre. A plank of wood with three holes drilled through it was used to hold the rebar vertically as the concrete cured. Three pull-out samples were cast for each mix design.

Figure 3.8: Casting of pull-out test samples

3.4 Curing

The curing of the concrete samples was in accordance with AS 1012.8. Twenty-four hours after casting the concrete samples, they were demoulded and labelled before being placed in a fog room. The fog room is used to maintain moist curing conditions, as the surface of the concrete should remain wet throughout the curing stage. The compression and pull-out samples were allowed to cure for 28 days before testing, whereas the CMOD samples were left to cure for 56 days before testing.

3.5 Testing Procedures

In order to maintain the highest level of reliability and consistency for the research outcomes, all concrete testing procedures followed appropriate standards. Following the standards ensures that the tests are conducted in a manner that provides consistent and repeatable results. An overview of the concrete tests conducted in this project and their relevant standards are outlined in Table 3.2.

Table 3.2: Summary of tests and corresponding standards

Test	**Standards**
Sieve Analysis	AS 1141.11.1
Slump Test	AS 1012.3.1
Density Measuring	AS 1012.12.1
Compression Test	AS 1012.9
CMOD Test	AS 3600 (2018)
Pull-out Test	BS EN 10080

3.5.1 Sieve Analysis

Well-graded aggregates are essential for minimising voids and creating stronger and more durable concrete. The particle size distribution of the sand and glass was determined using the sieve analysis method. The grading of the fine aggregates can be assessed by conducting the sieve analysis, and the percentage of particles within a specific size range can be determined.

The methods set out in AS 1141.11.1 were used to determine the particle size distribution of the sand and RCG fine aggregates. A representative sample of approximately 1 kg of fine aggregate was collected. The sample was dried in an oven between 105 °C and 110 °C overnight, and the dry weight was recorded. Each sieve was weighed and stacked in ascending order of mesh size, with the 75 μm sieve at the bottom and the 4.75 mm sieve at the top. The sample was placed in the top sieve, and the sieves were then placed in a mechanical shaker for five minutes. Five minutes in the mechanical shaker ensured there were no significant changes in the retained mass on each sieve. The mass retained on each sieve was recorded, and the percentage passing each layer was calculated. The particle size distribution for the sand and glass was then plotted on a graph for comparison to ensure they were within the recommended grading limits for fine aggregates set out in AS 2758.1, as seen in Figure 3.9.

FINE AGGREGATE—RECOMMENDED GRADINGS

Sieve aperture	Mass of sample passing, percent	
mm	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 3.9: Recommended gradings for fine aggregate (AS 2758.1).

3.5.2 Slump Test

The slump test is performed to assess the workability and consistency of fresh concrete. It indicates the ease with which the concrete can be placed and compacted. The slump test will also help demonstrate how the addition of RCG in place of sand can affect workability.

Using the methods set out in AS 1012.3.1, the following procedure was used to determine the workability of the fresh concrete. The cone mould used for the slump was cleaned, the internal faces were moistened before adding concrete. The mould was placed on a smooth, level, and rigid surface. While firmly holding down the mould, fresh concrete was added in three equal layers. Each layer was compacted with a rod by evenly distributing 25 strokes across the cross-sectional area of the cone, ensuring minimal penetration of the previous layers. After the mould was filled and compacted, the excess concrete was removed using a trowel. The mould was removed carefully by raising it vertically and then placed next to the slumped concrete. The slump was then determined by measuring the height difference between the top of the cone mould and the top of the slumped concrete.

3.5.3 Density Measuring

The density of the hardened concrete was measured in accordance with AS 1012.12.1. The concrete cylinders for compression testing were measured and weighed before testing to calculate the concrete density. As shown in Equation 3.1, the density was calculated by dividing the mass of the concrete cylinders by their volume.

$$\rho = \frac{m}{V} = \frac{4m}{\pi D^2 h} \tag{3.1}$$

Where $\rho =$ density (kg/m^3)

$m =$ mass (kg)

$V =$ volume (m^3)

$D =$ diameter (mm)

$h =$ height (mm)

3.5.4 Compression Test

To determine the compressive strength of the concrete, the cylindrical concrete samples were placed under a crushing load until failure occurred. The compression test was conducted following methods set out in AS 1012.9. The machine was calibrated and cleaned of debris before starting the compression tests. The specimen dimensions were recorded, a rubber cap was placed over the uneven surface of the end of the cylinder (casting face) to ensure even distribution of pressure across the surface. The cylinder with the rubber cap was the placed in the testing machine as depicted in Figure 3.10. A constant loading rate of 1 kN/s was applied to the concrete until failure occurred, the results were recorded. The compressive strength of the concrete is calculated by dividing the maximum applied force by the cross-sectional area of the specimen. The formula to calculate compression strength is detailed in Equation 3.2.

$$f_c = \frac{P}{A} \tag{3.2}$$

Where f_c = compressive strength (MPa)

P = max applied load (kN)

A = cross-sectional area of cylinder (mm^2)

Figure 3.10: (a) concrete compression samples (b) test setup

3.5.5 CMOD Test

The CMOD test is conducted to evaluate the fracture behaviour and cracking resistance of concrete. This test is typically done on fibre-reinforced concrete. However, it can still help us understand the fracture behaviour of concrete without any reinforcement and serve as a basis for comparative studies or future research in the field.

The parameters of the beam dimension and notch were in accordance with AS 3600 (2018). The concrete specimen had to have a 25 mm deep notch cut into the centre of the beam with a saw, as depicted in Figure 3.11(a). This notch helps initiate a controlled crack. Figure 3.11(b) shows that a digital image correlation (DIC) camera was set up to measure the crack displacement. The DIC measures the displacement of the crack by tracking several points marked on the concrete beam. The beam was placed into a four-point loading system with the notch side facing down. A constant loading rate of 0.5 kN/s was applied to the concrete until failure, and the results were recorded. The flexural strength of the concrete was calculated as per Equation 3.3.

$$f_{R.j} = \frac{Fl}{bh_{sp}^2} \tag{3.3}$$

Where $f_{R.j}$ = residual flexural tensile strength (MPa)

F = max applied force (kN)

l = span of beam between supports (mm)

b = width of beam (mm)

h_{sp} = height of beam above notch (mm)

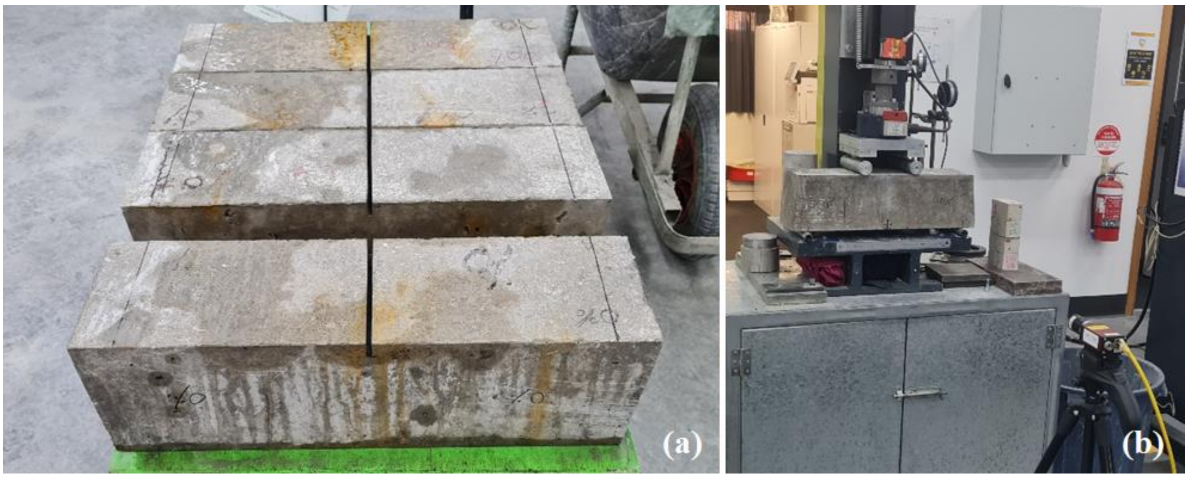

Figure 3.11: (a) CMOD samples (b) Test setup with DIC camera

3.5.6 Pull-Out Test

The pull-out test is used to assess the bond strength between reinforcement and concrete. The test involves applying a gradually increasing load to the embedded reinforcement to determine the maximum force at which the bond between the rebar and concrete fails. The test specimens and equipment are depicted in Figure 3.12, and testing procedures are in accordance with BS EN 10080. The samples were inverted and placed into the testing equipment. The concrete cylinder was held in place whilst steel jaws grabbed the rebar and pulled it downwards through the concrete cylinder. A linear variable differential transducer (LVDT) is located at the top of the specimen, which measures the slip of the rebar as it is pulled through the concrete. The bond strength was calculated as per Equation 3.4, using the ultimate force recorded and the surface area of the bonded rebar.

$$\tau = \frac{P}{A} = \frac{P}{\pi d l} \tag{3.4}$$

Where τ = bond strength (MPa)

P = ultimate load (kN)

A = surface area of bonded rebar (mm^2)

d = diameter of rebar (mm)

l = length of bonded rebar (mm)

Figure 3.12: (a) pull-out samples (b) pull-out test setup with LVDT

3.5.7 Scanning Electron Microscopic (SEM) Analysis

A Scanning Electron Microscope (SEM) analysis is a powerful imaging and analytical technique used to examine the surface of specimens at a very high level of detail. An electron beam is emitted from an electron gun inside the SEM, which is focused into a fine, controllable point. The data collected from these signals creates high-resolution, detailed images of the sample's surface, revealing its topography, composition, and microstructure. A SEM analysis was conducted in this study to evaluate the microstructure of the concrete specimens in terms of porosity and homogeneity.

Small, thin samples of 20 – 30 mm length were collected from each concrete sample after compression testing. The samples were placed into a sputter coater, which applied a thin layer of gold to the surface of the material to enhance the electron conductivity needed for the microscope to work. The sample was then placed in the microscope's vacuum chamber, where multiple images were captured at 50x magnification.

3.6 Theoretical Evaluation

The compressive strength of concrete often shows a predictable relationship with other mechanical properties of concrete, such as flexural and tensile strength. This correlation enables us to use the compressive strength as a foundation for predicting other mechanical property values. Therefore, the results obtained from compression testing in this project were used in theoretical prediction models to determine the potential CMOD and pull-out test results.

3.6.1 Theoretical CMOD Results

Although results for the CMOD test can be estimated by evaluating results of similar studies, AS 3600 (2018) provides an equation to estimate the characteristic flexural tensile strength of concrete. This relationship between flexural and compressive strength can be seen in Equation 3.5.

$$f'_{ct.f} = 0.6\sqrt{f'c} \tag{3.5}$$

Where $f'_{ct.f}$ = characteristic flexural tensile strength (MPa)

$f'c$ = characteristic compressive strength (MPa)

3.6.2 Theoretical Pull-out Results

A number of studies have conducted pull-out testing and developed theoretical prediction models to demonstrate the relationship between the compressive strength of concrete and bond strength. However, these models can vary significantly between different studies, with bond strength becoming more unpredictable as the compressive strength increases. In this project, the results of the pull-out test have been compared against several prediction models. These models have been compiled in Table 3.2, and Figure 3.13 illustrates the extent to which these theoretical predictions differ depending on the compressive strength.

Table 3.3: Theoretical predictions models

Reference	Equation
C. O. Orangun & Breen (1977)	$\tau = 0.083045\sqrt{f_c'}\left(1.2 + 3\frac{c}{d_b} + 50\frac{d_b}{L_d}\right)$
AS 3600 (1994)	$\tau = 0.265\sqrt{f_c'}\left(\frac{c}{d_b} + 0.5\right)$
Hadi (2008)	$\tau = 0.083045\sqrt{f_c'}\left(22.8 - 0.208\frac{c}{d_b} - 38.212\frac{d_b}{L_d}\right)$
Shen et al. (2016)	$\tau = 1.65\,{f_c'}^{0.7}$
Kangavar et al. (2023)	$\tau = 2.63\,{f_c'}^{0.53}$

τ	=	Bond Strength (MPa)
$\sqrt{f_c'}$	=	Concrete compressive strength (MPa)
c	=	Minimum concrete cover (mm)
d_b	=	Diameter of rebar (mm)
L_d	=	Bonded rebar length (mm)

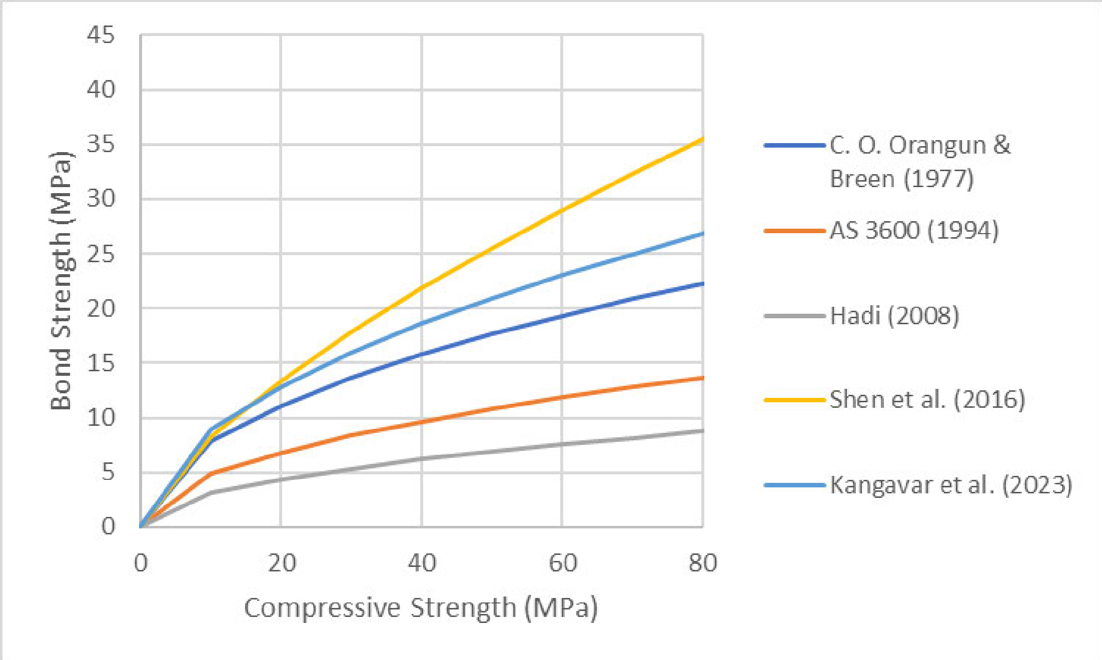

Figure 3.13: Comparison of theoretical prediction models for bond strength

Chapter 4: Results and Discussion

4.1 Particle Size Distribution (PSD)

The outcomes of the sieve analysis highlight a similar particle size distribution for the sand and glass particles, as illustrated in Figure 4.1. The similar grading curves ensure that the glass is a more suitable substitute for the sand being replaced in the concrete mix. Although they share a similar size distribution curve, the sand has a higher percentage of material passing for each sieve size, indicating the glass contains a greater amount of larger particles.

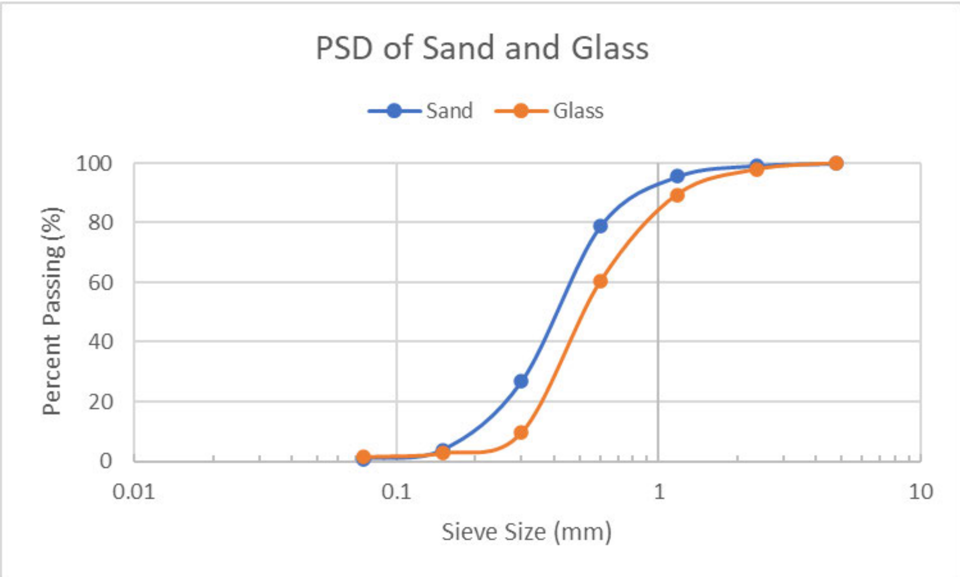

Figure 4.1: Particle size distribution of sand and RCG

After the sieve analysis on the sand was completed, the four different sizes of RCG were added together in certain quantities to try and replicate the PSD of the sand. As seen in Table 4.1, the particle size distributions for the sand and glass both fall within the recommended grading limits of AS 2758.1. Adhering to recognised grading standards facilitates quality control and quality assurance processes. It allows for easier monitoring and verification of aggregate characteristics, which is important for meeting structural and performance requirements.

Table 4.1: Percentage passing for sand, glass and recommended by AS 2758.1

Sieve (mm)	Percentage Passing (%)		
	Sand	Glass	Recommended (AS 2758.1)
4.75	99.93	100.00	90 - 100
2.36	99.19	97.72	60 - 100
1.18	95.52	89.42	30 - 100
0.6	78.78	60.32	15 - 100
0.3	26.71	9.64	5 - 50
0.15	3.73	2.72	0 - 20
0.075	0.78	1.45	0 - 5

4.2 Workability

A slump test was conducted for the control, 20% and 40% mix to determine the workability and to see how it is affected by the addition of RCG. As seen in Figure 4.2, the control had a slump of 90 mm and significantly reduced to 60 mm and then 35 mm at the 20% and 40% replacement levels, respectively. These high reductions in slump are similar to the results of Arivalagan & Sethuraman (2021) and Ismail & Al-Hashmi (2009). Similar studies that showed a decrease in slump with the addition of RCG attributed the reduced workability to the glass's sharp angular nature, which creates an interlocking effect within the concrete mix. Another point to note is that the sand used in this concrete mix had a moisture content of 4.6%. Therefore, as sand was being removed and replaced with RCG, some water content would have also been removed from the concrete mix. This reduction in available water content can also contribute to the decreased workability, as water helps facilitate the flow and consolidation of concrete. The combined influence of the sharp-edged glass particles and the reduction in water content due to replacing sand with RCG are believed to be the primary factors contributing to the concrete's substantial decrease in workability.

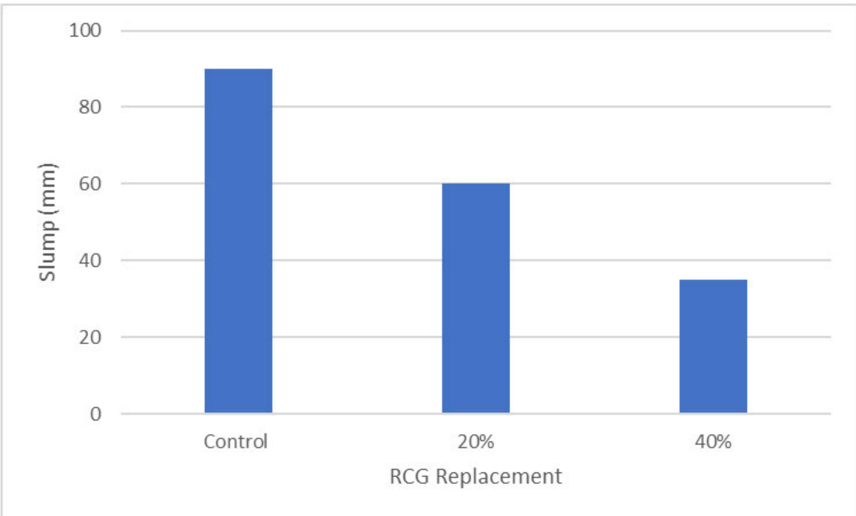

Figure 4.2: Results of slump tests for control, 20% and 40% mix

The 40% concrete mix design proved challenging to compact the fresh concrete into the specimen moulds properly. The lower workability of the 20% and 40% mix designs may also lead to issues such as segregation and challenges in achieving a smooth surface finish. Therefore, when using RCG, it is recommended to adjust the water content of the mix design or incorporate a superplasticizer to improve the workability of the concrete.

4.3 Density

As seen in Table 4.2, the average hardened densities remained relatively consistent across the various replacement levels. However, the addition of recycled crushed glass did lead to a slight reduction in density when compared to the control samples. These results align with similar studies who also saw a slight reduction in density with the addition of RCG such as Ekop et al. (2022), Ismail & Al-Hashmi (2009) and Lee et al. (2013).

Several factors have been proposed to account for the influence of RCG on concrete density. Glass typically has a lower specific gravity than sand and, therefore, would result in a lower concrete density with an increase in RCG content. The addition of RCG could have also introduced more voids into the concrete mix. This may occur due to the particle size distribution of the RCG, which did not perfectly match the replaced sand. The difference in the particle size distribution could have affected the packing density, resulting in a higher number of voids. Additionally, the workability of the fresh concrete was significantly reduced with the addition of RCG, which posed challenges during the compaction process within the moulds.

Table 4.2: Average density of hardened control, 20% and 40% concrete

Mix	**Avg. Density (kg/m³) @ 28 Days**
Control	2482.3
20%	2464.7
40%	2459.4

4.4 Compressive Strength

Figure 4.3 shows the results of the compressive strength tests after 28 days of curing. An average compressive strength of 69 MPa was achieved for the control samples, which is classified as high-strength concrete. The average compressive strength remained constant at 69 MPa for the concrete samples containing 20% RCG. However, a notable reduction of 13% was seen with the samples containing 40% RCG, which had an average compressive strength of 60 MPa. These results align with those of Ekop et al. (2022) who reported no loss in strength at 20% RCG replacement and a reduced strength at 25% RCG replacement. Other studies such as Arivalagan & Sethuraman (2021) and Bisht & Ramana (2022) also achieved an optimum compressive strength at 20% RCG. However, instead of achieving a similar strength to their control samples, these studies reported an increase in strength at 20% RCG replacement. These results suggest that there may be an optimal or threshold level of RCG content beyond which the compressive strength begins to decline more rapidly. This threshold may vary depending on factors such as the specific characteristics of the RCG and the mix design.

Although the average density for the 40% RCG samples remained the same as the control and 20% RCG samples, it still showed a significant reduction in compressive strength. The decoupling of strength and density in the 40% RCG samples indicates that other factors, such as the quality of the interfacial bonding between RCG and the cement mix and the poor workability of the concrete, are responsible for the loss in strength. The poor workability of the 40% RCG mix may result in a non-uniform distribution of aggregates within the concrete mix, which creates weak spots within the hardened concrete. Although not measured in this project, another factor to consider is the alkali-silica reaction, as discussed in the literature review. Due to the reactive silica minerals found in glass, as the RCG content increases, the chance for ASR expansion to occur also increases.

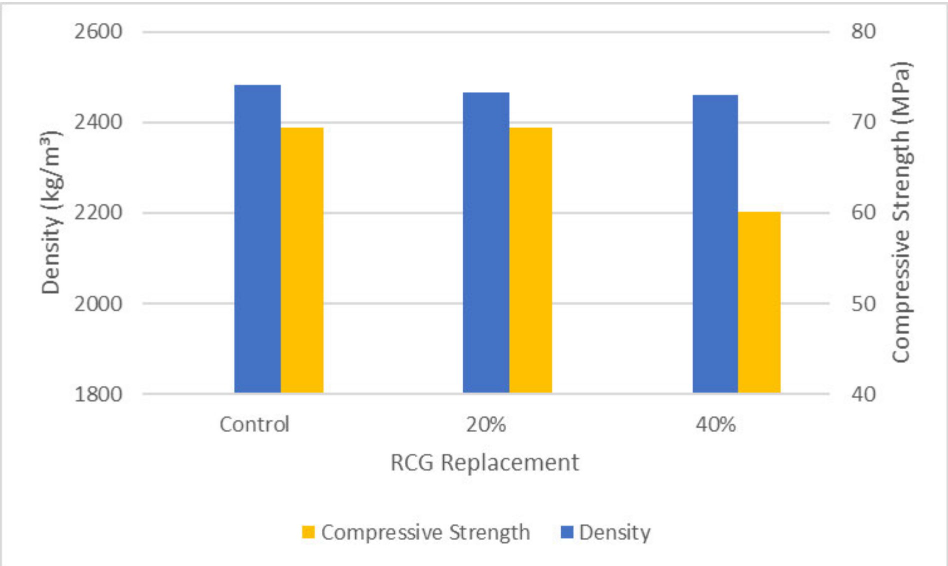

Figure 4.3: Average compressive strength for control, 20% and 40% concrete

The failure patterns of the concrete cylinder specimens are shown in Figure 4.4. Although cone failure is most common when conducting cylindrical compression tests, the control and 20% RCG samples exhibited shear failure. However, the 40% RCG samples showed a more evenly distributed crushing pattern with cone and shear failure. These failure patterns suggest that the control and 20% RCG samples are more brittle than the 40% RCG samples.

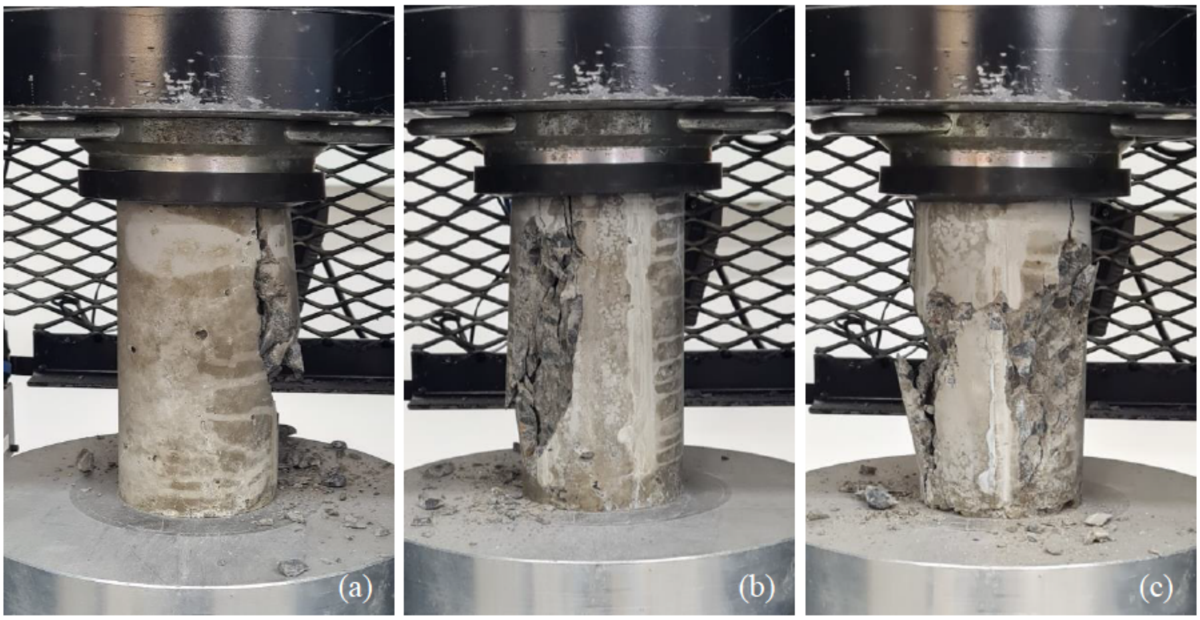

Figure 4.4: Failure patterns of concrete cylinders (a) control (b) 20% RCG (c) 40% RCG

4.5 CMOD Results

Whilst undertaking the CMOD testing, all concrete beams failed almost immediately after starting the procedure. As a result, the DIC camera failed to produce any viable data that could be used for crack displacement analysis. While the crack displacement could not be measured, the vertical displacement of each concrete beam and the corresponding load were recorded and is depicted in Figure 4.5. All concrete beams reached a deflection of approximately 1mm before immediately failing. However, the 4-point bending test results have shown that the concrete beams containing more RCG content can withstand a higher load before failing.

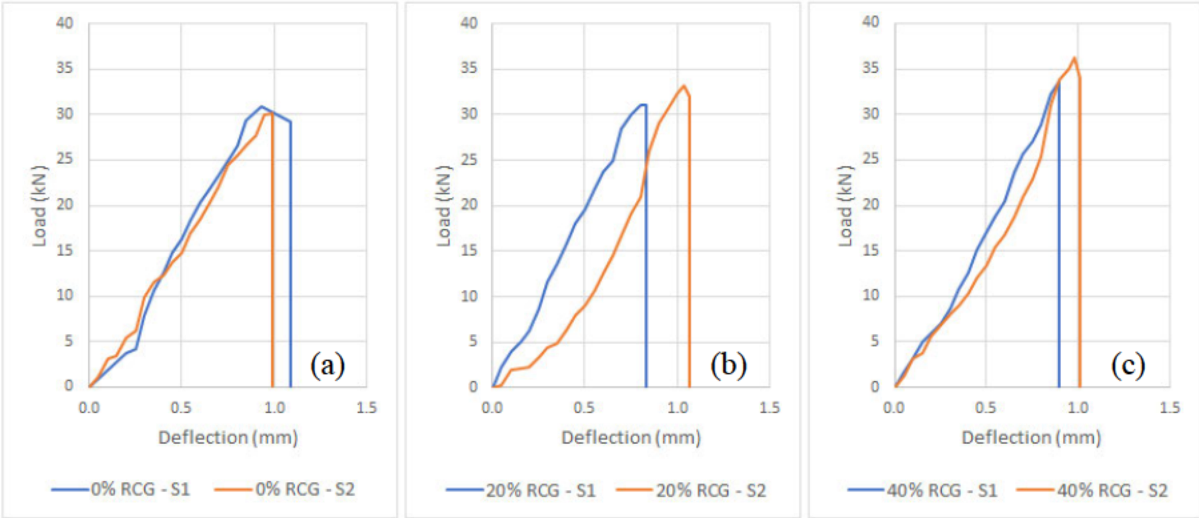

Figure 4.5: Load-deflection curve of all 6 concrete samples (a) control (b) 20% RCG (c) 40% RCG

The average flexural strength of the concrete samples and theoretical predictions are depicted in Figure 4.6. The flexural strength of the control concrete closely mirrored the theoretical prediction, measuring at 5.4 MPa compared to the predicted 5 MPa. The flexural strength was expected to follow a similar trend to the compressive strength as the theoretical prediction does. However, instead of following the same trend as the compressive strength, the flexural strength of the concrete was shown to increase with the addition of RCG. Compared to the control sample, the flexural strength for the 20% RCG concrete increased by 5.5% to 5.7 MPa and the 40% RCG concrete increased by 14.6% to 6.2 MPa. This steady increase in flexural strength with an increase of RCG content is similar to the results of Ekop et al. (2022) and Ismail & Al-Hashmi (2009).

The increase in flexural strength may be attributed to the glass particles acting as micro-reinforcement in the concrete matrix due to their unique angular and irregular shape. These particles may help distribute stresses more effectively during flexural testing, particularly in the tension zone, thereby increasing the flexural strength of the concrete.

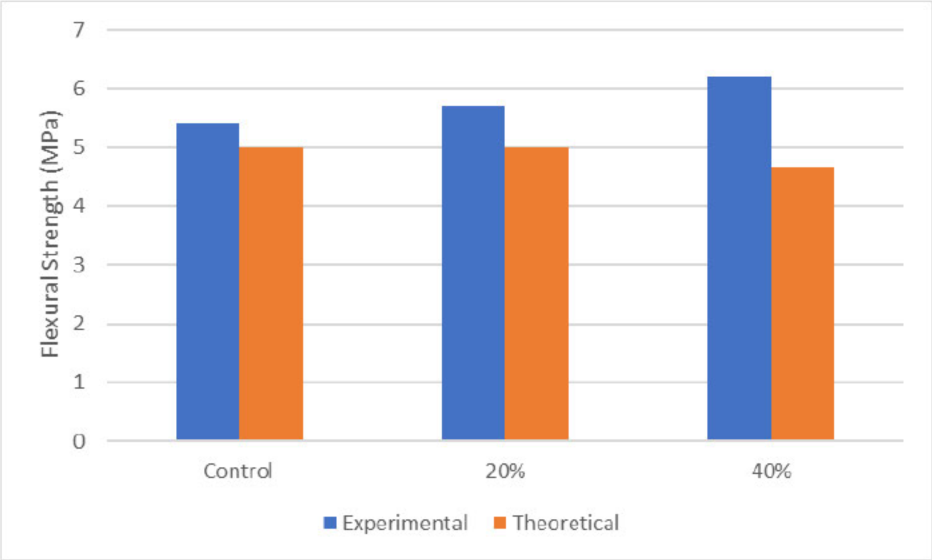

Figure 4.6: Experimental and theoretical results for flexural strength of concrete

The failure patterns of the concrete beams are depicted in Figure 4.7. All CMOD samples failed in the same manner, splitting along the middle without any additional visible cracks. The immediate brittle failure of the concrete is due to its high strength and lack of reinforcement.

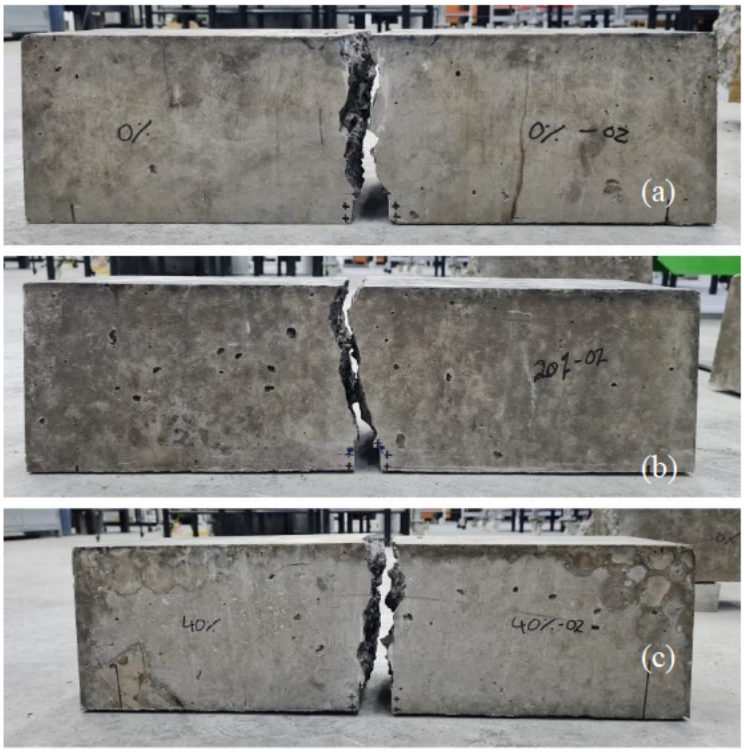

Figure 4.7: Failure pattern of concrete beams (a) control (b) 20% RCG (c) 40% RCG

4.6 Pull-out Results

The data recorded during the pull-out test is presented in Figure 4.8. The results show inconsistent results between samples from the same mix design. For example, the first pull-out sample of the control concrete reached an ultimate load of 61 kN when the rebar had slipped 3 mm. In contrast, the third sample from the same control concrete mix reached a maximum load of only 45 kN, with the rebar slipping by 2 mm. The 4% RCG concrete samples display similar variations, and the 20% RCG concrete was the only one to show somewhat consistent results between all three samples.

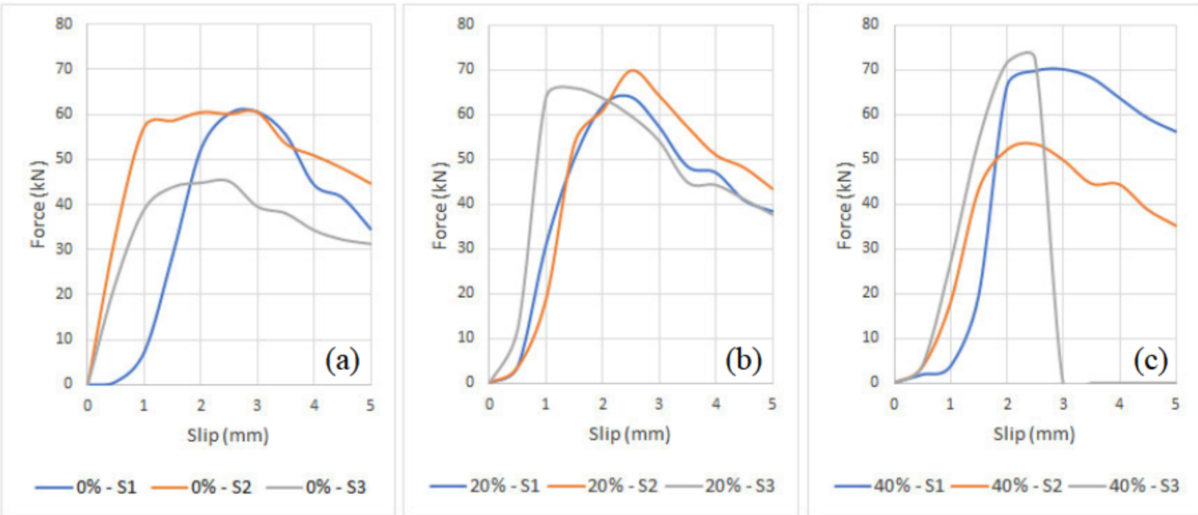

Figure 4.8: Force-slip curves of all 9 pull-out samples (a) control (b) 20% RCG (c) 40% RCG

The average bond strengths of the concrete samples and the theoretical predictions are illustrated in Figure 4.9. The control samples had an average bond strength of 27 MPa, similar to that of the theoretical prediction model from Kangavar et al. (2023). However, the experimental results then diverge from the Kangavar et al. (2023) theoretical results with increased RCG content. Compared to the control samples, the bond strength of the 20% RCG concrete increased by 22.2% to 33 MPa and the 40% RCG concrete increased by 18.5% to 32 MPa.

Although the experimental results are comparable to the prediction models of Kangavar et al. (2023) and Shen et al. (2016), they notably surpass the majority of theoretical predictions. One of the 40% RCG concrete samples displayed an exceptionally high bond strength, to the extent that the rebar itself failed before the concrete bond did, as evident in Figure 4.10(a). Furthermore, it's worth noting that the ultimate load in the pull-out tests occurred at a slip of 2 – 3 mm, a value significantly higher than the typical expectation from the literature, which suggested slip values less than 1 mm. These inconsistent results observed during the pull-out testing prompted a need for further investigation.

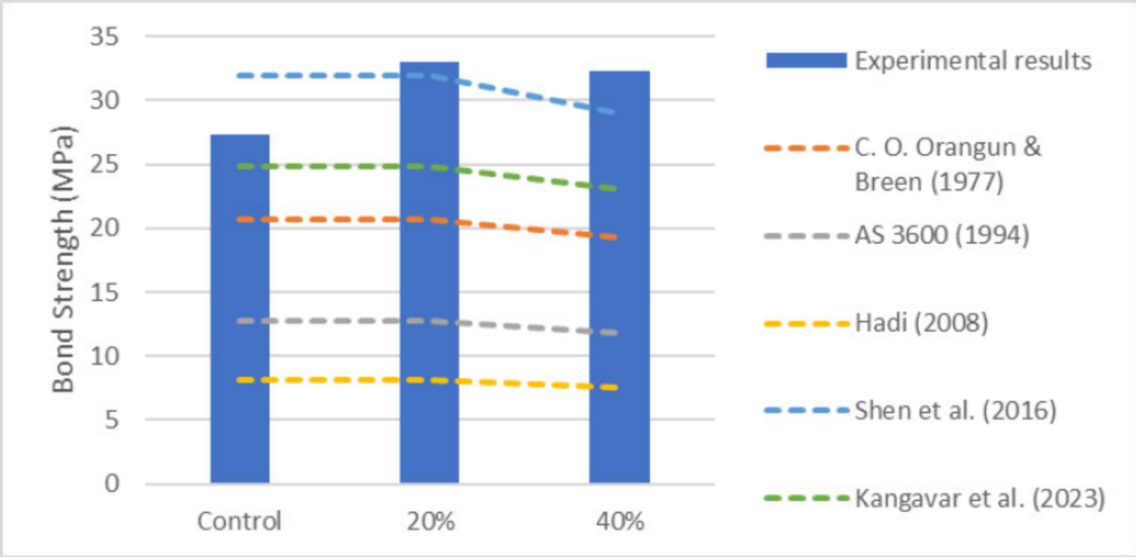

Figure 4.9: Experimental and theoretical results for bond strength of concrete samples

Figure 4.10(b) shows a concrete pull-out sample after testing. It was noticed that the top aluminium pipe covering had been pulled out of the concrete cylinder along with the rebar. This led us to believe that the aluminium pipe had bonded with the rebar, indicating that the experiment had not worked as intended. A closer examination was conducted on one of the pull-out samples depicted in Figure 4.10(c) to gain a better understanding of this unexpected outcome. When the sample was cut in half, it was apparent that concrete had seeped in between the rebar and the aluminium pipes, which caused them to bond together. This cross-sectional view also clearly illustrates the synchronised displacement of the top aluminium pipe with the rebar. The bonding of the rebar with the aluminium pipes helps provide an explanation for the inconsistency between results, unexpectedly high recorded bond strengths and high slip values at the ultimate load.

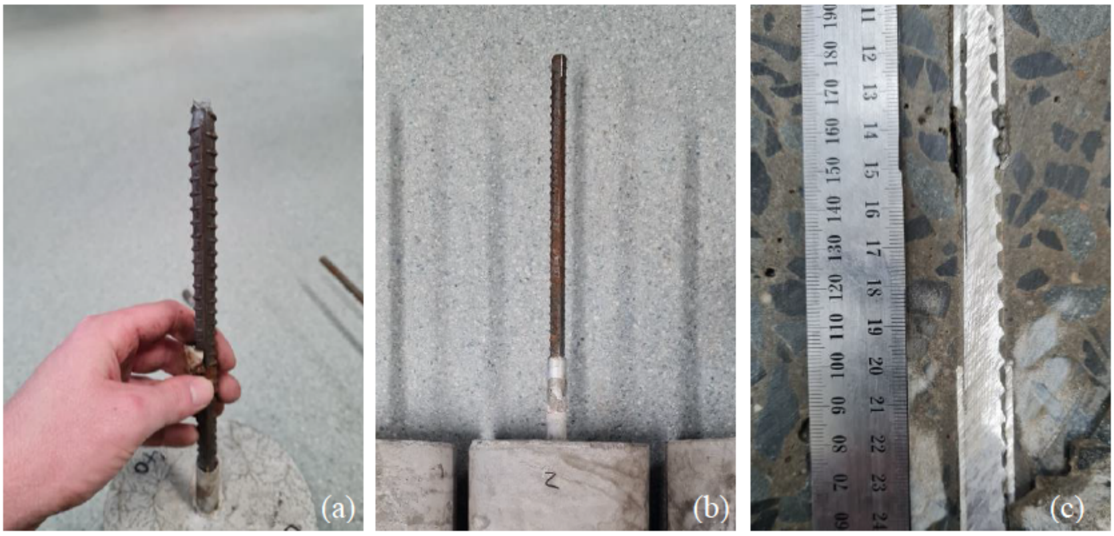

Figure 4.10: (a) rebar failure (b) slip failure (c) concrete sample cut in half

4.7 SEM Analysis

The SEM images for the control, 20% RCG and 40% RCG concrete are presented in Figure 4.11. The SEM images for the 20% RCG concrete reveal a relatively uniform and cohesive concrete matrix similar to that of the control mix. However, the control and 20% RCG concrete samples exhibit occasional black spots, suggesting possible voids within the concrete matrix. In contrast, the SEM images for the 40% RCG concrete show a more pronounced presence of these potential voids, as well as areas of rough, uneven surfaces, indicating a non-uniform distribution of aggregates due to the poor workability of the fresh concrete mix.

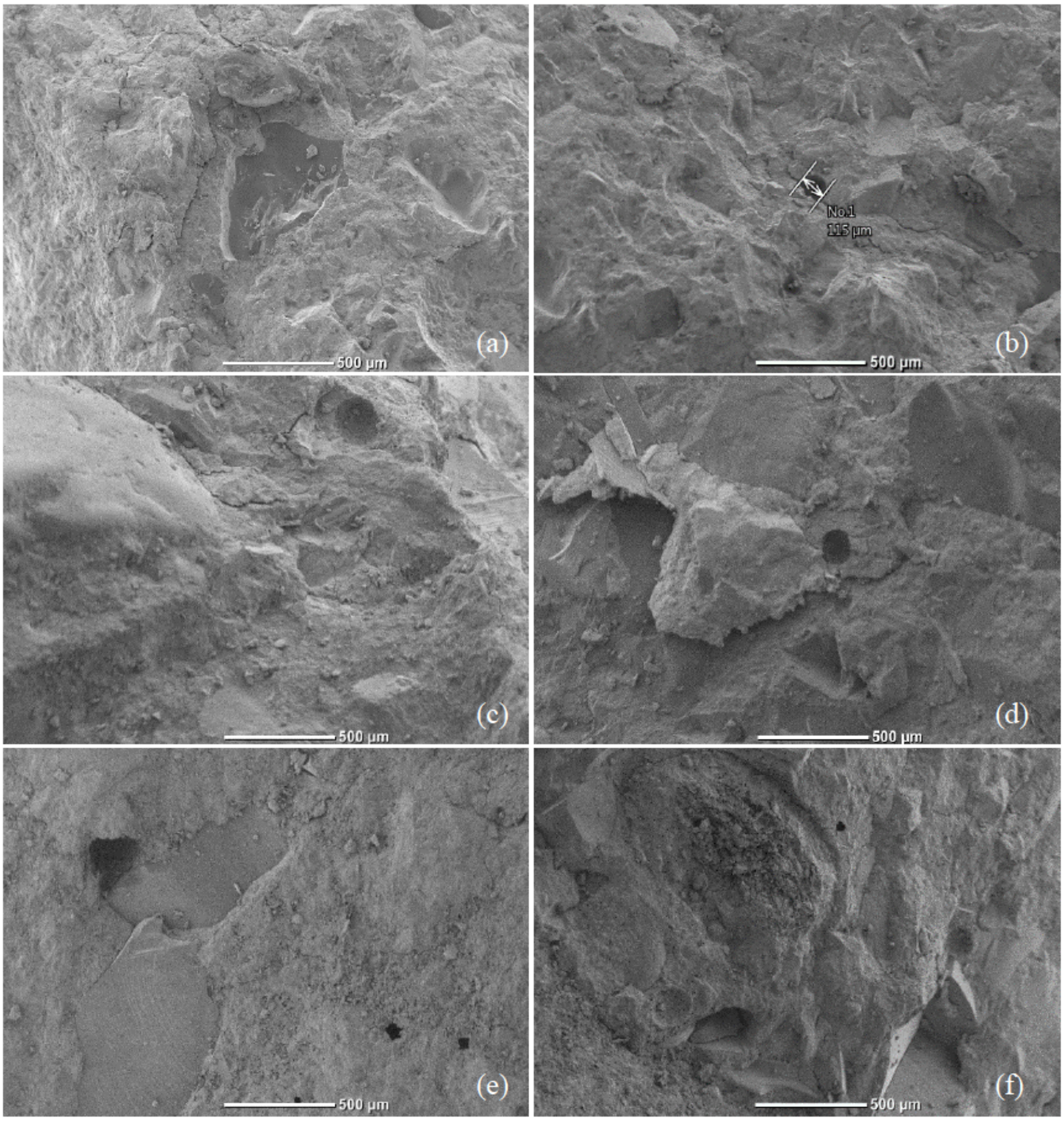

Figure 4.11: SEM Analysis (a,b) control (c,d) 20% RCG (e,f) 40% RCG

Chapter 5: Conclusions & Recommendations

5.1 Conclusions

The aim of this study was to investigate the performance of concrete with recycled crushed glass as a partial replacement for fine aggregate. It involved a comprehensive review of relevant literature as well as undertaking various laboratory tests on concrete samples to determine the fresh and hardened properties of concrete made with RCG. The literature review highlighted multiple studies that investigate the effects of RCG on concrete properties; the results of these studies have been mixed and often contradictory. Despite the conflicting results, most studies suggest an optimum RCG replacement level of 20%. Based on the literature findings, this project utilised three high strength mix designs, including the control, 20% and 40%, where the sand is replaced with RCG by weight. Three main tests were used to evaluate the RCG concrete's performance, including compression, CMOD and pull-out testing. The key findings of these laboratory tests are summarised below:

- The RCG had a well-graded particle distribution similar to that of the replaced sand, both falling within the recommended gradings of AS 2758.1.
- The addition of RCG significantly decreased the workability of fresh concrete by 33.3% and 61.1% for the 20% and 40% RCG replacement levels, respectively. However, the 20% RCG replacement level still produced a workable concrete mix, unlike the 40% mix design.
- The 20% RCG samples saw no decrease in compressive strength when compared to the control samples, with both having a compressive strength of 69 MPa. However, the 40% RCG mix saw a reduction of 13%, reaffirming that the 20% RCG replacement level may be the optimum replacement level.
- Although the CMOD test did not work as intended, the results showed increased flexural strength with increased RCG. Compared to the control sample, the flexural strength increased by 5.5% and 14.6% for the 20% and 40% RCG samples, respectively.
- The results of the pull-out test were inconsistent and higher than expected. A closer inspection of the samples concluded that the test did not work as intended, and the results were inconclusive.

The results of this research suggest that 20% is the optimum RCG replacement level, as there was no loss in compressive strength. This optimum RCG replacement level of 20% aligns with the results of several similar studies. All the results in this project are most similar to a study by Ekop et al. (2022), who also reported a slight decrease in density, no loss in compressive strength at 20% RCG, and a steady increase in flexural strength with the addition of RCG.

5.2 Recommendations

While conducting the pull-out test, it was observed that the concrete had seeped between the rebar and pipe coverings, leading to variations in the bonded length of the rebar and resulting in inconsistent and inconclusive data. Several effective ways to address the problem have been brainstormed upon reflecting on this issue. These include:

- Ensuring that the pipe cover fits tightly and uniformly around the rebar.
- Lubricating the inside of the pipe coverings, making it less prone to bond with the concrete.
- Sealing the gap between the rebar and pipe using either silicone sealant or a rubber O-ring.

As sustainable construction and materials science keep advancing, it is clear that more research is required to be undertaken within the field. To expand on the topic of using glass aggregates in concrete production and fill in the remaining gaps in knowledge, recommended future research is outlined below. These recommendations are meant to improve current methods, explore new possibilities, and help sustainable construction practices keep evolving.

- Test higher RCG replacement levels, i.e., 60%, 80% and 100%, for high strength concrete.
- Investigate the effects of adding superplasticizers to increase the workability of RCG concrete.
- Investigate potential benefits of introducing fibre reinforcement to RCG concrete.
- Optimising the size of RCG instead of recreating particle size distribution of sand.
- Conduct long-term studies to assess the durability of RCG concrete, investigating factors such as freeze-thaw resistance, corrosion resistance, and structural integrity over extended periods.
- Conducting an environmental impact assessment, including a life cycle assessment, to quantify the sustainability benefits of using RCG in concrete.

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Jesse Hjort

Title: Performance of concrete made with recycled glass

Major: Civil Engineering

Supervisors: Sourish Banerjee

Enrollment: ENG4111 – EXT S1, 2023

ENG4112 – EXT S2, 2023

Project Aim: To experimentally measure the mechanical properties of hardened concrete made with recycled crushed glass (RCG) as a fine aggregate replacement. RCG concrete specimens will be tested using the pull-out and crack mouth opening displacement (CMOD) tests. Results will be compared against concrete that uses sand as a fine aggregate, existing literature, and theoretical prediction.

Programme: Version 1, 9th March 2023

1. Review existing literature related to using recycled glass in concrete.
2. Determine a mix design for the concrete.
3. Obtain all required materials/resources.
4. Create concrete specimens.
5. Test concrete specimens.
6. Process and evaluate experimental data.
7. Compare with existing literature and theoretical predictions.
8. Liaise with supervisor throughout the project.

If time and resource permit:

9. Experiment with mitigation strategies for the effect of alkali-silica reaction (ASR) in RCG concrete.

Appendix B – Risk Assessment

2471	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
	ENG4111/ENG4112 - Performance of concrete made with RCG		Low	Low

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Jesse Hjort	22/05/2023	22/05/2023	22/05/2024

RISK FACTOR(S)	EXISTING CONTROL(S)	CURRENT	PROPOSED CONTROL(S)	TREATMENT OWNER	DUE DATE	RESIDUAL
Potential for a driving accident to occur when commuting to and from the testing facilities.	Control: Adhering to road rules and speed limits.	Low	Take precautions to avoid driving fatigue such as plenty of rest and regular breaks. Share drive if possible. Catch public transport if possible.			Low
Inhalation of cement dust can lead to respiratory issues such as irritation, coughing, or lung damage. Also skin/eye damage from cement.	Control: Ensure correct handling procedures of materials. Work to be undertaken with supervision of competent person. ____________ Control: Wear gloves and safety glasses. Wear mask when handling cement powder.	Low				Low
Manual lifting of cement bags, aggregate equipment and concrete samples. Can lead to stress and strain on muscles, back injury or crush injuries.	Control: Use lifting aids for heavier items such as concrete specimens. ____________ Control: Work to be undertaken with supervision of competent person. Ensure correct lifting techniques are used. Use team lift if needed. Keep hands clear from pinch points. ____________ Control: Appropriate PPE including steel cap boots and gloves.	Low				Low
Cement mixer: Potential for pinch points when interacting with moving machine parts. Testing Equipment: Potential of pinch points and flying concrete debris when testing concrete specimens.	Control: Ensure safety cages/guards are in place when operating machinery. ____________ Control: Work to be undertaken with supervision of competent person. Ensure equipment is in good working order and standard operating procedures are followed. Restrict access in and around equipment when in use. Keep clear from pinch points. ____________ Control: Use gloves and safety glasses	Very Low				Very Low
Potential for slips, trips and falls from power cords, water (used in concrete mix), equipment and other objects.	Control: Good housekeeping. Ensure paths are clear and free of tripping hazards. Eyes on path. ____________ Control: safety boots with good grip.	Low				Low

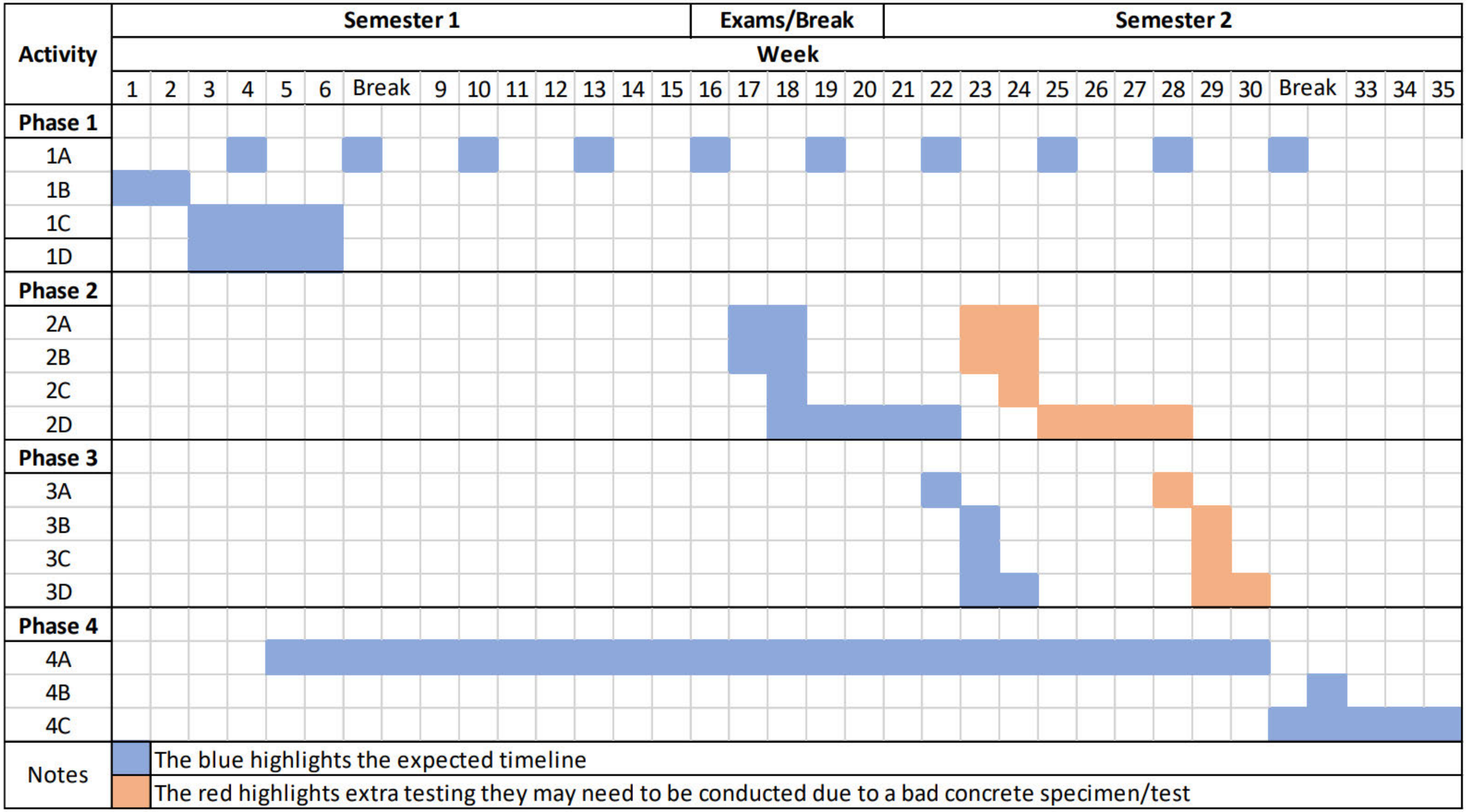
Appendix C – Project Resources

Item	Quantities	Source	Cost	Comment
PC	1	Student	-	PC is required for completing dissertation.
Microsoft Word	1	Student	-	Microsoft Word is required for completing dissertation.
Microsoft Excel	1	Student	-	Excel is needed for processing and presenting data.
Permanent Marker	1	Student	-	Handy for labelling the test specimens.
Hand Tools	1	Student	-	Needed to prepare the concrete specimens.
Travel	1	Student	TBD	As an external student there will be travelling expenses to conduct concrete experiments.
Cement	TBD	USQ	TBD	To create concrete test specimens.
Coarse Aggregate	TBD	USQ	TBD	To create concrete test specimens.
Sand	TBD	USQ	TBD	To create concrete test specimens.
Recycled Crushed Glass	TBD	USQ	TBD	To create concrete test specimens.
Anchor Bolt Testing Equipment	1	USQ	-	To test the concrete test specimens.
Flexural testing device	1	USQ	-	To test the concrete test specimens.

Appendix D – Project Plan/ Timeline

Phase 1	Project Setup
1A	Liaise with supervisor via zoom every 2-3 weeks
1B	Obtain formal approval from USQ and a relevant supervisor to research this topic for capstone project`
1C	Finalise what concrete mix designs will be used for testing and confirm the required dimensions of the test specimens
1D	Ensure the required testing equipment is available at USQ facilities or elsewhere
Phase 2	**Creating Test Specimens**
2A	Obtain all required materials to create the concrete test specimens
2B	Obtain or construct the moulds to create the test specimens
2C	Create test specimens
2D	Allow the concrete to set for at least 28 days to ensure the concrete reaches its maximum strength
Phase 3	**Concrete Testing**
3A	Obtain approval for using testing equipment and conduct any necessary safety training and/or risk assessment
3B	Prepare the concrete specimens ready for testing
3C	Ensure the testing equipment is calibrated and ready for use
3D	Begin testing the concrete specimens and recording the data.
Phase 4	**Analysis and Presentation of Results**
4A	Prepare findings of the tests results in a draft dissertation
4B	Present findings to USQ staff and peers at Professional Practice 2
4C	Review any feedback and prepare final version of dissertation to submit for marking

Note: Gantt chart shows an estimation for creating and testing concrete specimens and is subject to change.


Activity
Semester 1
Exams/Break
Semester 2
Week
1 2 3 4 5 6 Break 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 Break 33 34 35
Phase 1
1A
1B
1C
1D
Phase 2
2A
2B
2C
2D
Phase 3
3A
3B
3C
3D
Phase 4
4A
4B
4C
Notes
The blue highlights the expected timeline
The red highlights extra testing they may need to be conducted due to a bad concrete specimen/test