University of Southern Queensland

Faculty of Health, Engineering & Sciences

Evaluation of the Performance of Recycled Concrete Aggregate in Fresh Concrete for Manufacturing Fence Posts

A dissertation submitted by

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ABSTRACT

The continued urbanisation and development driven by population growth around the world is resulting in large quantities of construction and demolition waste and the simultaneous depletion of natural resources. The production of recycled aggregates offers the potential to reduce the impact on landfills and the natural environment by redirecting waste concrete for use in fresh concrete.

Recycled aggregates are generally considered inferior to natural aggregates particularly due to their greater water absorption properties, and the effect this has on fresh concrete mixes, and the creation of an additional interfacial transition zone between the new mortar and the adhered mortar attached to the recycled aggregates.

This study evaluates the performance of recycled aggregates in the production of new pretensioned concrete fence posts with the aim to produce a commercially viable product. A two-stage-mixing-approach was adopted to optimise the performance of the recycled aggregate concrete with 30% replacement of the coarse aggregates. The aggregates were not subjected to any pre-treatment to keep production costs to a minimum.

Comparison was made with commercially produced versions of the posts using the manufacturer's standard concrete mixture and procedures. Cylinder test specimens were formed from each batch of concrete to enable an analysis of the compressive and splitting tensile strengths. Post samples were subject to four-point bending tests, and details of loads and deflections recorded enabling evaluation of the modulus of rupture and ultimate bending moments.

The results indicate that compressive strength and the ultimate moment of the samples is not significantly affected at the substitution ratio of 30% recycled aggregates at 38 days. Tensile strength was reduced by the addition of recycled aggregates, as was the overall deflection of the sample posts prior to failure. All of the sample posts failed due to flexure cracking, this lead to rupture of the reinforcement in the natural aggregate samples and bond slippage in the recycled aggregate samples.

The manufacture of concrete fence posts using 30% recycled aggregates is not limited by the compressive, tensile or flexural performance, and presents a potentially environmentally friendly alternative to 100% natural aggregate concrete posts.

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Limitations of Use

CERTIFICATION OF DISSERTATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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NOMENCLATURE

American Concrete Institute (ACI)

Interfacial Transition Zone (ITZ)

Natural Aggregate (NA)

Particle-size distribution (PSD)

Prestressed Concrete Institute (PCI)

Recycled Aggregate (RA)

Recycled Aggregate Concrete (RAC)

Saturated Surface Dry (SSD)

Water/cement (w/c)

CHAPTER 1. INTRODUCTION

1.1 Introduction

Developing sustainable construction materials is essential to enable modern society to meet current and future needs, while minimising impacts that can cause significant environmental damage. A balance must be maintained between development of society and reducing the reliance on the exploitation of natural resources.

Concrete is the second most widely consumed material in the world after water and the most widely used building material thanks to its versatility, strength and durability (Gagg 2014; T et al. 2019). As natural resource reserves become depleted, a compromise is needed between development and minimising the exploitation of these resources. One of the ways in which this can be achieved in concrete production is through the substitution of fresh materials with recycled materials such as glass, fly ash and recycled aggregates in fresh concrete.

The use of waste materials can potentially reduce costs and CO_2 emissions associated with the production of aggregates which can lead to project budget savings and environmental benefits. The diversion of waste products to be reused has beneficial effects due to the reduction in material sent to landfill.

The acceptability of RAC is becoming more widespread, it is not universal; this is due in part to a lack of confidence in the finished product. Other factors that contribute to a low demand to use RA include; lower quality compared to NA concrete, lack of financial incentives, distance to recycling facilities and the absence of standard specifications (Tam et al. 2018). Because RA is produced primarily from demolition waste it can sometimes contain contaminants such as gravel, other masonry, reinforcing steel, timber and plastic which often results in it being sent directly to landfill (Cement Concrete & Aggregates Australia 2008; Pickin et al. 2020).

Poorer performance of RAC compared with NA concrete has been well documented with reports of lower mechanical properties for compressive and tensile strengths, reduced workability and increased shrinkage and permeability (Eckert & Oliveira 2017). These changes to the properties are reported to be caused by the increase in the number of ITZ owing to the presence of adhered mortar on the RA which also leads to increased water absorption (Hanif et al. 2017). However, research indicates that these property changes can be minimised if the substitution rate of RA is minimised (Amer et al. 2016; Hanif et al. 2017).

The results of a number of studies have shown that an upper limit of 30% RA can give satisfactory results, particularly in non-structural concrete. In Australia, a threshold of up to 30% RA in fresh concrete has been recommended by several industry bodies as producing acceptable results (Cement Concrete & Aggregates Australia 2008; Austroads 2009; Holcim 2017).

Investigations on full scale RAC elements need to be carried out as in an effort to provide experimental data that can support increased confidence in the use of RA. A feature of this project is that the elements in this study were made in a commercial factory, using current industry processes, rather than in a laboratory setting.

1.2 The Problem

Much of the literature focuses on the production and testing of concrete in laboratory settings and its use in real world applications is not investigated. While reports on the properties of RAC generally point to poorer performance when compared to NA concrete, the studies have not investigated whether concrete produced with RA will perform to a satisfactory standard such as to allow its use in practice.

The aim of this project is to evaluate the performance of RAC in comparison to NA concrete under standard industry conditions and to verify whether RAC can be successfully used in the production of fresh concrete for civil infrastructure components.

This project will study the short term performance of RAC, produced using 30% replacement of NA with RA coarse aggregate, to manufacture concrete fence posts in a commercial environment, with a compressive strength of 32 MPa.

This research is proposed to fill the gap in the existing research in order to provide sound comparisons of concrete produced using 30% RA as replacement for coarse NA, to produce mixes for practical applications under standard construction practices and curing conditions. No existing study has been found that investigates the production of concrete components for use in civil works such as the fence posts which will be feature of this research.

1.3 Research Objectives

Successful results are expected to provide increased confidence in the use of RAC and promote further usage of RA in the construction industry, with the belief that this will lead to environmental benefits through the reduction of construction waste sent to landfill.

To achieve the abovementioned aims, the following objectives have been identified:

1. Remove contaminants from sourced RA, and produce a grading profile that replicates the NA used in the production of normal concrete posts.
2. Produce concrete mixes using 30% RA coarse aggregate replacement, with a characteristic strength of 32 MPa.
3. Produce concrete fence posts using RAC and evaluate their flexural strength while simultaneously manufacturing and testing standard concrete posts for comparison.
4. Increase confidence in the use of RA for low strength concrete production.
5. Further develop knowledge of the properties of RAC when used under standard industry conditions.
6. Contribute to the existing knowledge base to assist with further research in the field of RAC.

1.4 Expected Outcomes

The project aims to enhance the understanding of the behaviour and properties of RAC in the manufacture of civil infrastructure components.

Further to this, the project will strive to deliver the following outcomes:

1. A viable recycled concrete product in the form of a pretensioned fence post.
2. Increased confidence in the use of RA as a replacement for NA in fresh concrete for low to medium strength concrete production.
3. Further developed knowledge of the properties of RAC when used under standard industry conditions.
4. Provide a knowledge base from which further research can be conducted in the field of RAC, such as considering the long-term performance of these elements.

In order for RAC to overcome the reluctance of industry to embrace its use, one of the hurdles that must be overcome is the lack of faith in the finished product. The use of RAC in simple non-structural elements is seen as a good stepping stone to further expansion of its range of uses and it is hoped that this will lead to improved economies of scale, thereby making the product commercially viable.

CHAPTER 2. LITERATURE REVIEW

2.1 Background

Throughout history, humans have utilised natural resources for their own purposes, ranging from food and energy production through to raw materials to manufacture materials for building infrastructure, such as transport systems and buildings (Koenders et al. 2014).

As supplies of non-renewable resources become scarcer, there has been a greater focus on sustainable construction practices which seek to make efficient use of resources, by using fewer raw materials and causing less waste (Stubbs 2008; Kou et al. 2012; Behera et al. 2014; World Economic Forum 2016).

Concrete is a mixture of cement, sand, aggregate and water, to which various admixtures and additives can be combined to enhance particular properties for special purposes (Gagg 2014). After mixing, the water and cement react through a hydration process which solidifies and hardens the mixture binding the sand and aggregate in the cement matrix (Gagg 2014).

There are various methods by which the environmental impacts resulting from concrete production can be minimised. These include the use of concrete that has been crushed to produce recycled aggregate (RA) as a replacement for natural aggregates (NA), through to using by-products from other industries such as steel slag, fly ash and rice husk ash (Stubbs 2008; Koenders et al. 2014; Lavado et al. 2020; Tayeha et al. 2020).

In recent years, industry has focused on use of environment friendly materials, sustainable materials and finding greener ways to produce concrete, particularly encouraging the use of recycled materials to replace virgin materials (Pradhan et al. 2017; Jiménez et al. 2018). The use of recycled concrete aggregates was first explored during World War II when it was used as a base material for road pavements (Behera et al. 2014; Tam et al. 2018). In the 1980s, European countries such as Denmark and the Netherlands began to consider the use of RA for new concrete structures (Behera et al. 2014; Lavado et al. 2020).

In order to promote this idea, a synergistic effort among various government departments, research groups, designers, construction engineers and certifying authorities is required (Pradhan et al. 2017). To this end, the National Waste Policy Action Plan (Australian Government 2019) has been developed with the aim of reducing waste per capita by 10% and achieving 80% average waste recovery rate by

2030 through a range of regulatory, financial and legislative options. It also seeks to significantly increase the amount of recycled materials used by all levels of Government.

The Victorian State Government has been promoting sustainability in construction for many years and recently announced the Sustainable Infrastructure Fund, which aims to support the use of recycled materials in infrastructure projects (Sustainability Victoria 2020).

Approximately 22.9 Mt of masonry waste, including concrete, bricks and rubble, was produced in Australia in 2018-19 (Pickin et al. 2020) and during this period the recycling rate grew to 82%, which is a significant increase over the figure from 2006-07 when only 62% of masonry was recycled (Pickin et al. 2020). The recent trends of masonry recycling and waste to landfill are shown in Figure 2.1. It can be observed that the popularity of recycling masonry materials has increased significantly, particularly over the period 2015 to 2019.

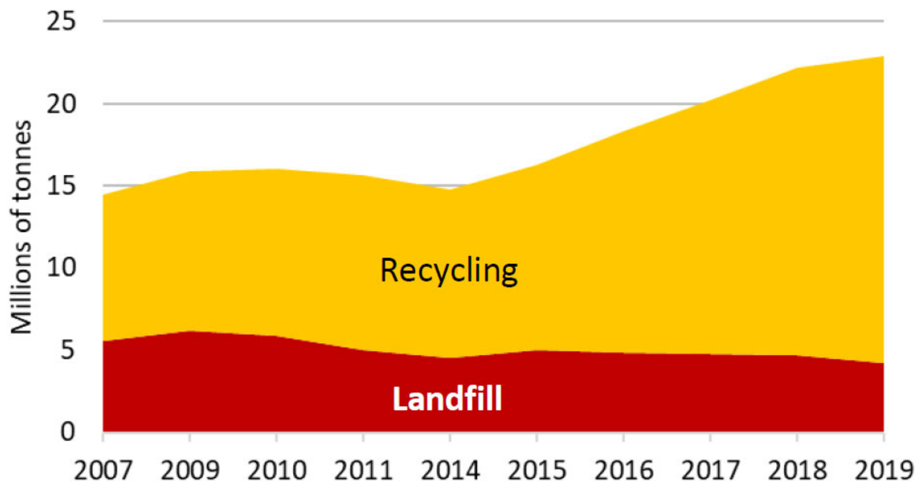

Figure 2.1: Historical Trends in Masonry Waste Generation and Recycling in Australia (Pickin et al. 2020).

The estimated benefits when comparing costs of recycled aggregates with normal aggregates, range from savings of almost 26% per cubic metre of aggregate and almost 9% per cubic metre of concrete (Jiménez et al. 2018) to claims of savings up to 60-80% (Eckert & Oliveira 2017).

2.2 Recycled Aggregate Concrete Performance

Poorer performance of RAC, compared with NA concrete, has been well documented with reports of lower mechanical properties for compressive and tensile strengths, reduced workability and increased shrinkage and permeability (Behera et al. 2014; Amer et al. 2016; Eckert & Oliveira 2017; Fraj & Idir 2017).

These changes to the properties are reported to be caused by the increase in the number of ITZ owing to the presence of adhered mortar on the RA, which also leads to increased water absorption and a reduction in workability (Amer et al. 2016; Hanif et al. 2017). However, research indicates that these property changes can be minimised if the replacement fraction of RA is minimised (Hanif et al. 2017). Alternatively, it has been proposed that comparative weakness of RAC may be due to RA containing many small cracks in the adhered mortar as a result of the crushing process (Dong et al. 2019).

Various studies have investigated methods to remove the adhered mortar from the RA. Butler et al. (2011) investigated submersing the RA in a nitric acid solution, subjecting it to repeated freeze-thaw cycles and using rapid temperature changes in a thermal expansion method. They found that the nitric acid immersion was the least effective method while the freeze-thaw method removed approximately 85% of the old mortar. However the best method was the thermal expansion method which removed almost 100% of the adhered mortar.

Poon et al. (2004) reported that the preferred moisture state for the use of RA is dry (air-dried) which showed negligible differences in compressive strength and workability when compared to NA. This was in contrast to oven-dried or saturated surface dry (SSD) condition where both properties were affected considerably.

These findings are contradicted somewhat by Mefteh et al. (2013) who found that pre-wetting of the RA was necessary to maintain workability, by negating water absorption properties of RA, and that the mix proportions played a larger role in compressive and tensile strengths. They also found that dry aggregate produced the best strength results and claimed that this was due to a lower porosity concrete being produced.

Studies conducted by Kou et al. (2012), Behera et al. (2014), Fraj and Idir (2017), Gholampour and Ozbakkaloglu (2018) and Ahmed et al. (2020) have investigated the replacement of NA with a range of RA percentages. These results have shown that an upper limit of 30% RA can give satisfactory results though research by Medina et al. (2014) suggests replacement ratios of up to 50% can be used for housing construction. In Australia an upper limit of 30% RA in fresh concrete has been adopted by several industry bodies (Cement Concrete & Aggregates Australia 2008; Austroads 2009; Holcim 2017).

Research into the properties of reinforced concrete beams produced with RAC have found that it is possible to design structural members to comply with existing overseas codes for use in buildings and other structures (Sato et al. 2007; Pacheco et al. 2015). While this project will not focus on structural members per se, the pretensioned concrete posts do share design characteristics with reinforced beams, and as such, these findings build on the body of work relating to the use of RAC in situations where flexural strength is of importance.

Cantero et al. (2020) investigated the mechanical properties of RAC using 50% mixed construction and demolition waste containing not only concrete waste but also bricks and other masonry. They discovered a 5% decrease in density, 25% decrease in compressive strength and 17% reduction in tensile strength. This was attributed to the addition of supplementary water to maintain workability and the presence of lower quality fired clay particles.

2.3 Recycled Aggregate Concrete Properties

2.3.1 Adhered Mortar

Normal concrete is considered a three-phase composite material consisting of coarse aggregate, mortar paste with fine aggregate and ITZs between the mortar matrix and coarse aggregate (Tam et al. 2005; Pepe et al. 2014). The bond at the ITZs between the coarse aggregate and mortar matrix principally governs the mechanical performance of the concrete (Tam et al. 2005).

RA itself is a two-phase composite material consisting of adhered mortar and natural aggregate that is produced from the crushing of demolition waste (Pepe et al. 2016). This leads to a different situation when using a percentage replacement of RA, as a higher number of phases are present namely; natural aggregates, old natural aggregates, old mortar paste, new mortar paste and an increased number of ITZs between the RA and the fresh ingredients (Tam et al. 2005; Pepe et al. 2014; Fraj & Idir 2017). As a result RAC may produce a failure mechanism considerably different to that observed in normal concrete.

The amount of adhered mortar can be influenced by the strength of the parent concrete and the type of crusher used in its production. Impact crushers tend to remove more of the adhered mortar than jaw crushers (Butler et al. 2011). Seo and Choi (2014) also identified a relationship to the size of the

RA with the amount of adhered mortar decreasing as the aggregate size decreased. As such, smaller RA sizes can improve the strength of RAC and sizes smaller than 20 mm should be used to ensure the quality of the RAC.

The presence of the adhered mortar results in aggregate that has lower density, higher porosity and a greater water absorption capacity than NA due to the mortar being more porous than NA (Butler et al. 2011).

While some research proposes that the high water absorption capacity of RA creates difficulties in the design and mixing of fresh concrete causing increased porosity or decreased workability , Eckert and Oliveira (2017) claim that if used in appropriate manner, this property can sometimes be viewed as a benefit as it assists internal curing of the concrete.

2.3.2 Compressive Strength

The characteristic strength of concrete is given as a compressive value, expressed in mega Pascals (MPa) measured at 28 days. Neglecting considerations such as weak aggregate, the dominant factor in determining the strength of concrete is its w/c ratio with compressive strength inversely related to the w/c ratio (Kosmatka & Wilson 2011; Gagg 2014).

In concrete made with NA, compressive strength is influenced by the water–cement ratio, the extent to which hydration has progressed, the curing and environmental conditions and the age of the concrete (Gagg 2014).

Pradhan et al. (2017) state the replacement ratio of natural aggregate, and the w/c ratio, are the primary influence on the compressive strength of the hardened concrete. This is supported by the findings of Sato et al. (2007), who considered RA of known good quality (Series A) against RA from general demolition waste (Series B) and determined that compressive strength is controlled by w/c ratio.

Figure 2.2 shows the typical relationship between compressive strength and water to cement ratio. It can be clearly seen that with increasing w/c ratio there is a corresponding decrease in compressive strength.

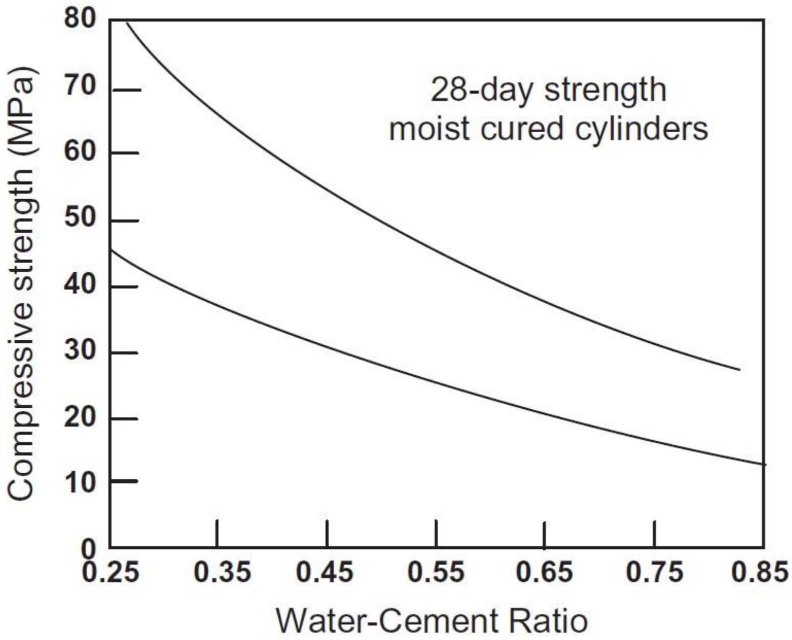

Figure 2.2: Typical Compressive Strength to W/C Ratio Relationship (Gagg 2014).

Research conducted by Etxeberria et al. (2007) found that, the strength of the parent concrete is a significant qualifying factor in determining the compressive strength of RAC. In drawing conclusions from the research of (Sato et al. 2007) it appears as though the quality of the RA has no effect on concrete strength. However, there is no evidence in within the research that the Series B aggregate is in fact of poorer quality than the Series A aggregate.

Pradhan et al. (2017) also suggested that other factors affecting the compressive strength of RAC include the age and exposure condition of parent concrete, number of crushing stages, strength properties of the parent concrete, and the amount of adhering mortar. Additionally, Eckert and Oliveira (2017) note that the LA coefficient, shape index, fines content and specific density also play a role in the reduced mechanical properties of RAC.

There are varying amounts of RA replacement that have been reported to be acceptable without significant compressive strength loss, these range from 20-40% (Mefteh et al. 2013), 30% (Pradhan et al. 2017) and up to 50% (Eckert & Oliveira 2017). Some authors have even observed that compressive strength of RAC is sometimes higher than NA concrete (Butler et al. 2011; Behera et al. 2014; Kisku et al. 2017) which is often attributed to strengthening of the mortar aggregate bond, due to hydration of unhydrated cement in the old mortar, and the angularity of the RA causing increased friction.

A study by Gonzalez-Fonteboa and Martınez-Abella (2008) showed normal concrete achieving a higher early age strength, up until approximately 60 days when the strength of the RAC was higher than normal concrete. In testing a range of RA replacement ratios, up to 56 days, Fonseca et al. (2011) found that neither RA replacement ratio or curing conditions provided conclusive data.

Collated results from some of the previous studies are displayed in Figure 2.3 and show variances in strength trends with increasing percentages of RA replacement.

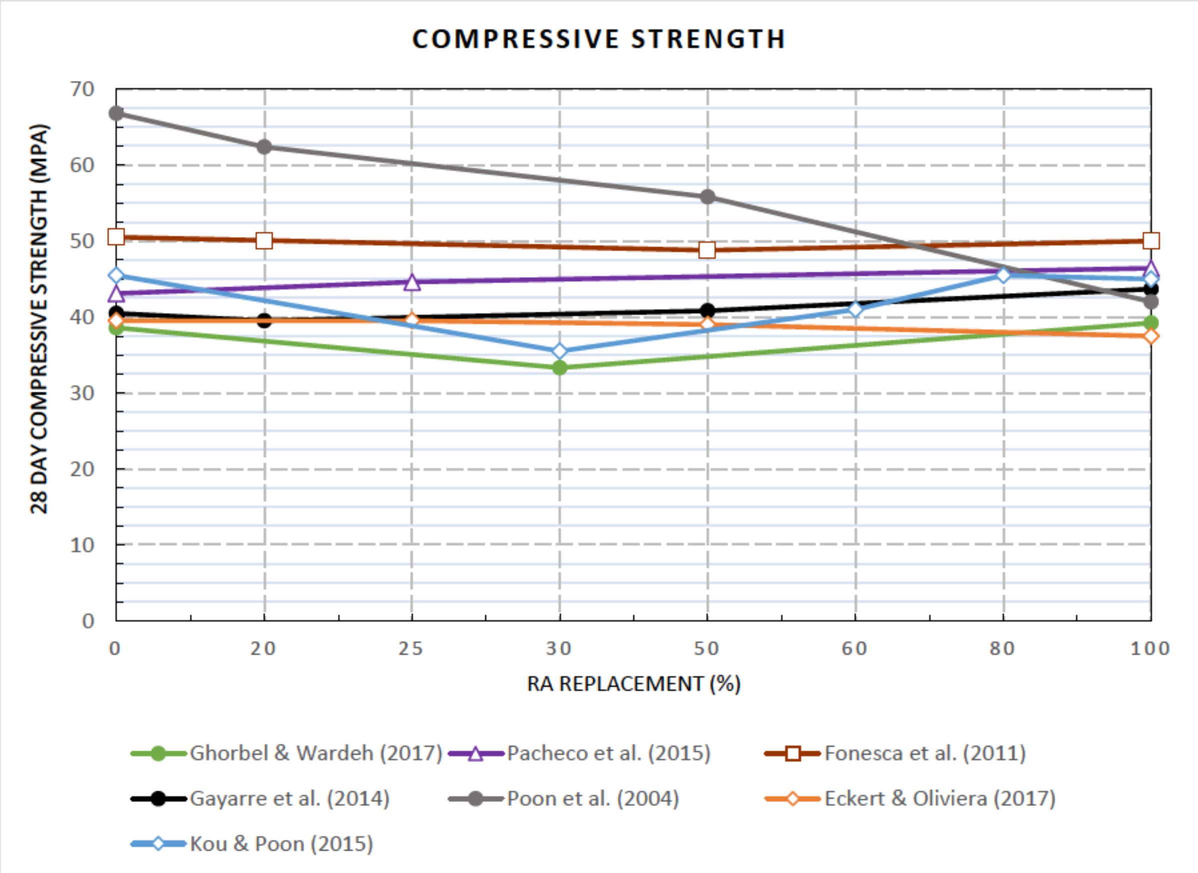

Figure 2.3: Comparison of Compressive Strength from Previous Studies

According to Amer et al. (2016), a reduction in compressive strength observed when using RA results when additional water is added to maintain workability with this water being trapped into the pores of the adhered mortar which inhibits the cement hydration. This is supported by Mefteh et al. (2013) who found that using dry RA with a constant w/c ratio gave the best strength results. They apportioned this to the porous RA absorbing excess water and thus lowering the effective w/c ratio.

Butler et al. (2011) noted that failure around the aggregate suggested that the mortar-aggregate ITZ is the limiting factor while failure through the aggregate indicates that the limiting factor is the strength of the coarse aggregate itself. They concluded that the increase in compressive strength when RA is used is because of the more angular profile of the RA, this increases the friction between the paste and aggregate surface. Whereas Kou and Poon (2015) suggest it could be due to hydration of unhydrated cement in the RA mortar.

As part of the study conducted by Gonzalez-Fonteboa and Martınez-Abella (2008) the loss of compressive strength under sustained load was evaluated by applying a load at a slow rate. They reported a loss of strength of 4.77% for normal concrete and 9.03% for 50% RA concrete which indicates that the RAC is a weaker material under sustained loads.

2.3.3 Tensile Strength

The data on tensile strength is somewhat inconsistent; some studies report tensile strengths higher or equal than that of ordinary concrete when using RA, while other studies report a lower tensile strength (Behera et al. 2014; Eckert & Oliveira 2017). Possible reasons for the variation in results could be due to the variable quality of the source RA, it has been reported that RA from high strength concrete displays better mechanical properties when used in RAC. This is likely due to the bond strength between the aggregate surface and matrix, which has an influence on split tensile strength, and in some longer term studies this has been shown to increase with age due to further hydration (Kou et al. 2012; Behera et al. 2014).

The split tensile strength of RAC decreases as the replacement ratio increases, particularly under air curing conditions (Fonseca et al. 2011), with the reduction reported being up to 10% at different replacement percentages (Pradhan et al. 2017), 6.5% for 25% RA replacement (Pacheco et al. 2015). This is challenged by the investigation carried out by Gonzalez-Fonteboa and Martınez-Abella (2008) who observed no significant differences between normal concrete and RAC with 50% aggregate replacement and that the addition of superplasticiser had no discernible effect.

Collated results from some of the previous studies are displayed in Figure 2.4 and show variances in strength trends with increasing percentages of RA replacement.

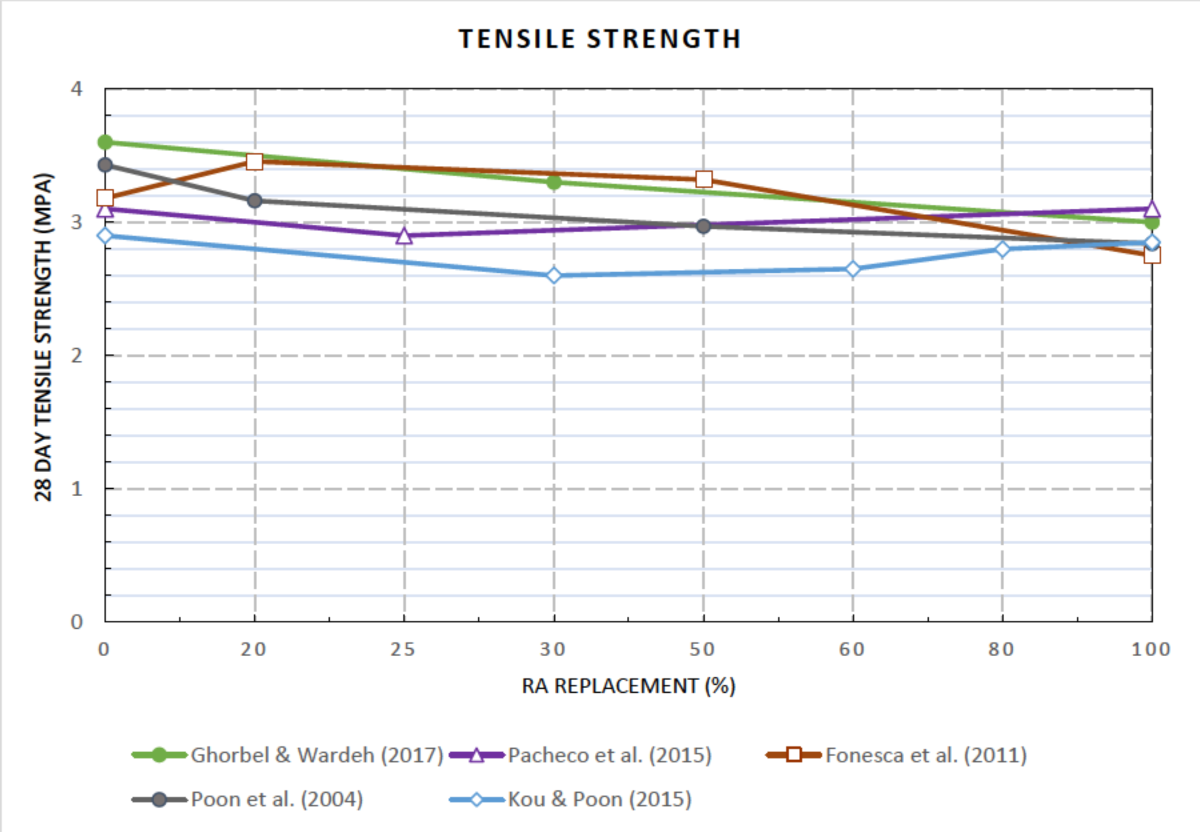

Figure 2.4: Comparison of Tensile Strength from Previous Studies

Concrete is a brittle material regardless of the aggregate used and is characterised by strain softening when subjected to tensile stress (Ghorbel & Wardeh 2017). Strain softening is defined by Choi et al. (1996) as the decrease in strength due to the propagation of cracks under loading. This leads to increased deformation, from which further cracking ensues, and the load carrying capacity diminishes as softening continues.

Fracture toughness is the resistance to brittle fracture of the concrete (Kazemian et al. 2019). During three-point beam testing, Kazemian et al. (2019) found that fracture toughness was marginally reduced with RA proportions up to 25%, after which losses increased substantially. The strength of concrete in tension directly affects its fracture toughness and therefore its shear and flexural strengths (Li et al. 2019).

2.3.4 Shear and Flexural Strengths

One of the critical failure modes for concrete fence posts is failure in shear and flexure due to pressure from animals as they pass. The shear strength of a reinforced member depends on a number of factors such as the concrete properties, additional actions acting on the member, the amount of longitudinal reinforcement and the size of the member. However, typically the properties of the concrete are considered the most influential factor (Rahal & Alrefaei 2017).

The replacement ratio of RA has little influence on the flexural strength of RAC, with reports that the flexural strength is reduced up to 10% with the increase in RCA replacement up to 100% (Pradhan et al. 2017). According to Pacheco et al. (2015), the incorporation of RA has minimal effect as the performance of reinforced RAC under flexural loading is mostly controlled by the steel reinforcement.

In considering unreinforced concrete specimens, Li et al. (2019) found that with increasing replacement ratios of RA, there was an increase in strain softening under three-point testing. This was attributed to the fact that RA may contain defects from the crushing process reducing its strength and resulting in rapid propagation of cracks after initial cracking takes place.

In studying the shear transfer across cracks for concrete mixes with 0, 30, 50, 70 and 100% RA replacement, Xiao et al. (2012) found that for replacement ratios of RA up to 30%, the ultimate shear load was similar to that for NA concrete. However as the RA proportion increased towards 50% there was up to a 15% reduction in the ultimate load. They evaluated these results against the ACI and PCI design equations for shear strength, and determined that both can be safely applied to RAC situations. However, these results were not validated against Australian design standards.

Ignjatović et al. (2017) studied a series of 200 mm wide and 300 mm deep concrete beams made with a 0%, 50% and 100% RA replacement and with 0%, 0.14% and 0.19% shear reinforcement ratios. They found that RAC concrete performed similar to NA concrete (within 5-10%) in relation to shear strength, while noticing that the angle of the shear cracks differed in RAC beams without reinforcement. This study only tested one of each type of beam and as Rahal and Alrefaei (2017) noted, shear strength variations are not uncommon and reported a 17% difference in duplicate beams during their testing. It is therefore suggested that testing of duplicate or triplicate beams better gives a greater degree of reliability in the results obtained.

During their study of the flexural performance of reinforced beams made using RAC, Seara-Paz et al. (2018) found that cracking moments were inversely proportional to the percentage of RA in the concrete, which is noted as correlating with reducing split tensile strength under the same conditions. They observed no significant differences between normal and RA concrete when considering yielding and ultimate moments, and as such concluded that RA content was not a significant factor when considering the flexural strength of a reinforced concrete beam.

Kazmi et al. (2019) noted a 41% reduction in compressive strength for RAC when compared with NA concrete. They attributed this to poor bonding between old and new cement pastes, however they found that treatment of the RA with acetic acid and mechanical rubbing resulted in observed flexural strength at 94% of that for NA concrete. They proposed that this improvement over the untreated RA was due to the removal of old adhered mortar.

These findings on flexural strength are supported by the work of Kazemian et al. (2019) who reported 10-14% reduction in flexural strength, for 25% and 50% RA replacement respectively, under three-point load testing. In line with previous research, the reason for reduced strength was reported as being the loose and pre-cracked adhered mortar; these results were improved when treated RA was used when the decrease in strength was only 3%. They discovered that the failure mode for RAC was more likely to be tensile opening rather than shear failure. The better interlock of RA due to its angular shape and rough texture improved the shear resistance of RAC over NA concrete.

The long term flexural behaviour of reinforced concrete beams results in greater deflections for RAC beams under sustained loads and with increasing ratios of RA replacement (Zhu et al. 2020). However for short-term loading Arezoumandia et al. (2014) found that while shear strength decreased 12%, the load-deflection response was similar for NA concrete beams and those with 100% replacement with RA.

2.3.5 Water Absorption

The higher water absorption characteristic of RA when compared to NA has been reported in many studies.

(Gonzalez-Fonteboa & Martınez-Abella 2008) noted that water penetration into the pores of the RA results in a considerably higher water absorption capacity for RA, which can lead to difficulties in achieving the required slumps. Fonseca et al. (2011) considered that 90% of this water absorption occurred in the first 5 minutes of being exposed to water. This theory was later adopted by people such as Tam et al. (2005), Pradhan et al. (2017), Eckert and Oliveira (2017), (Zhang et al. 2019) and Ghorbani et al. (2019) in the development of optimised two-stage and three-stage mixing methods.

An investigation into the effect of the moisture state of RA was conducted by Mefteh et al. (2013), they found that RA that was pre-wetted or in saturated surface dry condition had a negative effect on the strength of concrete. They reported that the water absorption capacity of the RA in their study was between 6% – 10.5% after 24 hr, this compared with NA which was in the range of 3.5% – 5%. They also found that most of the water absorption occurred within the first 15-30 minutes.

The use of pre-saturated RA was also investigated by Amer et al. (2016) who found a resulting decrease in compressive strength, particularly early age strength, as it increases the effective w/c ratio. This is an undesirable quality, particularly in the production of precast components when the ability to demould components at an early age increases productivity.

Eckert and Oliveira (2017) proposed that their two-staged-mixing approach allowed the RA to reach its optimum moisture state and that this achieved the best possible RAC properties. They suggested that while this was true for RA, their results suggested that this was not the case for ordinary concrete, which underwent significant swelling as water flowed from the aggregates to the surrounding cement paste breaking the bonds.

Water absorption properties of RA can have beneficial effects as reported by Xu et al. (2017) who found that the bond strength of RAC with reinforcing steel can improve with the replacement ratio of RA. They proposed that this was due to a lowering of the effective w/c ratio as the RA absorbed additional water; this effect was more pronounced when using larger sized RA as it had greater amounts of adhered mortar attached.

Ghorbani et al. (2019), in their study into the effects of maximum particle size, found an inverse relationship between water absorption and maximum particle size. They found that RAC utilising maximum particles of 12.5 mm absorbed more water than that with maximum aggregate size of 25 mm.

2.3.6 Workability

The hydration of cement relies on water as a catalyst for the exothermic chemical reaction that results in the hardening of concrete (Koenders et al. 2014).

The workability of RAC is widely reported to be lower when compared to conventional concrete. This is due to the higher water absorption capacity of RA that reduces the lubrication between the particles within the concrete mixture (Pradhan et al. 2017). However, Behera et al. (2014), Amer et al. (2016) and Lavado et al. (2020) claim that reduced workability is also due to the poor shape properties of RA because of the angular shape and roughness caused by the remnant adhered mortar.

The use of saturated aggregate, and alternatively the addition of increased w/c ratios, in RAC mix design has been investigated previously. It has been reported that while it improves workability, as measured by a slump test, it also contributes to decreases in concrete properties such as compressive strength, with up to a 60% reduction at 28 days (Koenders et al. 2014; Bidabadi et al. 2020).

Increased w/c ratios and RA contents also lead to greater porosity making the concrete more permeable (Behera et al. 2014; Eckert & Oliveira 2017). This is a vital consideration when detailing RAC, as a higher penetration depth may increase the amount of cover required to protect the reinforcing steel (Thomas et al. 2013).

The degree of crushing of the RA has been found to have a significant effect on the workability of fresh RAC. RA obtained from primary crushing only produces concrete with reduced workability than that subjected to subsequent secondary crushing. The secondary crushing produces RA with less angularity and less adhered mortar (Mefteh et al. 2013; Lavado et al. 2020).

While moderate amounts of fines generally have a positive effect on the rheological properties of concrete, by decreasing the friction between the larger aggregate particles. A side effect of the increased amount of fines associated with RA is an increase in the volume of water required to wet the particle surfaces adequately to maintain workability (Westerholm et al. 2008; Amer et al. 2016). Ghorbani et al. (2019) found that decreasing the maximum particle size of the aggregate lead to a decrease in workability and proposed that this was caused by increased water absorption due to a larger aggregate surface area.

Gonzalez-Fonteboa and Martınez-Abella (2008) investigated the increasing the cement content 6.2% to maintain a similar slump in a RAC mixture. They found while that this increase in cement improved the workability of the RAC, it had an insignificant impact on mechanical strength properties.

2.4 Particle Size Distribution

Coarse aggregates typically represent approximately 45% of the volumetric proportion of a concrete mix (Meddah et al. 2010; Mehdipour & Khayat 2018). Along with the shape and strength of aggregates used, the size of the particles has a significant effect on the mechanical performance and density of concrete (Pradhan et al. 2017). The PSD has an influence on various properties relating to fresh and hardened concrete which affects the placement and strength characteristics, the impacts of which can determine the fitness for purpose of the concrete mixture.

Broadening or narrowing the PSD of the aggregates affects the flow characteristics of the fresh concrete which in turn affects the workability characteristics of the mix (Mehdipour & Khayat 2018). Meddah et al. (2010) suggested that the grain size distribution of the coarse aggregate plays an important role in determining the compressive strength of normal strength concrete. They proposed that a wider range if particle sizes leads to a better compacted granular skeleton and hence a denser concrete which improves the compressive strength.

Pradhan et al. (2017) investigated utilising the Particle Packing Method (PPM) with the aim of maximising the packing density through optimising the ratios of the various particle sizes so as to reduce the voids content of concrete. This method involves determining aggregate fractions and packing density by experimentally selecting the ratio of coarse and fine aggregates that produces the largest bulk density. Their investigations reported marginal improvements by utilising the PPM over standard mix proportioning methods for both NAC and RAC.

It is therefore important that the RA to be used in the test concrete batches closely replicates the particle distribution profile of the NA to ensure a fair and equitable comparison can be made. Deviating too much from the NA PSD will result in a change to the strength of the granular skeleton and hence, a possible variance in the mechanical properties which may distort the test data.

Conversely, aggregate grading is not considered an influencing factor in shear strength according to Rahal and Alrefaei (2017) who hypothesised that, instead increasing the maximum aggregate size had a positive effect on shear strength. The maximum particle size in this project is between 13.2 and 19 mm for both the RA and NA mixes. However, the proportion of aggregate that is in the top 50th percentile for each mix has not been determined. Therefore there is a possibility that one mix or the other may contain a larger proportion of aggregate closer to 19 mm than 13.2 mm which could affect shear behaviour.

2.5 Steel Reinforcement in Recycled Aggregate Concrete

While concrete is strong in compression, it is inherently weak in tension and as a result steel reinforcement is generally strategically placed into the formwork prior to pouring concrete. The use of pretensioned bars in concrete acts to impart a compressive force on the concrete which increases its ability to withstand tensile forces (Cement and Concrete Association of New Zealand 2010).

Bond is an important structural behaviour of reinforced concrete which is achieved through a combination of chemical adhesion, friction and mechanical interlock. The mechanical interlock is enhanced by the use of deformed bars whereby the protrusions on the surface of the steel increase the effectiveness of this interlock (Kim & Yun 2013).

As part of their research Butler et al. (2011) suggested that the use of RAC caused significant impacts on the bond with reinforcing steel with between 10 to 20% lower bond strength than for normal concrete. A reduction in bond strength was also noted by (Breccolotti & Materazzi 2013) although they concluded that it was not a significant enough decrease so as to prevent standard design formulae from being used for determining anchorage length.

While the mechanical performance of RAC is considered lesser that that of NA concrete, it does not require an increase in the area of reinforcing steel for beams in bending (Silva et al. 2016). In testing on slabs, it has been noted that deflections on the associated beams is not dependent on the type of aggregate used with beams containing RCA recorded the same load-deflection characteristics as did those containing NA (Pacheco et al. 2015).

Dong et al. (2019) found that during flexural testing, the failure mode was the same for normal concrete and RAC and was related only to the anchorage length and reinforcement surface profile i.e. whether plain or deformed bar was used. Pull-out failures were observed with plain bars and deformed bars with shorter anchorage length.

2.6 Curing of Recycled Aggregate Concrete

Curing plays an important role in producing the desired properties of any concrete as it provides a constant source of water to ensure the hydration process carries through to completion (Gayarre et al. 2014; Koenders et al. 2014). Exposure to hot weather, low humidity or freezing temperatures during curing may lead to drying shrinkage that generates micro-cracks which can affect the performance on the concrete (Fonseca et al. 2011).

It is even more critical in the production of RAC to provide a suitably moist and warm environment for the advancement of hydration to reduce the porosity of the hydrated cement paste thereby producing a denser microstructure (Fonseca et al. 2011; Behera et al. 2014). This mitigates somewhat the greater porosity and permeability of RAC, and hence produces concrete with better durability performance (Eckert & Oliveira 2017).

The work of Fonseca et al. (2011) was unable to identify a sensitivity to curing conditions for both NA concrete and RAC however noted that the process of pre-wetting for 5 minutes may have had an effect.

Another factor, which they did not consider in depth in their research, is the environmental conditions under which air-curing took place. No records were provided of temperatures or humidity conditions throughout the curing time that could indicate whether or not air-curing conditions were analogous with the water curing conditions.

Gayarre et al. (2014) also considered the results of air-curing and recorded environmental conditions during the curing period with temperature ranging from 19-33° C and relative humidity from 48-80%. A control environment cured specimens at 20° C and 95% humidity for comparison with RA replacement of 0%, 20%, 50% and 100% tested. The results show the importance of curing RAC with a reduction in compressive strength of 10% and 14% for concrete with 20% and 50% RA respectively under air-curing conditions. When specimens were cured under controlled conditions compressive strength variations were minimal.

A study into the effects of steam curing on the hardened state properties of RAC was found that steam curing produced higher 1-7 day compressive and tensile strengths however, this trend was reversed when considering strengths at 28 and 90 days with reductions in the order of 2-8% reported (Poon et al. 2006).

Figure 2.5 shows the reported compressive strengths from these three studies and the comparison between air- and water-curing. The chart shows that RAC compressive strength is adequate when compared to NA concrete when moist curing conditions are provided to allow hydration to advance.

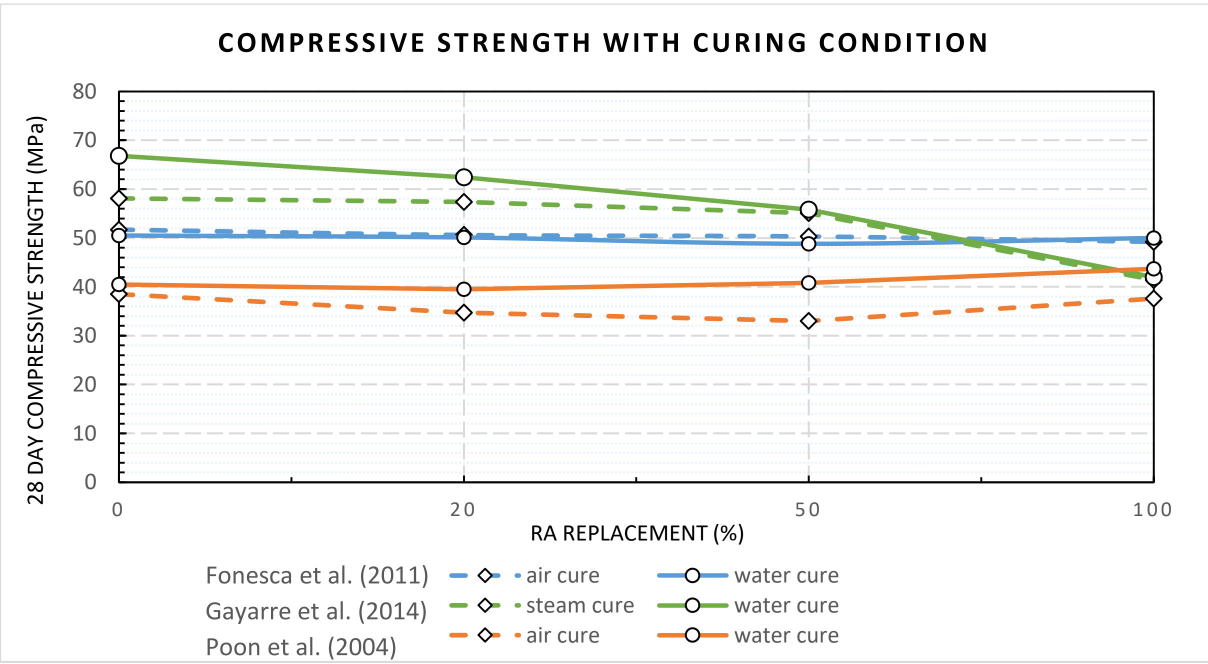

Figure 2.5: Compressive Strength Variation with Curing Condition for Different % RA Replacement

Steam curing is widely used within in the manufacture of precast components as it allows rapid turnover of formwork which facilitates increased productivity (Cement and Concrete Association of New Zealand 2010). The process involves subjecting the concrete elements to saturated steam to provide heat and moisture to accelerate the rate of strength gain. (Cement and Concrete Association of New Zealand 2010).

The benefits of steam curing in early strength gain can be seen in Figure 2.6. This shows a typical day 1 compressive strength equivalent to a standard day 7 compressive strength. In the case of pretensioned concrete posts, this accelerated strength gain allows the stressing tendons to be released on the day following casting to allow the moulds to be re-used on the same day.

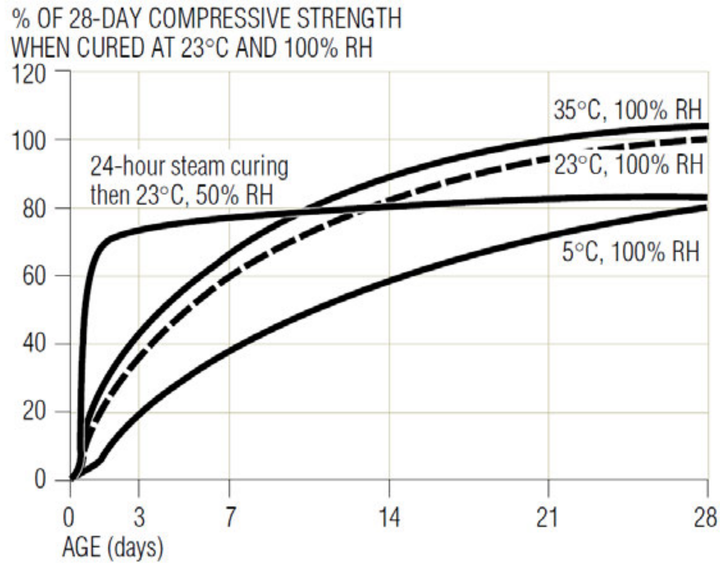

Figure 2.6: Effect Curing Temperature on the Compressive Strength Development of Concrete (Cement and Concrete Association of New Zealand 2010).

During flexural testing, Sato et al. (2007) discovered that both NA concrete and RAC reinforced beams suffered from increased deflection under equivalent loading when cured under dry conditions as opposed to those cured under wet conditions. For each concrete mix under the different curing conditions, the moment of cracking, M_{cr}, was found to be less under dry curing when compared to wet curing. This indicates the importance of ensuring moisture is available for complete hydration of the cement, to ensure the concrete can reach its maximum potential and satisfy design criteria.

These results correlate with those of El-Hawary and Al-Sulily (2020) who discovered that for 50% replacement with coarse RA the ultimate load during flexural testing was lower when specimens were air-cured in laboratory conditions compared with those that were moist cured.

2.7 Improving Recycled Aggregate Concrete Properties

The performance of both fresh and hardened RAC can be improved by reducing the amount of old mortar that is adhered to the RA. A variety of different methods for minimising the mortar layer and obtaining cleaner RCA have been explored such as, freeze-thaw method, mechanical grinding and ultrasonic treatment method and thermal treatment methods (Pradhan et al. 2017). However, as noted by Ismail and Ramli (2013) and (Kazmi et al. 2019), these methods require complicated processes and equipment, result in high energy consumption and processing costs and produce waste products than need to be disposed of.

An investigation into the use of silica fume by Katz (2004) found that silica fume improved the compressive strength of RAC by improving the ITZ between the RA and the new mortar that worked better the more cracked and porous the adhered aggregate was. The effects of ultrasonic cleaning, to removed loose adhered mortar, was also investigated by Katz (2004). While this also produced positive results, the strength gain was a modest 7% at 28 days compared with 15% for silica flume addition at a rate of ~2.5% of the cement content.

Wang et al. (2017) investigated soaking the RA in acetic acid to weaken the attached mortar, by reacting with the calcium compounds, allowing it to be removed by mechanical rubbing. The cleaner aggregate produced concrete with higher compressive strength and produces useful waste products such as vaterite (which has a range of uses from drug delivery, paper making and plastic and rubber manufacturing), calcium carbonate (used as binder in concrete) and recovered acetic acid. A solution with 3% concentration was recommended with the best results achieved when combined with supplementary mechanical rubbing of the aggregate to remove additional mortar.

Improvements to RAC compressive, tensile and flexural strengths were achieved by Kazmi et al. (2019) through the application of a variety treatments to determine the most effective. They found either acetic acid immersion with mechanical rubbing or lime immersion with mechanical rubbing provide helpful improvements to the RAC mechanical properties.

Another option to improve the strength of RAC is to increase the cement content, however of the ingredients used in the production of concrete cement has the highest environmental impact. Therefore increasing its content counteracts the benefits from using RA in trying to achieve a sustainable construction material (Silva et al. 2016).

2.7.1 Mix Design Methodology.

The Direct Weight Replacement (DWR) method which maintains the same aggregate, cement and water content for any replacement ratio, it has been reported that this method provides the best workability (Pradhan et al. 2017).

The Equivalent Mortar Replacement (EMR) method that includes adhered mortar on the RA in the calculation of total mortar content in the fresh concrete (Pradhan et al. 2017).

Finally, the Direct Volume Replacement (DVR) method whereby the volume of recycled concrete aggregate (RCA) added equals the volume of NA it replaces (Pradhan et al. 2017). However, the compressive strength is not influenced significantly by any of these mix design methods at any replacement ratio (Pradhan et al. 2017).

The use of saturated aggregates has been proposed to cause reduced compressive strength in RAC (Mefteh et al. 2013; Tam et al. 2018). Koenders et al. (2014) suggest that this is due to higher local w/c ratios on the surface of the saturated RA as this extra moisture is released into the cement paste during mixing. Mefteh et al. (2013) reported that stronger RAC was achieved when using dry rather than saturated or pre-wetted RA.

2.7.2 Mixing Methods

A number of different mixing methods have been explored, in an attempt to determine the approach that produces the best results when working with RA, to create stronger ITZ by filling the voids and cracks in the RA.

A double mixing, or two stage mixing approach, proposed by Pradhan et al. (2017) adds half the water volume to the dry mix of coarse aggregate first prior to adding the remaining ingredients. An alternate method used by Ghorbani et al. (2019) mixed the aggregates and cement together firstly for two minutes before adding the water.

In the two stage mixing approach developed by Tam et al. (2005) fine aggregate and aggregate are mixed for 60 seconds before 50% of the required water is added and mixed for 60 seconds prior to the cement being added and mixed for 30 seconds. Finally, the remaining water is added and the concrete mixed for 120 second. This process sees cement slurry fill the cracks and pores within the RA, developing a stronger ITZ and thereby improving the compressive strength of the concrete.

This method utilised a w/c ratio of 0.45 and aggregate/cement ratio of 4.5 to produce concrete with a target strength of 50 MPa (Tam et al. 2005).

In the study conducted by Butler et al. (2011) both the NA and RA were soaked for 24 hours and then drained so as to be at or above SSD prior to being added to the concrete mix, in an effort to mitigate the effects of increased water absorption by the RA. A two-stage mixing method was then used whereby the coarse aggregates were added along with one third of the mixing water which was then mixed for 30 seconds. Following this the sand, cement and the remaining two-thirds of the water were added and mixed for a further 3 minutes followed by a three minute rest and another 2 minutes of mixing. Damp hessian was used to cover the mixer during the rest period to minimise moisture loss due to evaporation.

In the triple mixing method investigated by Pradhan et al. (2017), mineral admixture, superplasticiser and water are added at three different phases resulting in greater workability, compressive strength and tensile strength over the two stage mixing approach method. This work was extended by Zhang et al. (2019) who trialled different timings for addition of the various elements of the concrete mix in an effort to create an optimised triple mixing method. They reported increases of 8.4% and 19% in compressive strength for mixes created using the triple mixing method and optimised triple mixing method respectively, when compared with a double mixing method.

2.8 Summary

The use of RA as a replacement for NA does not appear to provide advantages in terms of mechanical performance. Its use can be enhanced by modifications to mixture methods, and proportions, to maintain both workability and strength characteristics. The benefits in its use come from the perceived environmental outcomes resulting from reduced quantities of waste sent to landfill and a decrease in the reliance on quarrying NA.

Due to the variable cleanliness of the source concrete that the RA is produced from, the production of RAC benefits from a screening process to remove contaminants such as timber, vegetation and masonry materials.

The variances in collected data from previous studies makes it difficult to arrive at a definitive answer in relation to the optimum mixture design, replacement ratio or curing conditions. These differing outcomes could be the result of a variety of factors including RA quality, parent concrete strength, crushing method, aggregate PSD, aggregate pre-wetting and effective water ratio to name a few. The conflicting evidence does however seem to indicate that the use of RA in fresh concrete produces results that, if not equivalent, are at least adequately close to those of NA.

The results of previous research seem to suggest that a replacement ratio of 30% will produce satisfactory results, and that using air-dried RA along with a staged mixing method has a beneficial influence on the rheological and mechanical properties of RAC.

The relationship between RAC and reinforcing steel is of no detriment and the response to steam curing appears to be favourable. This suits the production of precast concrete components as steam curing is an effective way of increasing early strength which allows de-moulding on the day following casting.

Because shear and flexural strength variations are not uncommon, a testing regime including at least three beams should be chosen, so as to be able to find an average strength value and minimise the risk of an outlying test result skewing the data.

Using test results from this study, and information collected during the research phase, the mechanical properties of RAC can be evaluated for the production of precast concrete fence posts. The proposed mix proportions and method may be an important step towards the production of greener, eco-friendly precast concrete components.

CHAPTER 3. METHODOLOGY

3.1 Outline

The following methodology will be adopted for the project:

1. Source all the materials and equipment required to carry out the casting of recycled aggregate concrete posts.
2. Create a RA blend that emulates the PSD of the NA used in manufacture of commercial concrete posts.
3. Prepare two batches of concrete one using normal concrete; the other with a percentage of RA as replacement for NA and utilising a specified mixing method.
4. Assess the consistency of each fresh concrete batch by conducting slump tests.
5. Prepare a series of test specimens for each batch of concrete to test for compressive strength and splitting tensile strength.
6. Manufacture a set of concrete posts made using the normal concrete and a set made using concrete made with RA replacement.
7. Conduct laboratory testing of the test specimens to determine the properties of the hardened concrete.
8. Conduct destructive flexural testing on the selected concrete posts.
9. Analyse and discuss the results obtained from the testing.
10. Determine the viability of RAC as a material for use in the precast construction of concrete fence posts.

3.2 Assumptions

For the purposes of this study, the following assumptions have been made:

1. The RA sourced for the study is indicative of the RA that could be expected to be obtained for general use.
2. That the RA has properties relating to water absorption that are broadly in line with those reported in the literature as a basis for selecting a w/c ratio and mixing method.
3. The PSD supplied by the NA aggregate supplier is representative of the PSD of the aggregate used in the concrete mixes.

3.3 Concrete Mixing Method

Mefteh et al. (2013) reported that 90% of the water absorbed by RA occurred in the first 5 minutes of mixing or saturation. This finding was used by Eckert and Oliveira (2017) to develop a two-stage mixing approach that initially combines the aggregates and half the water content which are then mixed for 5 minutes as stage one. Stage two then proceeds by adding the remaining water and the cement before mixing the concrete for a further 2 minutes. The benefits of this method were validated by (Tam et al. 2006) and this approach was adopted for mixing the RAC in this study.

As waste concrete is often of unknown quality and strength, for the purposes of this research the mixed recycled aggregates were graded and had visible contaminants removed, but did not undergo any further testing or treatment. This was done in an attempt to replicate the typical circumstances that could be expected if the process was to be commercialised.

While a range of different treatment options have previously been explored such as ultrasonic cleaning (Katz 2004; Behera et al. 2014), the thermal expansion method, mechanical grinding and low concentration acid baths (Ismail & Ramli 2013; Behera et al. 2014), secondary treatment was not considered for this project due to the increased costs and resources involved. The project seeks to evaluate an economical process and it is believed that the cost and time involved in this treatment is not warranted for low strength concrete, and that it would prove prohibitive to the take-up of RAC usage.

The normal concrete mixture for the concrete posts uses a w/c ratio of 0.43. A w/c ratio of 0.45 has been found to be effective in the production of low strength concrete, resulting in adequate strength and an acceptable level of workability (Mefteh et al. 2013; Thomas et al. 2013; Gholampour & Ozbakkaloglu 2018; Tam et al. 2018), and was adopted for the RAC mix as part of this research.

The adoption of this w/c ratio is validated by research conducted by Butler et al. (2011) which found that water demand increased between 3-9% for concrete mixes with 30% replacement RA. Considering the control concrete mixture for this study has a w/c ratio of 0.43, this gives a range between 0.443 and 0.469 with the average being 0.456.

3.4 Aggregates

Sampling of aggregate is undertaken to determine the typical characteristics of the product in a supply of aggregate by taking a representative sample of the supply. It is critical that the sample is characteristic of the overall stock to ensure fluctuations in the processing of aggregate materials is reflected in the results (Standards Australia 2012).

To produce an aggregate mix that matches the PSD of the NA, the RA was sieved using standard sieves at the Geotechnical Services Southern laboratory in Bendigo and contaminating material was removed.

The aggregate was then remixed to match the PSD of the NA, as was performed by both Fonseca et al. (2011) and Ghorbani et al. (2019), in an attempt to remove aggregate grading as a point of difference between the concrete mixtures. During the sieving process it was difficult to collect the necessary amount of material passing a 0.075 mm sieve. The relative absence of this fine material could indicate that the RA is a relatively clean material without clay contamination that might be present in the NA.

This resulted in the increased addition of slightly larger fraction sizes, within the range of limits applying to the NA, so as to gather the necessary amount of material overall. This was deemed acceptable, as an alternate sample of the NA may have returned a slightly different PSD within the specified limits and the fines fraction makes up a small part of the overall sample.

3.5 Concrete Post Manufacture

3.5.1 Concrete Mixing

Production of the concrete mixes was undertaken on 25 June 2021. The normal concrete mixture was the post company's ready-mix concrete mixed in an agitator truck per their standard procedure. As the amount of RAC required was relatively small, this was produced in a portable electric concrete mixer.

3.5.2 Concrete Post Details

The concrete posts produced were 1800 mm long and 110 mm high with a trapezoidal cross section as shown in Figure 3.1 and Figure 3.2. Two 500L reinforcing wires of diameter 5.37 mm were installed longitudinally as shown in Figure 3.1. This equates to a longitudinal reinforcement ratio of ρ_s = 0.00257.

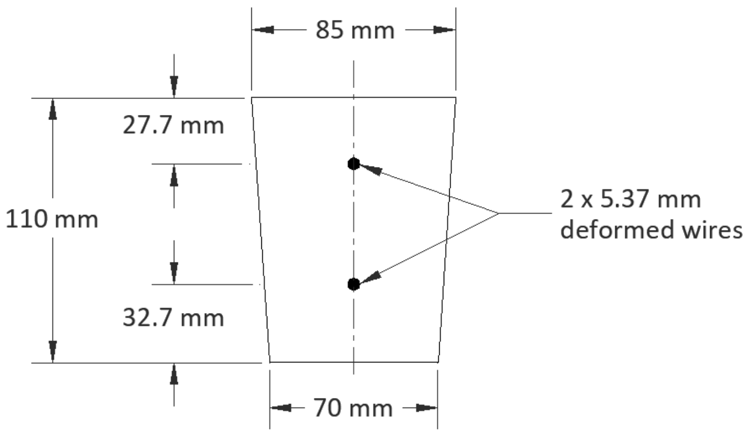

Figure 3.1: Concrete Post Cross Section

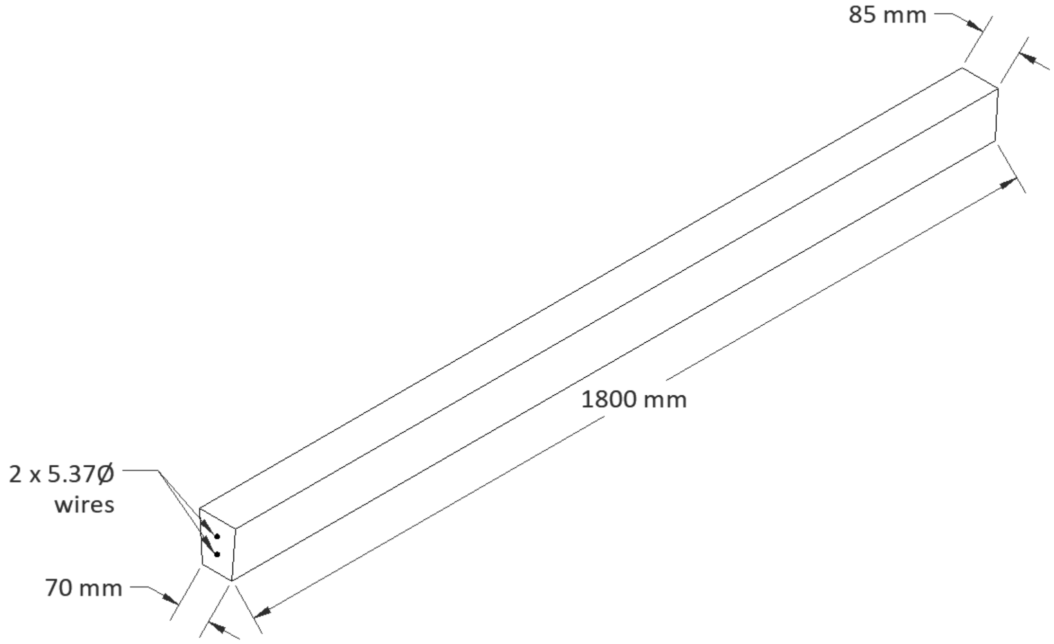

Figure 3.2: Isometric View

The concrete posts were cast in commercial moulds specifically designed for the purpose and shown in Figure 3.3. The tensioning apparatus shown at the end of the mould used to apply tension to the two 5.37 mm prestressing wires that run longitudinally through the post to apply compressive force.

The moulds 10 mm diameter poly inserts to form holes within the posts that allow fencing wire to be drawn through once the posts have been installed into the ground.

Figure 3.3: Tensioning Wire and Fence Wire Sleeves in Place

3.5.3 Curing Conditions

Initially posts were steam cured, following which they were air cured until testing was performed. This methodology was adopted so as to replicate typical conditions under which the posts are produced commercially. The test specimens were cured in tap water at a constant temperature.

3.6 Concrete Testing

3.6.1 Sampling

Test samples from the concrete mixes were taken in accordance with AS 1012.1:2014 which stipulates the following requirements:

- Sample size of not less than $0.015m^3$.
- Composite samples obtained from the discharge for mixtures greater than 1 m^3 in volume.
- Batch samples obtained from the discharge for mixtures less than $1m^3$ in volume.
- Samples not collected from the first or last 0.2 m^3 of the batch.
- Mix the sample to ensure uniformity.
- Measure the temperature of the concrete sample to the nearest 1°C by inserting a thermometer into a mix sample of approximately the volume of the slump cone (Standards Australia 2014g).

3.6.2 Workability

The workability of each concrete batch was determined via slump testing as detailed in AS 1012.3.1:2014 using a slump test cone as shown in Figure 3.4. The following the procedures were used as outlined in the standard:

- Moisten the internal surface of the mould, hold it firmly on a base plate, and ensure it remains in place during the rodding of the concrete.
- Fill the test cone in three layers, compacting each layer with 25 strokes of a 16 mm steel rod, evenly distributed over the surface of the layer. The second and top layers are rodded so that the strokes just penetrate into the underlying layer.

- After the top layer has been rodded, strike off the surface of the concrete by using a screeding and rolling motion of the rod so that the mould is filled exactly.

- Remove the mould from the concrete by raising it slowly and carefully in a vertical direction, allowing the concrete to subside.

- Immediately measure the slump by determining the difference between the height of the mould (300 mm) and the average height of the top surface of the concrete. The slump shall be measured to:

    - the nearest 5 mm for slumps of 100 mm and less; and

    - the nearest 10 mm for slumps greater than 100 mm (Standards Australia 2014a).

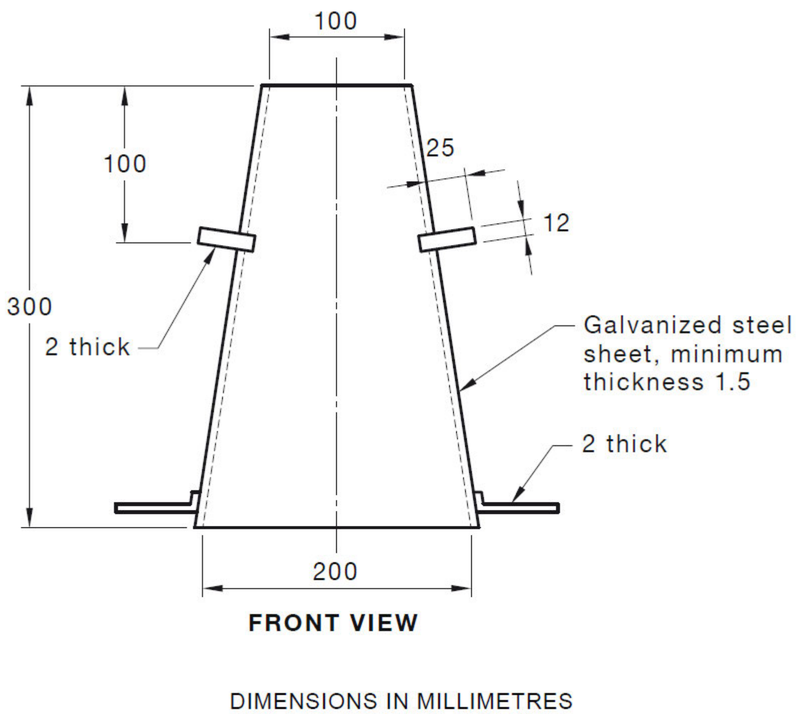

Figure 3.4: Typical Cone for Slump Test (Standards Australia 2014a).

3.6.3 Specimens

Specimens for testing to determine the characteristic compressive strength and estimation of the tensile strength were collected from each batch of concrete and then cured as specified by AS1012.8.1:2014. The procedure outlined in the standard states:

- Fill the moulds in two approximately equal layers.
- Compact each layer by rodding with 25 strokes per layer. For each upper layer just penetrate into the underlying layer with at least the first 10 strokes.
- Tap the sides of the mould with the mallet to close any voids.
- After the top layer has been compacted, finish off and smooth the surface of the concrete.
- As soon as is practicable after a period of 18 hours from moulding, the test specimens shall be placed under standard moist-curing conditions.

All the tests that were carried out on the concrete specimens, and the manufactured posts, were conducted with the assistance of laboratory technicians at the Latrobe University, Bendigo campus.

3.6.4 Compressive Testing

Compressive strength tests were performed in accordance with AS 1012.9:2014 using a MATEST C056PN173 compression testing machine, with a 200 kN operating force. Three specimens from each batch of concrete were tested with the result being the average of the three tests. Each of the specimens was checked for defects before being prepared for testing.

The testing procedure will align with that detailed in Clause 8 of AS 1012.9:2014 as follows:

a) Measurement and testing is to be carried out as soon as possible after being removed from the curing environment.

b) Clean the platens of the testing machine and the bearing surfaces of the specimens.

c) Align the specimen in the machine with the vertical axis in the centre of the platen.

d) Bring the upper platen into contact with the specimen.

e) Apply force without shock at a continuous rate of 20 ±2 MPa/min until failure. Record the result.

3.6.5 Indirect Tensile Testing

Three specimens from each batch of concrete were subject to indirect tensile testing with the result being the average of the three tests. The tests were performed in accordance with AS 1012.10:2014 using the same MATEST testing machine as for compression testing. Each of the specimens was checked for defects before being prepared for testing.

The testing procedure aligned with that detailed in Clause 5 of AS 1012.10:2014 and Figure 3.5 as follows:

a) Determine the diameter of the specimen by measuring to the nearest 0.2 mm in three locations and calculating the average dimension to the nearest millimetre.

b) Align the specimen in the machine along with hardboard bearing strips so that the specimen is centred over the lower platen.

c) Apply a small initial force and remove any side restraint.

d) Apply force without shock and increase at a continuous rate of 1.5 ±0.15 MPa/min until failure. Record the result.

e) Note the appearance of the concrete and the type of fracture (Standards Australia 2000b).

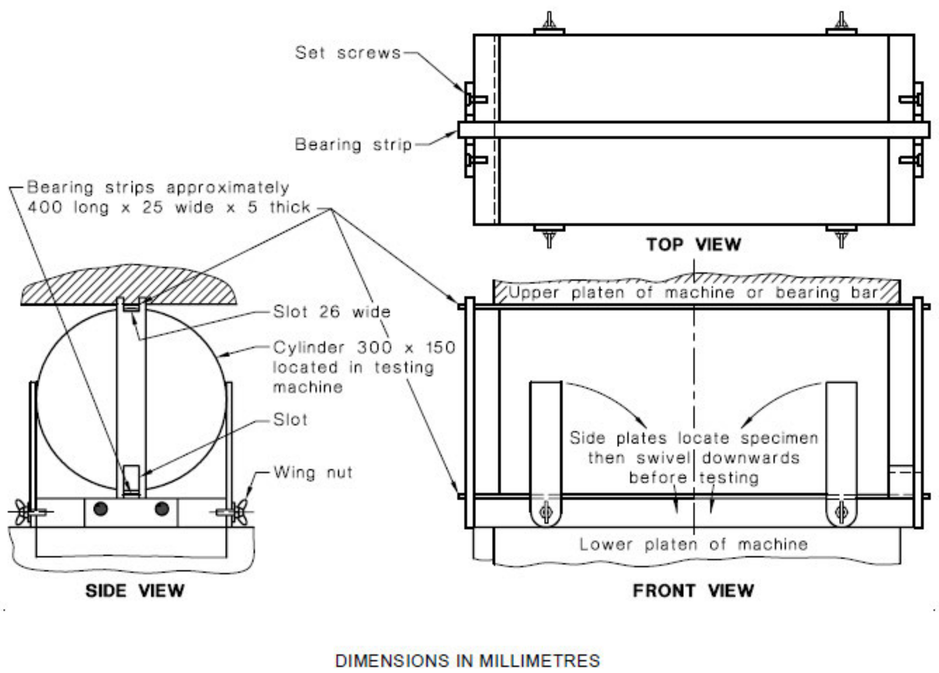

Figure 3.5: Typical Arrangement for Conducting an Indirect Tensile Test (Standards Australia 2000b).

3.6.6 Flexural Testing

Three concrete fence posts from each batch of concrete were subject to 4-point flexure testing, with the result being the average of the three tests. The tests were be performed with reference to AS 1012.11–2014 in the arrangement as shown in Figure 3.6. The testing machine used was an Instron 5982 with 100 kN capacity.

The testing procedure aligned with that detailed in Clause 6 of AS 1012.11–2014 as follows:

a) Clean the specimen free of grit and any excess fluids.

b) Locate the specimen centrally on the supporting rollers relative to its width and length.

c) Bring the loading rollers into contact with the specimen with a seating load not exceeding 100 N and mark the position of the rollers on the specimen.

d) Apply force without shock increasing continuously at a rate of 1 ±0.1 MPa/min until failure. Record the maximum force applied.

e) Measure the average width and depth of the post at the section nearest the failure.

f) Note the appearance of the concrete and the type of fracture (Standards Australia 2014h).

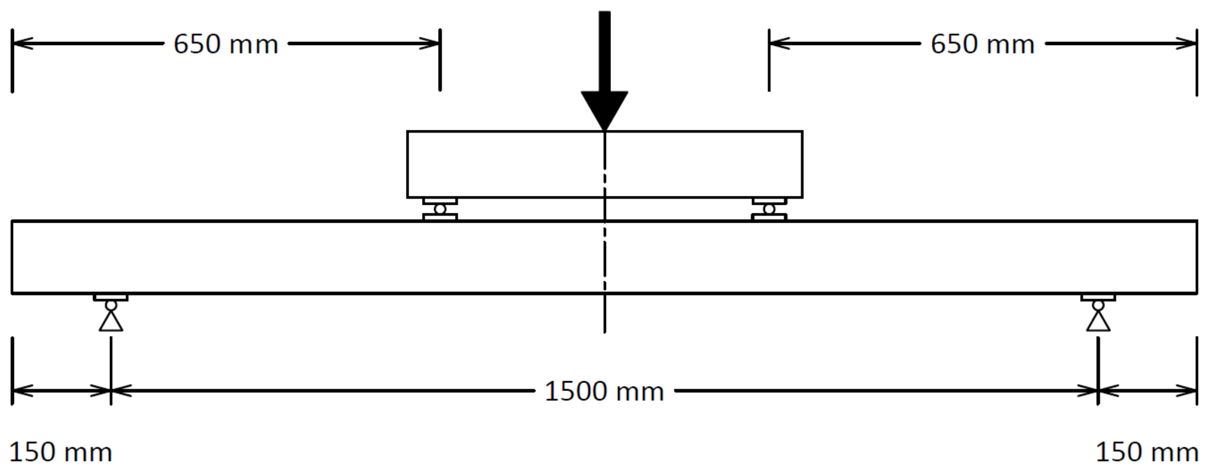

Figure 3.6: Flexural Test Apparatus Arrangement

CHAPTER 4. EXPERIMENTAL INVESTIGATION

4.1 Materials

Recycled aggregates (Figure 4.1) were sourced from Hopley Recycling in Bendigo at a cost of \$18 m^3 which is less than one third of the cost of the NA. The recycled aggregates are produced from clean waste concrete, although the material contained small quantities of brick, asphalt, glass, metal, timber and vegetation (Figure 4.2). The RA was sorted by hand and these impurities were discarded.

Figure 4.1: Sample of the RA Prior to Sorting and Grading

Normal Portland cement was used in the production of both the RAC and the control concrete mix. No additional additives or superplasticisers were used in either mix. The water used in making the concrete was drinking quality water from the local urban supply and be used at the environmental temperature.

Figure 4.2: Impurities Removed from RA during Grading

The sand, shown in Figure 4.3 was supplied by the concrete manufacturer and is a clean washed sand with no clay or organic particles present.

Figure 4.3: Washed Sand used in the Concrete Mixtures

A basalt natural aggregate sourced from a quarry at Newbridge in Victoria, made up the coarse aggregate component of the concrete mixes and is shown in Figure 4.4.

Figure 4.4: Natural Basalt Aggregate

4.2 Material Quantities

Dimensions of the concrete posts are shown in Figure 3.1 and Figure 3.2, using these dimensions the volume of concrete required to produce each post was calculated:

$$\frac{\mathbf{0.07+0.085}}{\mathbf{2}} * \mathbf{0.11} * \mathbf{1.8} = \mathbf{0.153}\ \boldsymbol{m}^3 \qquad \textbf{(4.1)}$$

Each 100 mm diameter x 200 mm high test cylinder required 0.002 m^3 of concrete (Standards Australia 2014g)

To produce 3 posts and 6 test cylinders from the batch of concrete, allowing 20% for wastage, results in a total concrete volume required:

$1.2 \times (3 \times 0.0153 + 6 \times 0.002) = 0.070\ m^3$.

The normal mixture to produce one cubic metre of concrete used in the production of the posts is shown in Table 4.1.

Table 4.1: Normal Concrete Post Mixture Quantities

Concrete volume	1 m^3
Coarse aggregate	1 165 kg
Sand	740 kg
Cement	420 kg
Water	180 kg

Using this ratio of materials, the amount of RA required for 30% replacement of NA is calculated using:

$$\mathbf{0.3} * \frac{\mathbf{1165}}{\mathbf{1}} = \frac{\mathbf{RA}}{\mathbf{0.070}} \tag{4.2}$$

$\mathrm{RA} = 0.3 * 1165 * 0.070$

$= 24.465 \text{ kg}$

Likewise, the mass of the other ingredients was calculated and are tabulated in Table 4.2 below.

Table 4.2: Recycled Aggregate Concrete Mixture Quantities

Concrete Volume (m^3)	Aggregate (kg)	% RA replacement	NA (kg)	RA (kg)	Sand (kg)	Cement (kg)	Water (kg) w/c = 0.45
0.070	81.55	30%	57.085	24.465	51.800	29.400	13.230

4.3 Particle Size Distribution

The RA sourced directly from the supplier was subject to preliminary grading to 12.7 mm, 10 mm, 6.5mm and material > 6.5mm, with contaminants such as brick, metal, plastic and wood being removed at this stage.

Further grading was undertaken using the standard sieve apertures shown in Table 4.3, to enable the aggregate to be divided into fractions and blended in the correct proportions to replicate the PSD of the NA.

Figure 4.5: Grading of the Finer Fractions of the Coarse Aggregate

Figure 4.6: Grading of Coarse Aggregate

The PSD of the NA has been provided by the supplier and is duplicated in Table 4.3 and a copy of the original report can be seen in Appendix D – Material Test Report.

Table 4.3: Natural Basalt Aggregate Particle Size Distribution.

Sieve size (mm)	Passed %	Passing Limits	
19	100	100	100
13.2	88	85	100
9.5	43		
6.7	9	0	30
4.75	4		
2.36	2	0	5
0.425	2		
0.075	1	0	2

Using the PSD supplied by All Stone Quarries for the NA, along with the RA volume calculated using Equation 4.2, the volume of each aggregate fraction size was calculated as shown in Table 4.4 below. The PSD of the blended RA is shown in Figure 4.7.

Table 4.4: Recycled Aggregate Volumes per Fraction Size.

Sieve size	% retained	Recycled aggregate weight	
19	0	0.000	kg
13.2	12	2.936	kg
9.5	45	11.009	kg
6.7	34	8.318	kg
4.75	5	1.468	kg
2.36	2	0.245	kg
0.425	0	0.000	kg
0.075	1	0.245	kg
< 0.075	1	0.245	kg
	100%	24.466	kg

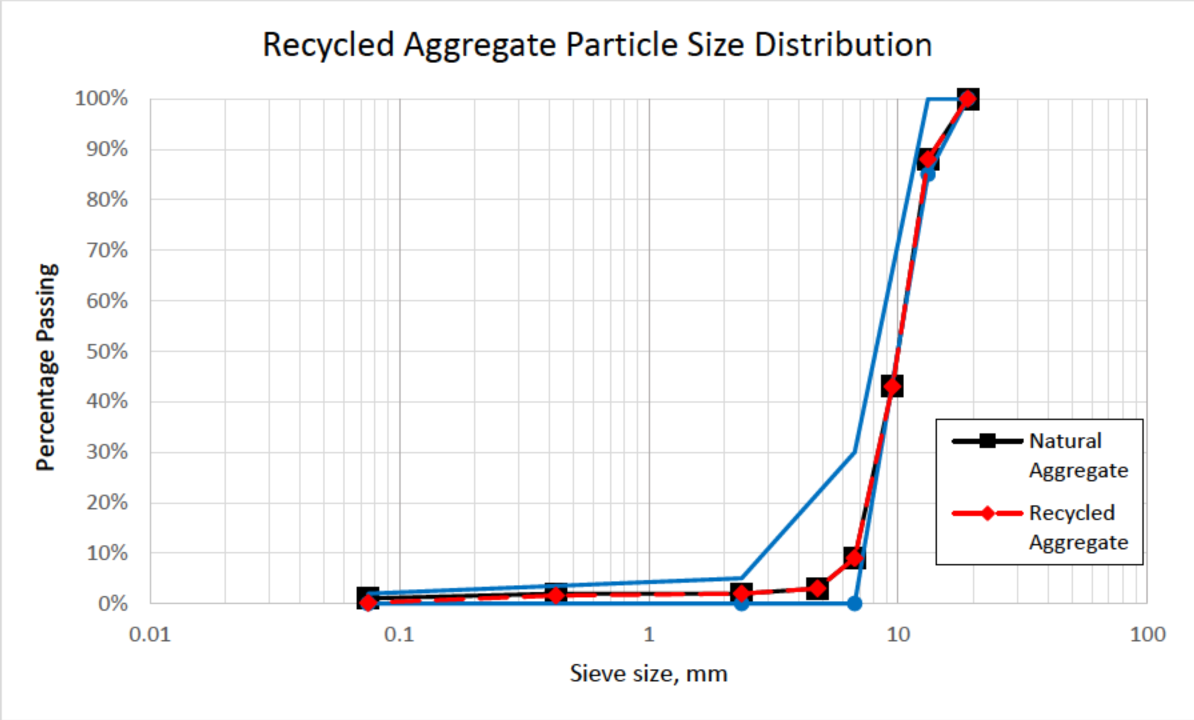

Figure 4.7: Particle Size Distribution of Natural Aggregate and Recycled Aggregate Blend

4.4 Concrete Post Sample Preparation

Production of the concrete posts samples was performed on 25 June 2021 at the Easydrive Post Company factory in Tate Drive, Kerang. The RAC was produced in a portable electric cement mixer, as shown in Figure 4.8, following the procedure detailed in Section 3.3. The RAC was mixed using the quantities as previously described in Table 4.2.

Figure 4.8: RAC Mixing Being Performed in a Portable Electric Mixer

A slump test was performed for each batch of concrete to determine the workability of the mixtures as shown in Figure 4.9. The NA concrete had a higher slump which can be attributed to due to the sand and aggregates used having excess moisture due to recent rain, and this not being adequately compensated for when batching the concrete resulting in a higher effective w/c ratio.

Figure 4.9: Slump Test for NA Concrete (left) and RAC (right)

Figure 4.10 shows the post mould prepared, with the pretensioning wires and blanks that form the voids for drawing fence wire through in place, ready for concrete to be added.

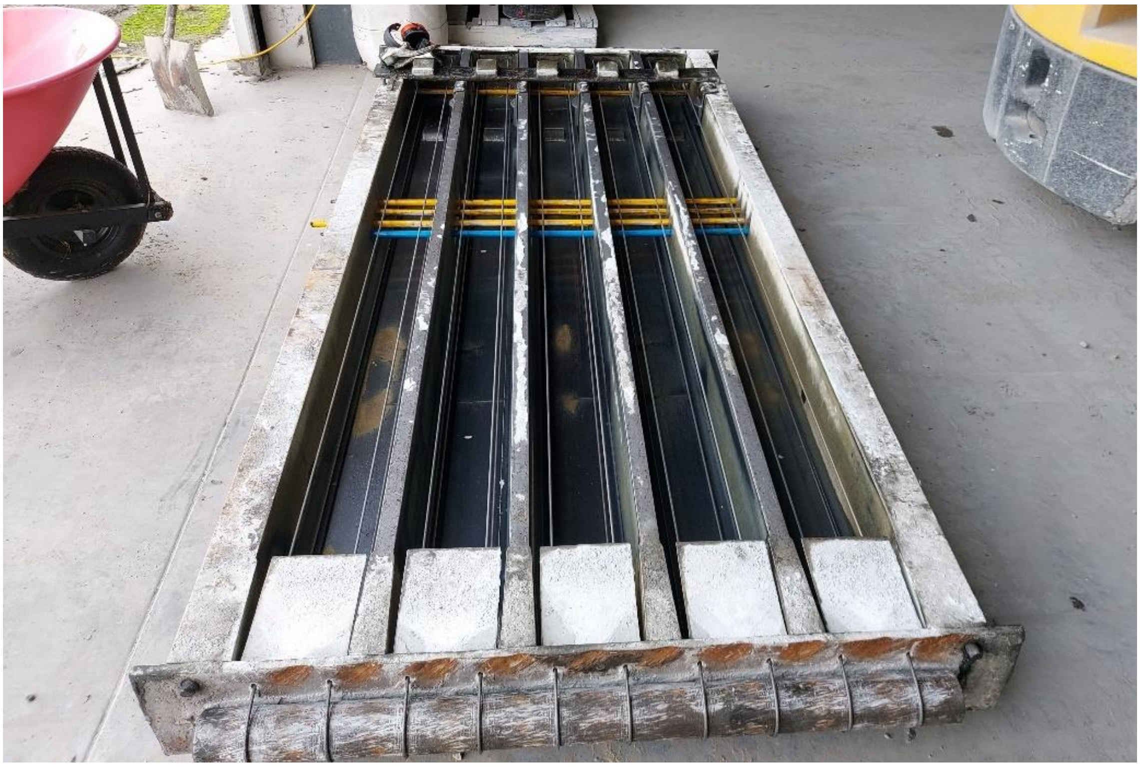

Figure 4.10: Moulds with Apparatus for Tensioning the Reinforcing Wire Visible.

Figure 4.11 shows the placement of the NAC into the moulds with the already filled sections containing the RAC mixture. The moulds were placed on a vibrating table which is used for compaction and the top of the exposed concrete is levelled and trowelled off flat and smooth.

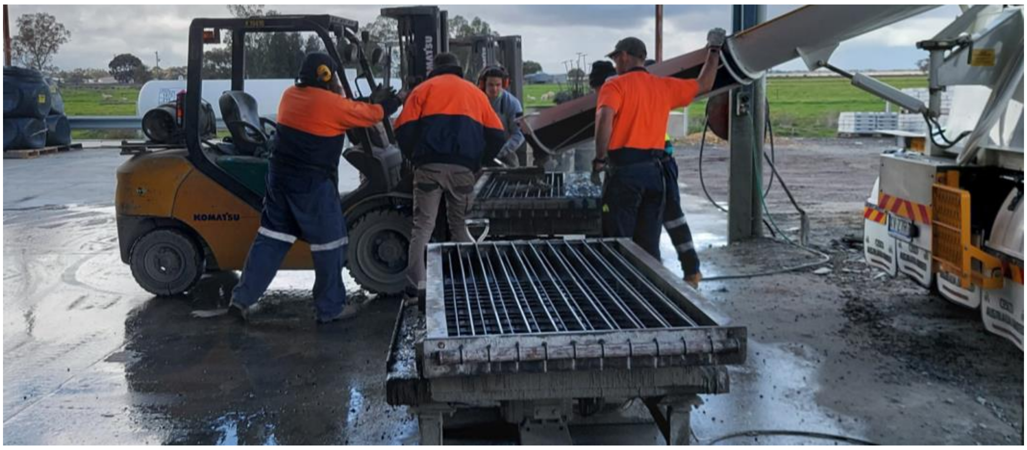

Figure 4.11: Placement of Concrete in Post Moulds

Initially the posts were steam cured (Figure 4.12) at between 50-60° C for 8 hours, following which the posts were exposed to the weather until testing was performed. This curing process was adopted so as to replicate the normal procedure followed by the company in producing posts for their customers. Two specimen cylinders from each concrete mixture were also cured under the same conditions to allow compressive testing to be performed. The remaining specimens were not steam cured, but instead were cured in tap water at a constant 16° C so as to allow for a comparison to be made with the aforementioned procedure.

Figure 4.12: Steam Curing of Concrete Posts

A total of six specimens were collected from each concrete batch, three each to undergo compressive testing and indirect tensile testing. Each specimen was formed in a single-use plastic cylinder mould, shown in Figure 4.13, 100 mm in diameter and 200 mm high.

After the initial curing time of 18 to 36 hours, the specimens were demoulded and immersed in a plain water bath to cure.

Figure 4.13: Specimens in Single-Use Plastic Cylinder Moulds – RAC Samples are on the Right

Two additional specimens were formed from each batch, and subsequently cured alongside the posts in the steam oven and then air cured under the same conditions as the posts, so as to allow for testing of samples subject to identical conditions as the posts. Details of the specimens are shown below in Table 4.5:

Table 4.5: Specimen Cylinder Details

Code	NA	RA	Curing condition
NA	100%	0%	Water
RA	70%	30%	Water
NAS	100%	0%	Steam/air
RAS	70%	30%	Steam/air

4.5 Testing

Testing of the concrete posts and specimens was carried out on 2 August 2021, 38 days after production of the concrete. The standard time between moulding the specimens and conducting testing is 28 days. The delay in testing was due to access to the laboratory being restricted for a short period.

All tests that were carried out on the concrete specimens, and the manufactured posts, were conducted with the assistance of laboratory technicians at the Latrobe University, Bendigo campus. Specimens were be inspected for defects likely to affect the test results, and to ensure that they conformed to the dimensional specifications detailed in AS 1012.9:2014 and AS 1012.10-2000.

4.5.1 Compression Testing

Compressive strength tests were performed using a MATEST C056PN173 compression testing machine as shown in Figure 4.14. Specimens were measured, weighed and checked for imperfections prior to being tested.

The length and diameter details of the specimens were input into the testing machine and then the loading rate of the machine was set at 19.8 MPA/min. Results for compressive strength were recorded directly from the test machine and also manually checked.

Calculation of the compressive strength of the specimen was calculated by dividing the maximum force applied by the specimen cross-sectional area (Standards Australia 2014b).

$$\boldsymbol{C = \frac{4P}{D^2\pi}} \tag{4.3}$$

Where

C = compressive strength, MPa

P = maximum applied force indicated by the testing machine, kN

D = diameter, mm (Standards Australia 2014b).

Figure 4.14: MATEST Compression Testing Machine

4.5.2 Indirect Tensile Testing

Determination of the indirect tensile strength is calculated using:

$$\boldsymbol{T} = \frac{\mathbf{2000}\boldsymbol{P}}{\boldsymbol{\pi L D}} \tag{4.4}$$

Where

T = indirect tensile strength, MPa

P = maximum applied force indicated by the testing machine, kN

L = length, mm

D = diameter, mm (Standards Australia 2000b).

Each of the specimens was checked for defects before testing and the tests performed in accordance with AS 1012.10:2014, using the same MATEST testing machine as for compression testing. Tensile testing of a RAC specimen is shown in Figure 4.15.

Figure 4.15: Indirect Tensile Testing of RA Specimen

4.5.3 Flexural Strength

4.5.3.1 Testing Regime

Specimens were first measured and the location of the supports and loading points were marked as shown in Figure 4.16 to ensure the posts were centrally located and the load consistently applied to all posts. Steel backing plates were placed at the supports and the loading points to avoid local failure of the specimen, Figure 4.17 shows a NA post ready for testing to commence.

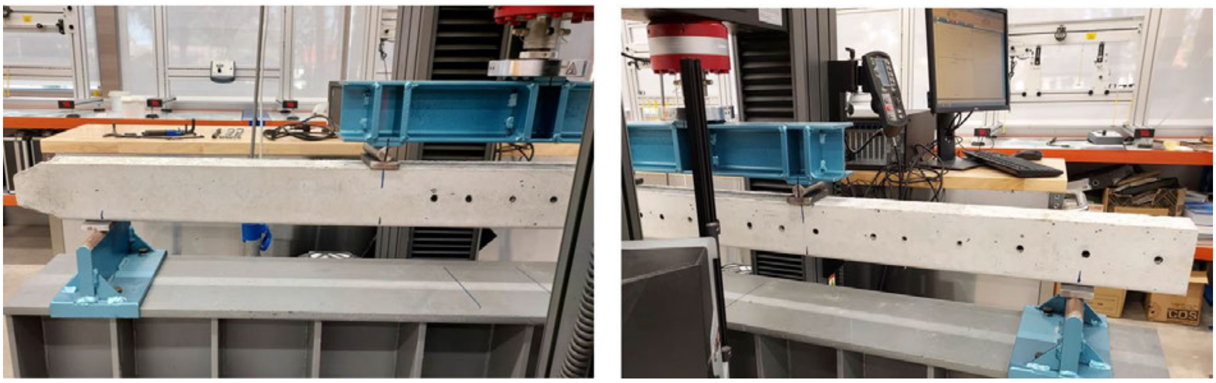

Figure 4.16: A NA Post with Supports and Loading Points Marked.

Figure 4.17: A NA Concrete Post Ready for Testing with the Instron Testing Machine

4.5.3.2 Modulus of Rupture

For fracture occurring in the middle third of the post; the modulus of rupture was calculated using:

$$f_{cf} = \frac{PL(1000)}{BD^2} \tag{4.5}$$

Where

f_{cf} = modulus of rupture, MPa

P = maximum force applied, kN

L = span length, mm

B = average width at the section of failure, mm

D = average depth at the section of failure, mm (Standards Australia 2014h).

4.5.3.3 Cracking Moment

An estimate of the moment of cracking can be obtained using the following equation from Warner et al. (1998):

$$\boldsymbol{M_{cr} = f'_{cf}\,\frac{bD^2}{6\times10^6}} \qquad \textbf{(4.6)}$$

Where

M_{cr} = moment of cracking, kN.m

$f'_{cf} = 0.6\sqrt{f'_c}$, MPa

b = width, mm

D = depth, mm

After conducting the flexural testing, this theoretical value can be compared to the experimental moment of cracking which is determined by considering the bending moment diagram for each post. The loading scenario and reaction forces for each post is shown in Figure 4.18 Each loading or reaction location is considered a discontinuity and is a point where the internal shear force and moment changes in magnitude.

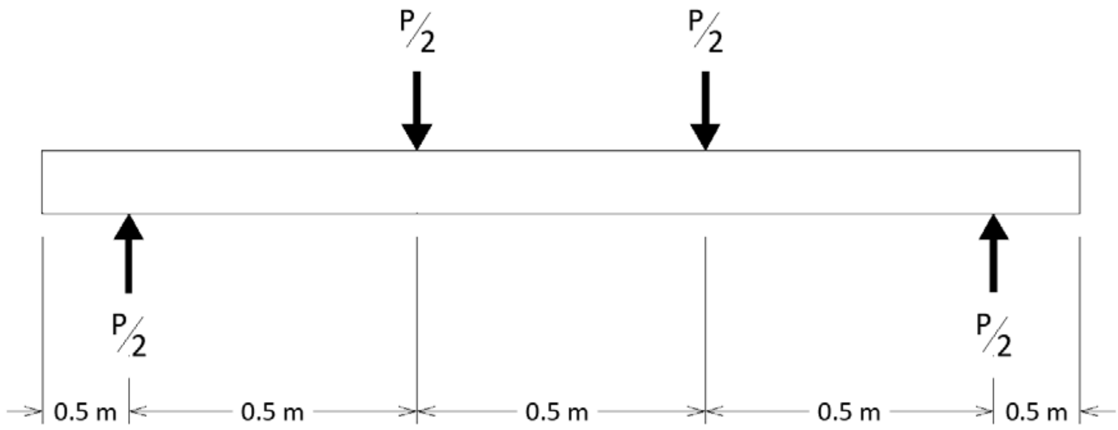

Figure 4.18: Equilibrium Forces Acting on the Posts

A bending moment diagram can therefore be developed using this diagram by considering equilibrium equations for each segment of the post. The general bending moment equations for each discontinuous segment of a post is shown in Figure 4.19 where P equals load in kN. These equations are applicable for each post. The cracking moment can be evaluated by substituting the relevant cracking load value P_c (kN) into each equation in place of P.

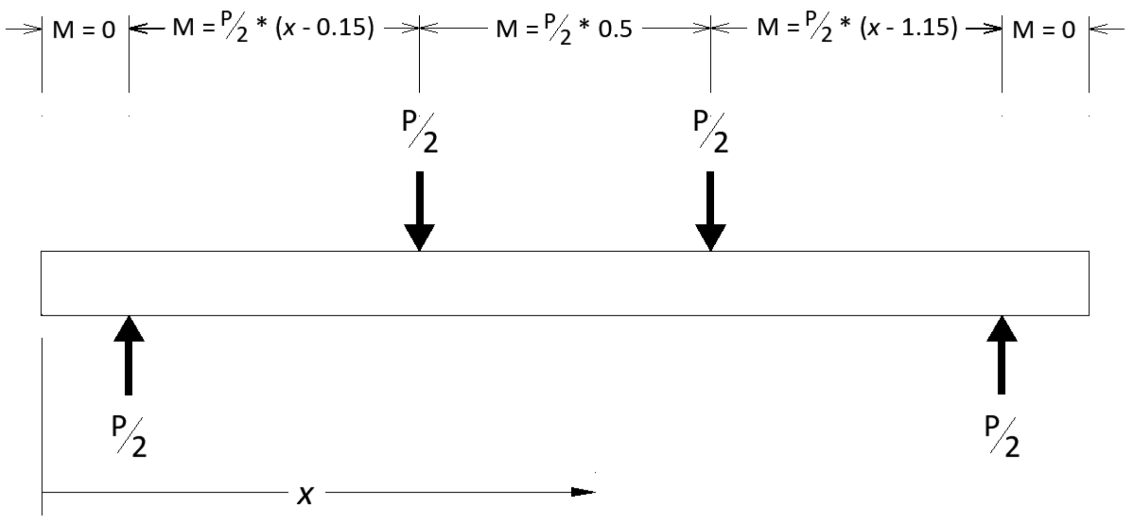

Figure 4.19: Internal Moment Equations over Length of the Posts

4.5.3.4 Ultimate Moment

Evaluation of the ultimate moment from the experimental data is identical to that for the cracking moment with the maximum loading, P_u substituted into the equations in Figure 4.19 instead of P_c.

CHAPTER 5. RESULTS AND DISCUSSION

5.1 Introduction

Due to a delay in being able to access laboratory facilities as a result of a Covid19 lockdown, testing was carried out at the concrete age of 38 days. This chapter presents the results of the testing program, including calculation of compressive and tensile strengths along with modulus of rupture and a review of flexural testing, and discusses the successes and limitations of the program.

5.2 Workability

Slump tests are used to determine the workability of the concrete in its plastic state. The results can be affected by aggregate size and shape, along with the w/c ratio. Slump tests on each of the mixtures were performed as detailed in Section 3.6.2 with the details of samples from each batch of concrete and slump testing shown in Table 5.1.

Table 5.1: Details of Samples from Each Concrete Mix

	NA concrete	RA Concrete
Date and Time	25/6/2021 12:05pm	25/6/2021 11:50am
Weather	Overcast 16° C	Overcast 16° C
Temperature of sample	16° C	16° C
Slump	130 mm	85 mm
Lateral collapse	No	No

The NA concrete exhibited a higher slump which can be attributed to due to the sand and aggregates used having excess moisture due to recent rain, and this not being adequately compensated for when batching the concrete. The RAC had a slump within the 80-100 mm target range. As the RA was in a dry condition, its water absorption properties are expected to have reduced the effective water content when compared to the NA mixture resulting in the better slump value.

5.3 Compressive Strength

Compressive strength was tested according to the procedure outlined in Sections 3.6.4 and 4.5.1. Results for compressive strength were recorded directly from the test machine, and also manually verified by dividing maximum load by the cross sectional area of the specimen. The details and test results for each specimen are shown in Appendix E Table E-1.

The failed NAC specimens are shown in Figure 5.1 and the RAC specimens in Figure 5.2. Inclusion of RA did not appear to significantly affect the failure mode of the compressive test samples, as all failed in a similar manner with the specimens exhibiting columnar vertical cracking through both ends. This indicates low friction between the plates and the specimen which gives a truer representation of the compressive strength than if significant friction is present (Talaat et al. 2021).

As concrete is a heterogeneous material, some variability between mixtures of the same composition, and even specimens from the same batch, may occur. Given the relatively small sample size, it is challenging to determine a definitive characteristic strength for the steam/air cured specimens. However, the decision of whether to include the NA1 observation or not can be analysed statistically and is discussed later in this report.

Figure 5.1: Water Cured NAC Specimens after Testing (front)

Figure 5.2: Water Cured RAC Specimens after Testing (front)

The results of the compressive testing program are displayed graphically in Figure 5.3 and show that the RAC exhibited good strength characteristics when compared to the NAC. In line with expectations, resulting from the literature review, the steam/air cured specimens displayed strength reductions in comparison to water cured specimens.

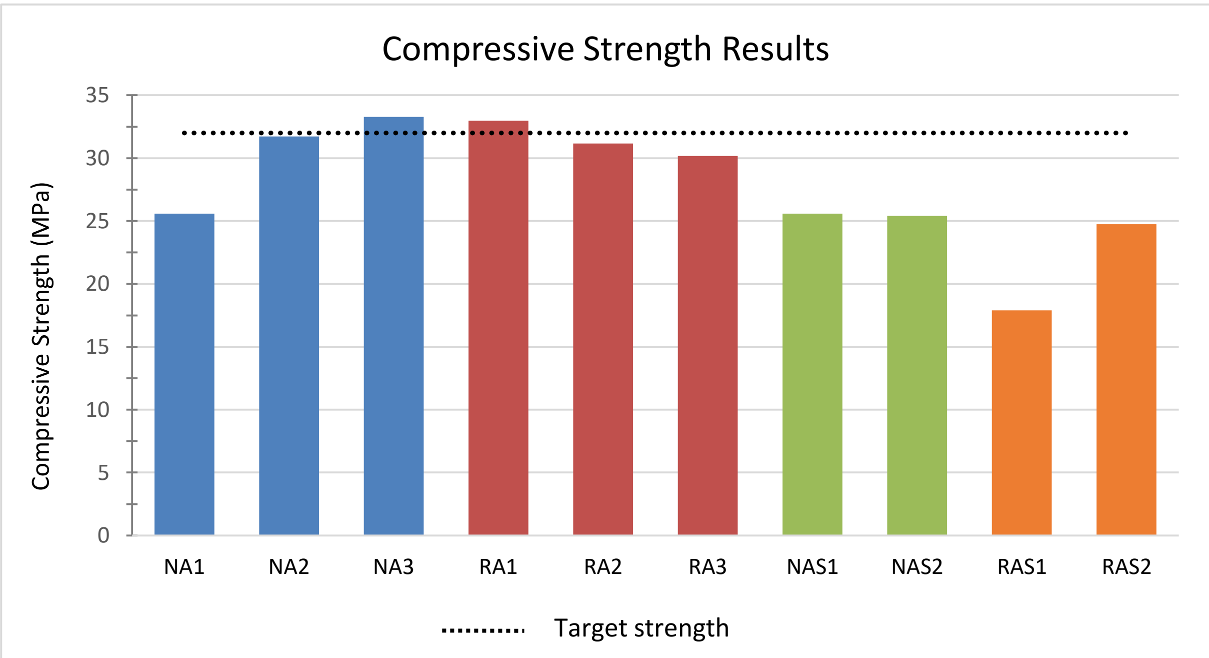

Figure 5.3: Experimental Compressive Strength Results

When considering the NA1 observation and to determine whether this datum should be excluded from the dataset, an examination was performed using Grubbs test. This test is designed to detect a single outlier using the sample mean and standard deviation assuming the data follows a normal distribution (Grubbs 1969; Moffat & Okon 2015).

The formula for finding the standard deviation of a sample is:

$$\boldsymbol{s} = \sqrt{\frac{\sum(\boldsymbol{x_i} - \overline{\boldsymbol{x}})^2}{\boldsymbol{n} - \mathbf{1}}} \tag{5.1}$$

Where

x_i = the individual measurement

$\bar{x}$ = the mean of the sample

n = the sample size (Grubbs 1969).

Table 5.2 shows the statistical analysis of the NAC observation from which the standard deviation of the sample can be calculated as;

$$s = \sqrt{\frac{33.1598}{3-1}} = 4.072.$$

Table 5.2: NAC Observation Statistical Analysis

Sample	f'_c	$(x_i - \bar{x})^2$
NA1	25.576	21.3004
NA2	31.721	2.3411
NA3	33.277	9.5182
Sum	**90.574**	**33.1598**
$\bar{x}$	**30.191**	

Grubbs formula for detecting an outlying observation is:

$$\boldsymbol{T_i} = \frac{\overline{\boldsymbol{x}} - \boldsymbol{x_i}}{\boldsymbol{s}} \tag{5.2}$$

Where

T_i = the test criterion

x_i = the individual measurement

$\bar{x}$ = the sample mean

s = the standard deviation of the sample (Grubbs 1969).

Grubbs (1969) provided a table of critical values corresponding to various numbers of observations for which the test criterion T_i must be equal to or lower for the datum to not be considered an outlier. For an experiment comprising three observations, the critical value is 1.15. When testing the NA1 observation:

$$T_1 = \frac{30.191 - 25.576}{4.072} = 1.133 \leq 1.15$$

Therefore, under this test case the observation is not considered an outlier and is included in the results.

The target compressive strength for this project was 32 MPa. From the observed data, both of the concrete mixtures failed to reach this benchmark and the steam/air cured concretes fell well short of this objective.

Table 5.3: Compressive Strength Comparison

	Average f'_c (MPa)	**Compressive strength ratio**		Average f'_c (MPa)	**Compressive strength ratio**	**Variance between curing methods**
NA	30.2	1	**NAS**	25.5	1	-16%
RA	31.4	1.04	**RAS**	21.3	0.68	-32%

The compressive strength ratio is a useful measure to compare the relative strength of the RAC with the control concrete mixture; it is derived by dividing the compressive strength of the RAC by the compressive strength of the NAC. Table 5.3 shows the average compressive strengths of each concrete mixture along with the compressive strength ratio. The magnitude of the strength reduction for the steam/air cured specimens is also displayed; while a reduction in strength for these specimens was expected the magnitude of the reduction is in the order of 2-4 times what has been reported in the literature.

When comparing the compressive strength of each mixture when considering the different curing conditions, a reduction in strength of 16% is recorded for the NAC and 32% for RAC.

This highlights two important points:

1. The large difference between the results for the RAC warrants further investigation. A lack of data makes it difficult to draw a conclusion based on sound research principles.

2. Preliminary compressive test results suggest the criticality of providing adequate curing conditions to allow hydration of the cement to advance. Additional testing focussing on steam/water cured specimens would be beneficial to understand the effects of steam curing further.

5.4 Splitting Tensile Strength

Tensile strength was tested according to the procedures outlined in Sections 3.6.5 and 4.5.2 as shown in Figure 5.4 and Figure 5.5 with three water cured specimens from each batch of concrete undergoing testing.

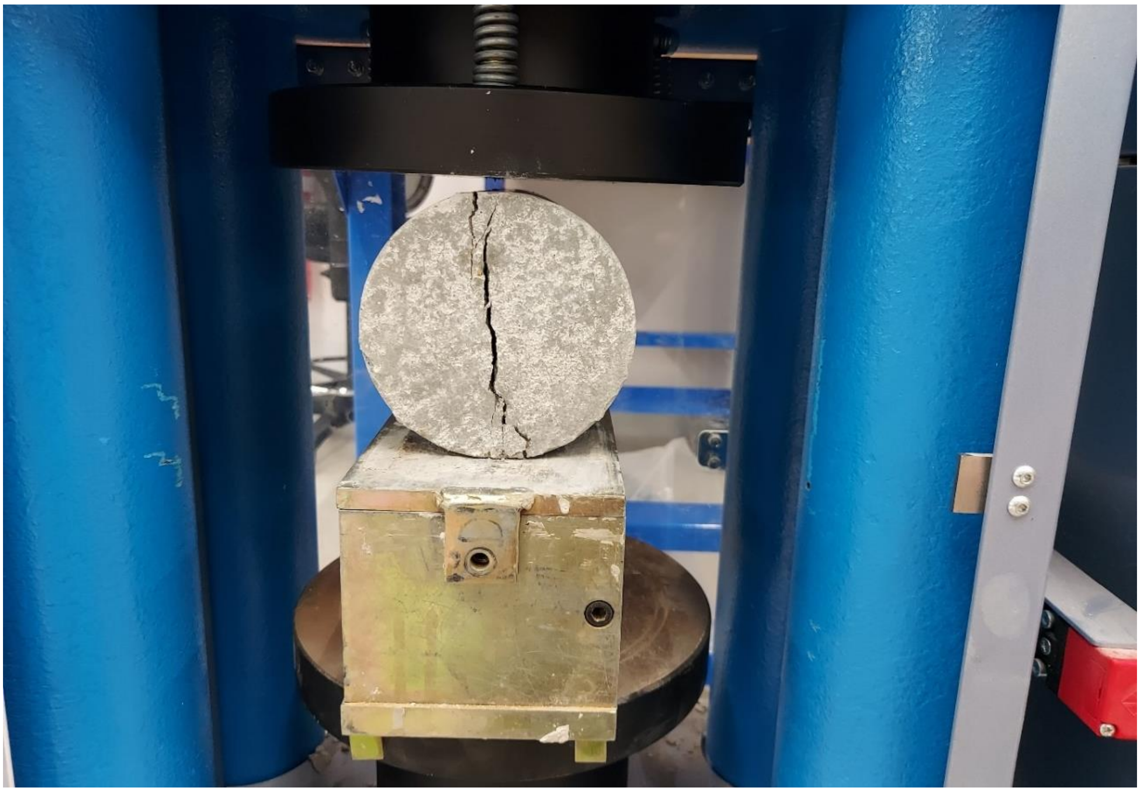

Figure 5.4: Competed Splitting Tensile Strength Test on a NAC Specimen

Figure 5.5: Testing of a RAC Specimen for Splitting Tensile Strength

Two of the failed NAC specimens are shown in Figure 5.6 and two RAC specimens in Figure 5.7. All failed in a similar manner with the specimens having a single vertical crack running completely through the specimen.

Figure 5.6: NAC Tensile Test Specimens

Figure 5.7: RAC Tensile Test Specimens

Results of the splitting tensile strength test were recorded directly from the test machine and verified with details of the specimen and the maximum applied load. The details and test results for each specimen are shown in Appendix E Table E-2.

The resulting average splitting tensile strengths are:

NAC: 4.02 MPa

RAC: 3.59 MPa

The theoretical tensile strength of concrete according to Cl. 3.1.1.3 of AS 3600–2009 (Standards Australia 2009) is found using:

$$\boldsymbol{f'_{ct.f} = 0.6\sqrt{f'}} \quad \textbf{(5.3)}$$

Where

$f'_{ct.f}$ = the characteristic flexural tensile strength of the concrete

f'_c = the characteristic compressive strength of the concrete

A comparison between the theoretical tensile strength, using the characteristic compressive strengths obtained in the previous section, and the experimental observations are shown in Table 5.4 below. It can be seen from this table that AS 3600–2009 underestimates the actual value of tensile concrete strength for both NAC and RAC. This observation corresponds with findings by Kilpatrick (2002) who noted that while AS 3600 underestimated $f'_{ct.f}$ for wet cured specimens, it did provide a reasonably accurate estimated when considering dry-cured specimens.

Table 5.4: Comparison between Theoretical and Experimental Tensile Strength

Concrete type	AS3600–2009	Experimental	Variance
NAC	3.30	4.02	-18%
RAC	3.36	3.59	-6%

The tensile strength results are graphically displayed in Figure 5.8 where it can be seen that the effect of RA replacement on tensile strength is more pronounced than for compressive strength.

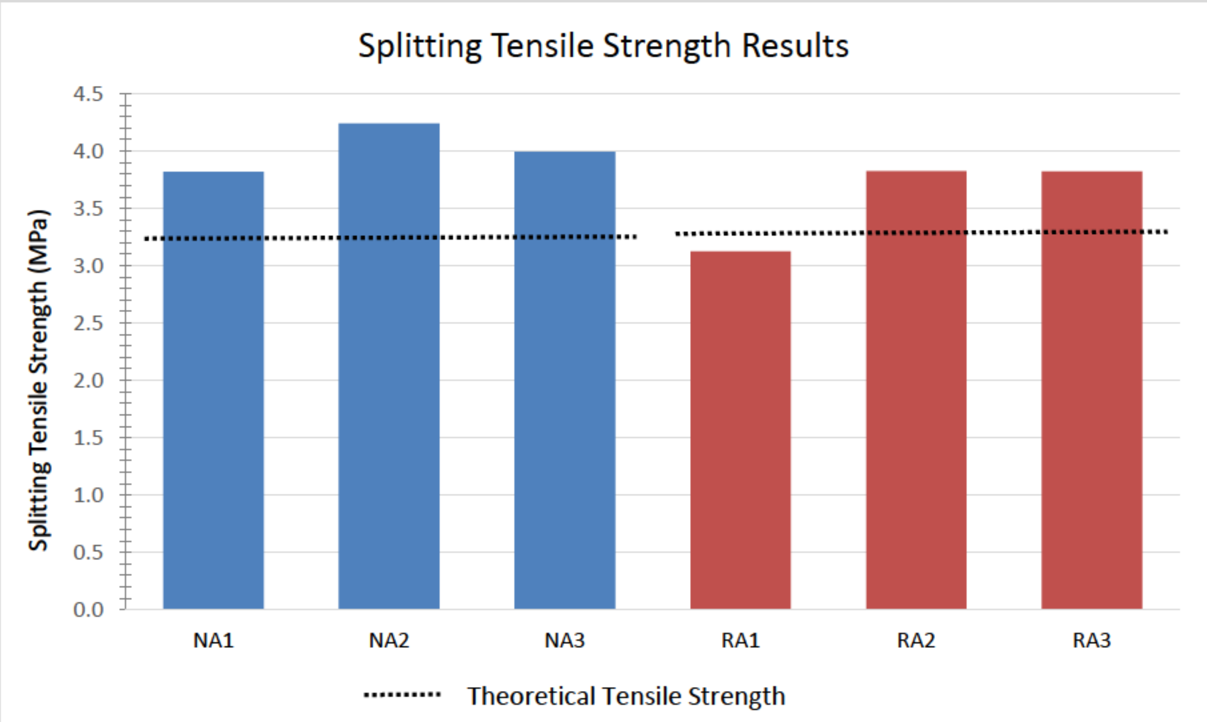

Figure 5.8: Splitting Tensile Strength Results

One each of the NAC and RAC specimens were completely separated to enable the interior of the specimen to be inspected. When considering these specimens it can be seen that both have instances where the aggregates themselves have split. The natural aggregate used is selected to be a higher strength class, as the source materials used to make the RA are unknown their strength class is also unknown. Because both types of concrete resulted in split aggregate it is reasonable to conclude that the tensile strength is influenced to some degree by the tensile strength of the aggregates. Therefore the lower tensile strength of RAC could be attributed a combination of cracked adhered mortar and the inclusion of lower strength aggregates.

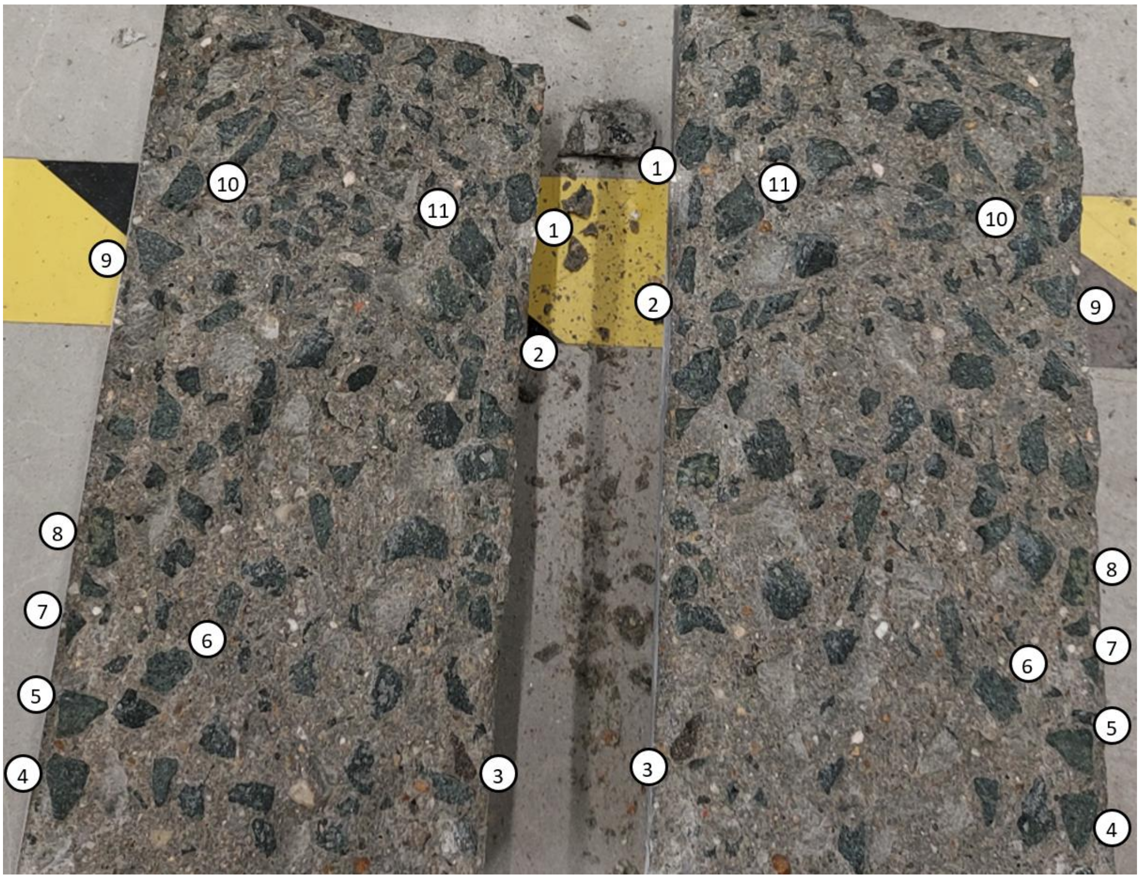

Figure 5.9: Separated NAC Specimen with Split Aggregates Highlighted

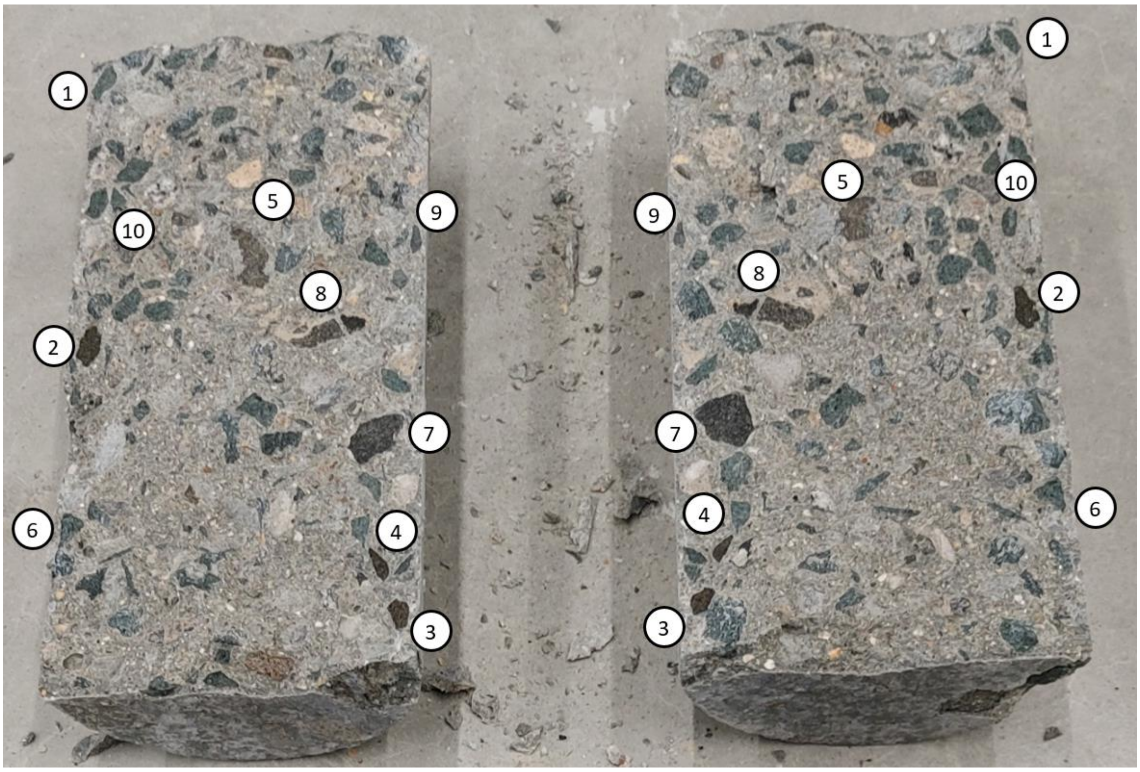

Figure 5.10: Separated RAC Specimen with Split Aggregates Highlighted

5.5 Flexural Strength

5.5.1 Introduction

During flexural testing, the posts were slowly loaded and proceeded go through three stages. The first stage was at the beginning of loading and is the elastic stage. During this stage the deflection changed slowly with increasing load, and no cracks were evident. During testing complications were encountered with recording the data for the first two samples to be tested, those being NA1 and NA2.

This resulted in data from two files for the NA1 sample having to be merged along with data sourced via inputting a plot of the load/deflection curve into an online data digitiser. This allowed data values to be recovered by placing points on the curve which were then digitised and exported to a .csv file and merged with the previous 2 data sets to form a complete data ensemble.

Unfortunately it was not possible to retrieve the initial part of the data from the NA2 test.

5.5.2 Cracking Moment

With increased loading, the second stage is the cracking stage. At this stage, flexural cracks appeared in the region of maximum moment located on the bottom of the post in the mid-span between the loading points. The deflection of the posts increased gradually and the flexural cracks grew vertically.

The MATLAB output showing the cracking load data is displayed in Appendix E Figure E.3. A comparison of experimental against the theoretical cracking moment, calculated using Equation 4.6, is displayed in

Table 5.5 and Figure 5.11 where it can be seen that the incomplete data for NA2 has an adverse effect on the results. As the NA2 data is incomplete, it was removed from calculations when determining the average cracking moment for the NAC mixture.

Table 5.5: Moment of Cracking Values

	NA1	NA2	NA3	RA1	RA2	RA3
P_c	4.343	0.179	4.654	5.394	4.382	6.261
$M_{cr(theoretical)}$ (kN)	0.532	0.532	0.532	0.542	0.542	0.542
$M_{cr(experimental)}$ (kN)	1.629	0.067	1.745	2.023	1.643	2.348
Experimental/Theoretical	3.06	0.13	3.28	3.73	3.03	4.33

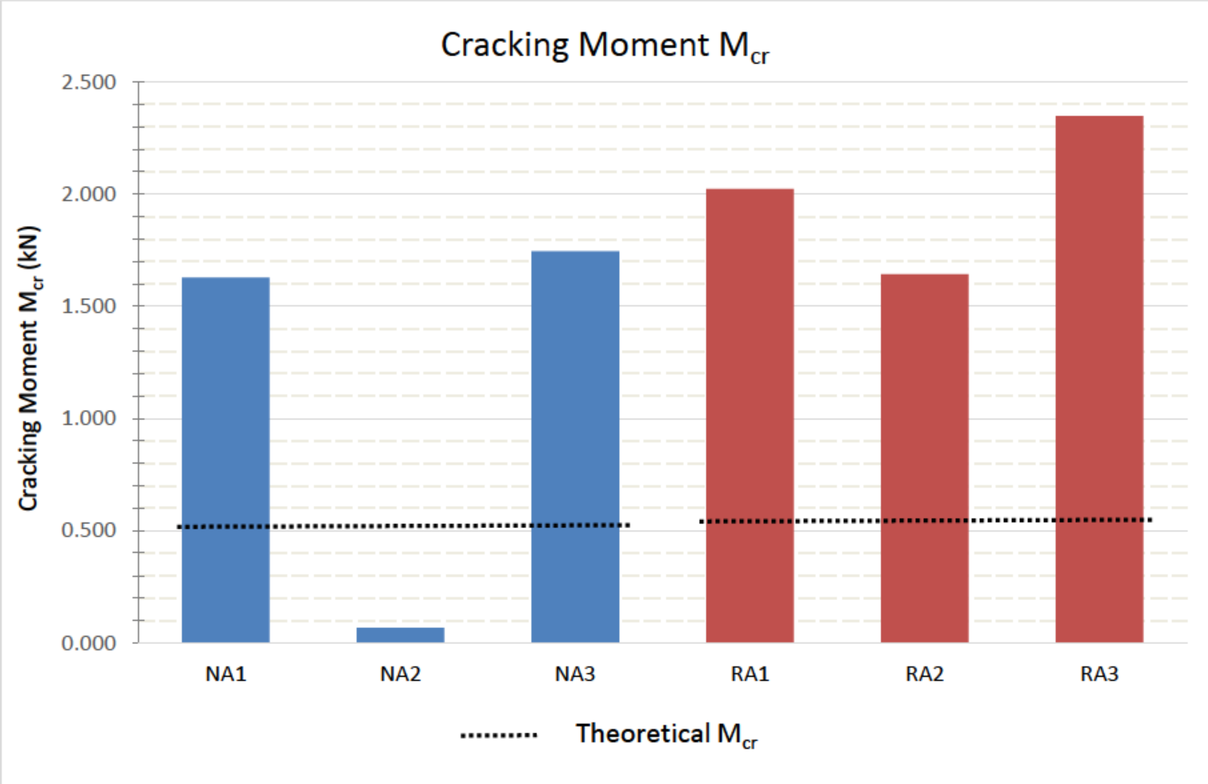

Figure 5.11: Comparison of Experimental and Theoretical Cracking Moments

The average experimental cracking moments of both the NAC and RAC posts were greater than the theoretical cracking moments as reported in Table 5.6. This significant increase can be attributed to the simplified equation used for determining M_{cr} not accounting for the pretensioning wires, which place the concrete into induced compression thereby delaying the onset of cracking.

Table 5.6: Moment of Cracking, M_{cr}

M_{cr} (kNm)	Theoretical	Experimental	Experimental /Theoretical
NAC	0.532	1.687	3.17
RAC	0.542	2.005	3.70

5.5.3 Modulus of Rupture

The post manufacturer's target is for their posts to be able to withstand a 500 kg load applied to the side of the post; this equates to a force of 500 x 9.81 = 4 905 N or 4.9 kN. The following graphs display the load/deflection curve for each of the concrete posts tested and show that each of the posts satisfies this condition.

Figure 5.12: Failed NA1 sample

Figure 5.12 shows the failed NA1 sample which was the first to be tested with concrete crushing evident on the compression zone. Open flexural cracks can still be seen even after the load has been removed. The load/deflection curve in Figure 5.13 shows the merged data to give a complete curve for the sample and shows the post surpassed the required ultimate load.

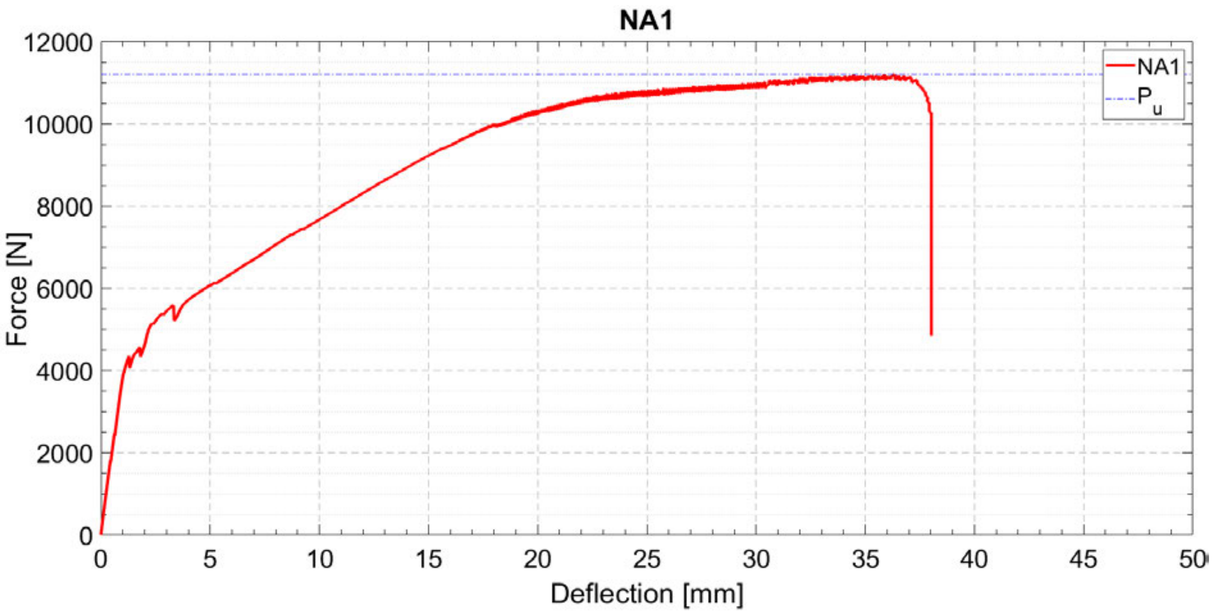

Figure 5.13: Load Deflection Diagram for NA Post 1

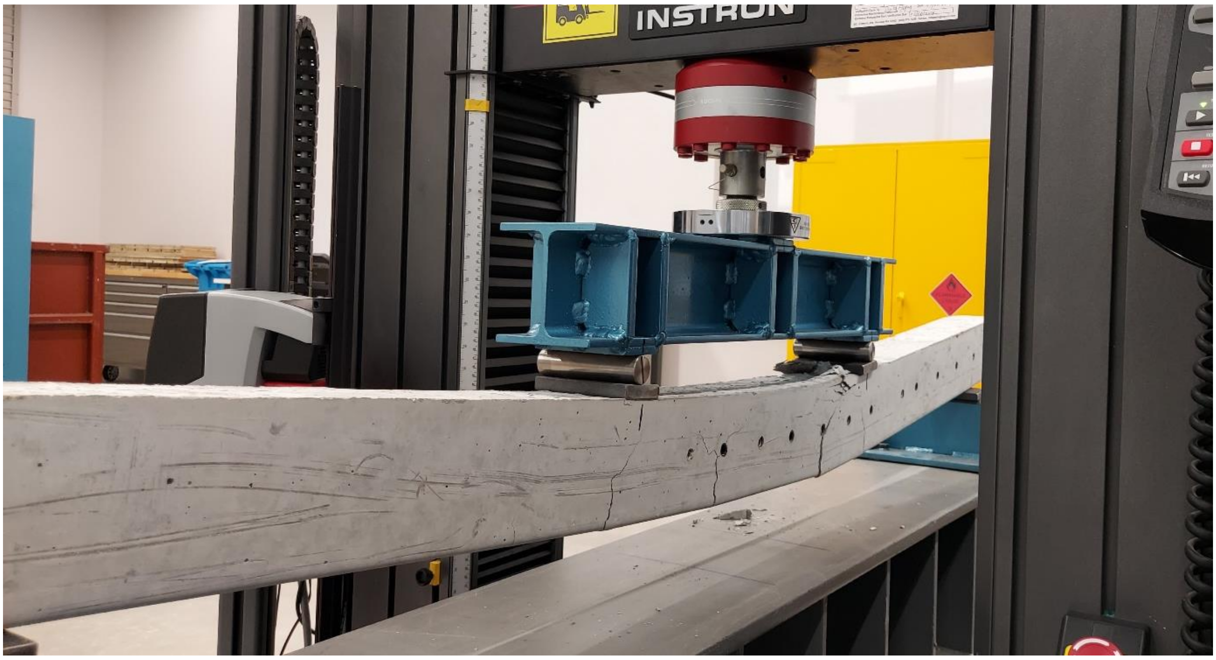

Figure 5.14: NA2 Sample at Failure

Concrete crushing can again be seen in the failure of sample NA2 in Figure 5.14. An error in the procedure when testing resulted in an incomplete data set that does not give a true reflection of the ultimate strength or maximum deflection of the sample. This is evident when considering the load/deflection curve in Figure 5.15 when is can be seen the initial elastic section of the curve is missing.

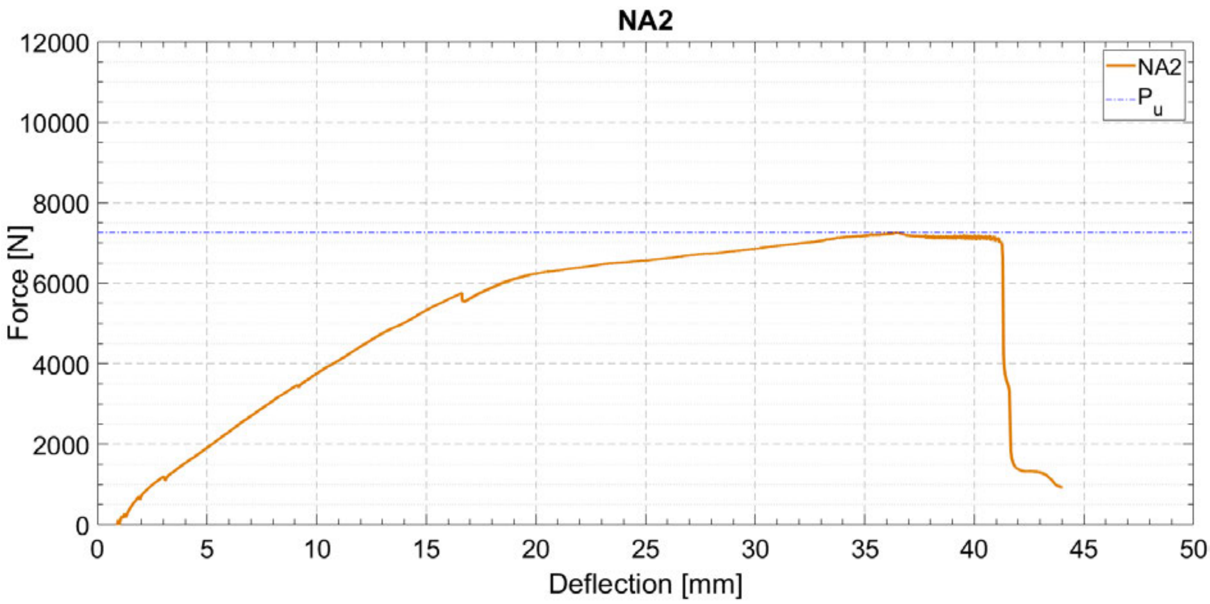

Figure 5.15: Load Deflection Diagram for NA Post 2

Figure 5.16: Failure of Sample NA3

The typical failure mode of the NA samples is clear in Figure 5.16 with several flexural cracks clearly evident however not extending through each of the penetrations made for running the fence wires. Some shear cracking can be seen outside the pure bending section however the failure mode is flexure with a wide crack below the location of concrete crushing. Figure 5.17 shows the load/deflection curve for this sample which reached the highest ultimate load of all the NA sample posts.

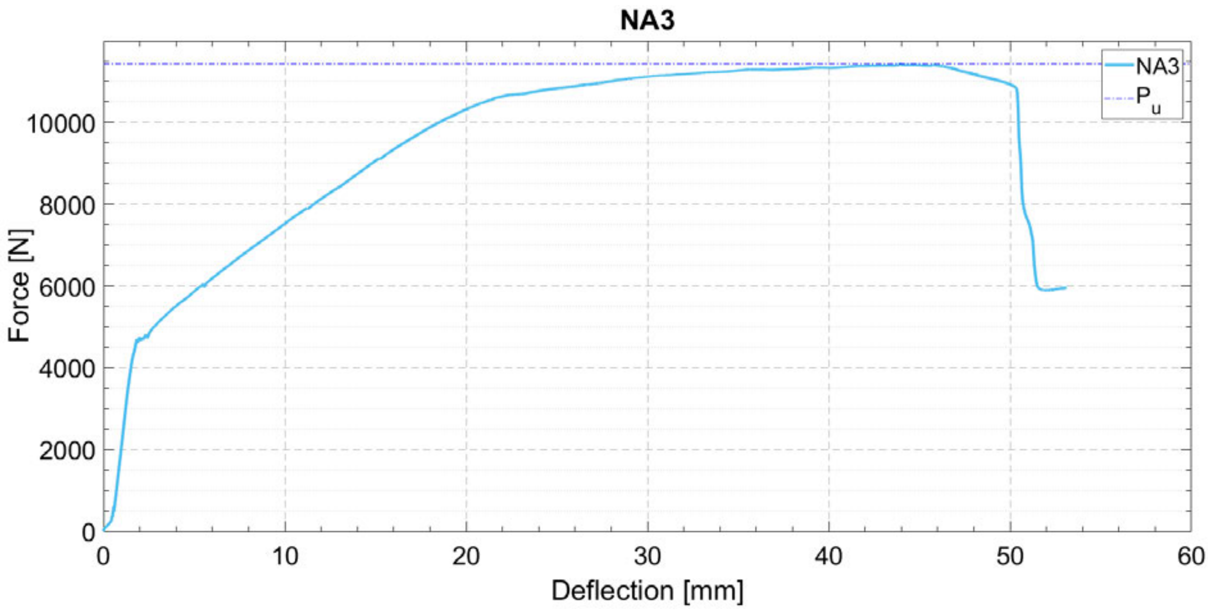

Figure 5.17: Load Deflection Diagram for NA Post 3

Figure 5.18: Failure of Sample RA1

In Figure 5.18 an identical failure mode can be seen as observed in the NAC samples with a fine shear crack outside the pure bending section, multiple flexural cracks in the mid-span and a wide flexural crack extending from the bottom of the sample towards the location of concrete crushing. This sample achieved the highest ultimate load, being 11.693 kN as seen in Figure 5.19, of all the posts tested.

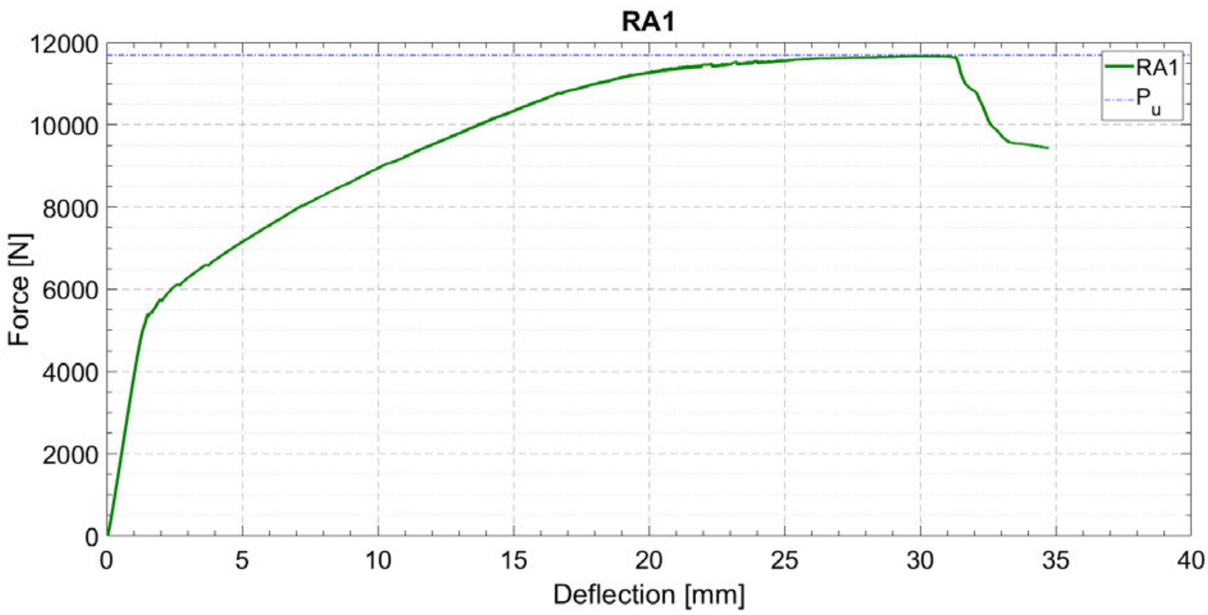

Figure 5.19: Load Deflection Diagram for RA Post 1

Figure 5.20: Progression of the Load/Deflection Curve for RA2 during Testing

Figure 5.20 shows the progression of the load/deflection curve for the RA2 sample during testing with the results of this test seen in Figure 5.21. Noticed here is the different load/deflection slope that was observed in the RAC samples, with a more gradual decline in loading and continued deflection leading to a more gradual failure.

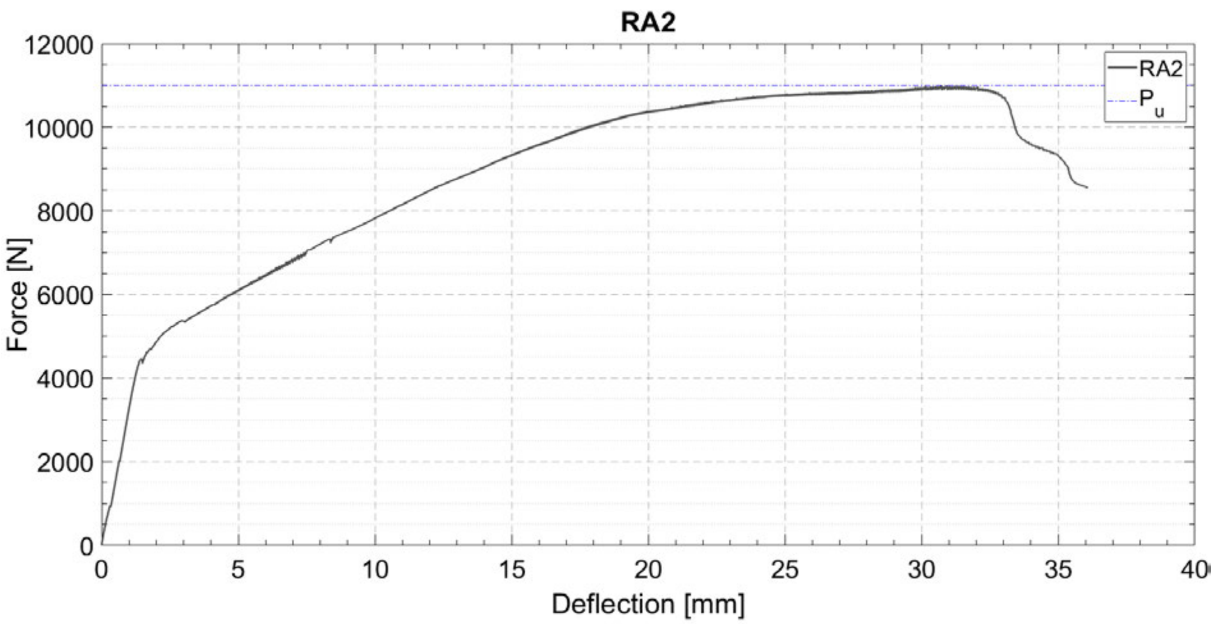

Figure 5.21: Load Deflection Diagram for RA Post 2

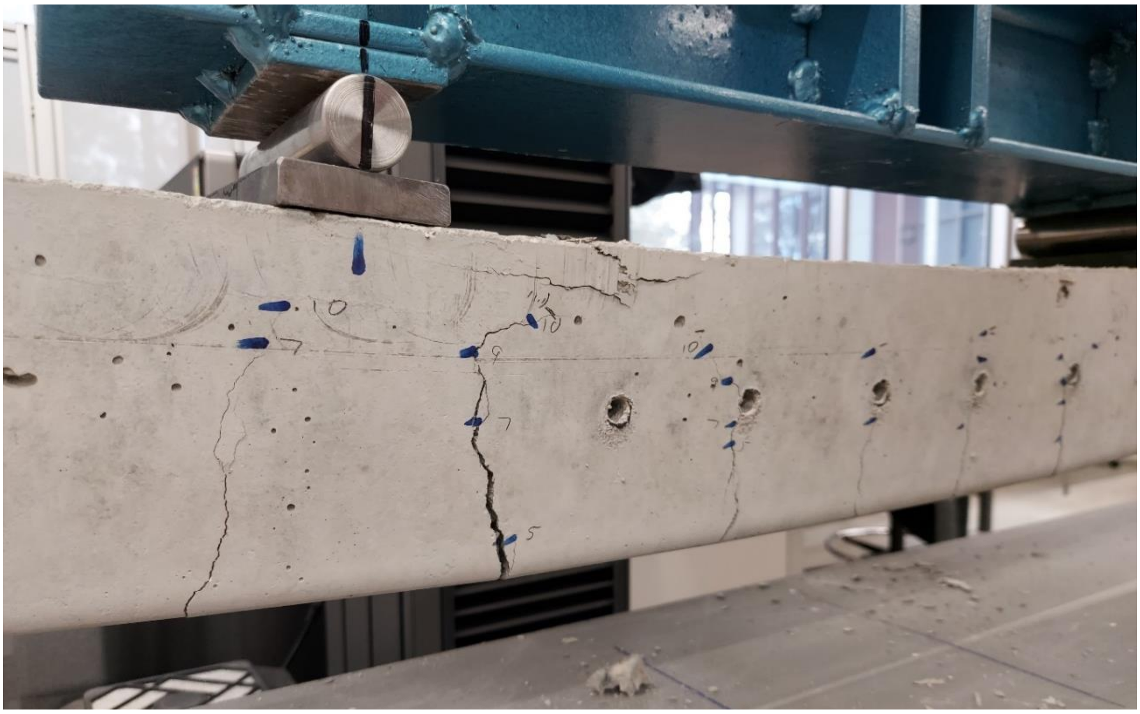

Figure 5.22: RA3 Sample with Crack Progression Marked at Various kN Loads

In Figure 5.22 the progression of crack development with increased loading can be seen marked on the side of the sample. A larger number of flexural cracks are evident than in the NAC samples with almost all the penetrations having a crack running through them. A single widening flexural crack is again observed as the post approached its ultimate loading which, as can be seen in Figure 5.23, is relatively high.

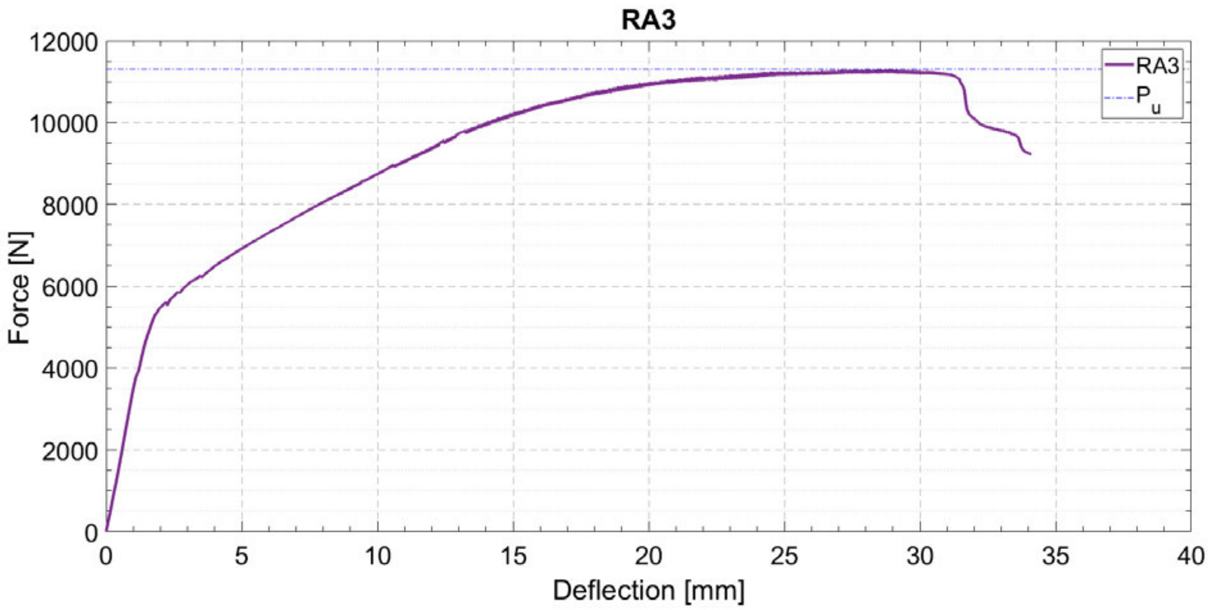

Figure 5.23: Load Deflection Diagram for RA Post 3

By studying the load/deflection curves in Figure 5.24 it can be seen that all of the posts failed in a ductile manner with the curve almost being parallel to the deflection axis prior to failure. There was however, differences in the load/deflection curve between NAC and RAC posts. The NAC posts exhibited a greater degree of deflection for any given loading after yielding of the steel reinforcement and at rupture the load immediately dropped significantly.

In contrast, the RAC posts exhibited a different failure curve where the slope of the line began a gradual descent. As the load approached the value where the concrete began to crush, the bearing capacity was drastically lowered and the posts failed. Before the damage, the deflection of the three beams kept growing, and the growth of the load faded.

This mode of failure is likely due to the decreased bond strength observed with RAC as reported by Breccolotti and Materazzi (2013) and Dong et al. (2019). The reinforcement de-bonds from the concrete prior to yielding resulting in slippage, although the reduction in bond strength is not sufficient to prohibit the use of RAC in structural members due to the conservative design values contained within established design standards (Breccolotti & Materazzi 2013).

This failure mode is analogous to that discovered by Butler et al. (2011) which they also attributed to being to the bond capacity between the reinforcement and the concrete being exceeded. They hypothesised that this was possibly due to the lower crushing values of the RA but suggested that further research was required.

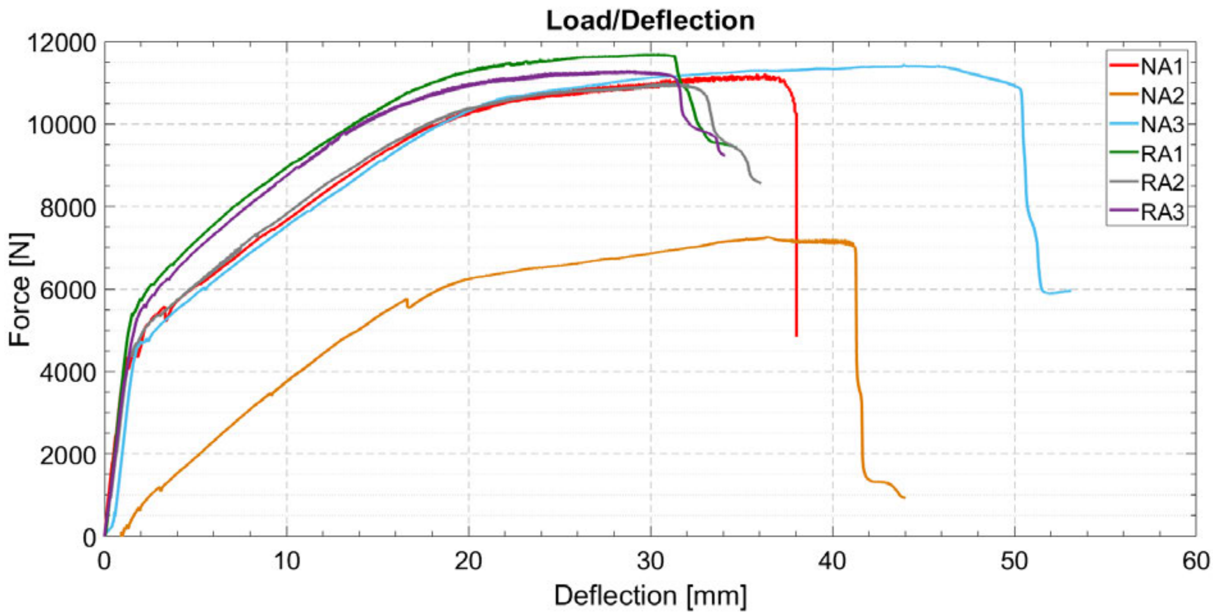

Figure 5.24: Comparison of all Flexural Tests

Another explanation for the increased deflection on the NAC samples, in the absence of other variables, is a variance in the modulus of elasticity between the concrete mixtures. Seara-Paz et al. (2018) suggested this as an explanation when investigating the flexural performance of reinforced concrete beams.

As all of the posts failed in the middle third, the modulus of rupture was calculated using Equation 4.5 from Section 4.5.3.2. The results of these calculations for each post are shown in Table 5.7 where it can be seen that the modulus of rupture is reasonably consistent across the range of posts with the exception of NA2. As previously noted, this data is incomplete due to a problem during testing where the initial part of the test was not captured. The NA2 curve appears to commence at what should be the beginning of the yielding part of the curve. If this is the case it then follows a similar profile to the other load/deflection curves from this point onwards.

Table 5.7: Modulus of Rupture

	Target minimum	NA1	NA2	NA3	RA1	RA2	RA3
P_u (kN)	≥ 4.9	11.018	7.2658	11.428	11.693	10.999	11.300
f_{cf} (MPa)	≥ 7.593	17.073	11.259	17.709	18.119	17.044	17.510
δ (mm)	N/A	30.411	36.469	43.980	30.490	30.945	28.761

5.5.4 Ultimate Moment

During increased loading, all of the posts for both batches of concrete exhibited tensile opening of vertical flexural cracks, with minimal shear cracking in line with findings of Kazemian et al. (2019). The flexural cracks grew towards the compression zone and shear cracks appeared on the bottom edge and extended towards the loading point.

As the steel reinforcement yielded, the flexural cracks in the mid-span widened until failure of the reinforcement. At this point a number of the flexural cracks widened rapidly, and crushing of the concrete in the compression zone was evident.

The failed post samples can be seen in Figure 5.25 while the ultimate moment for all of the samples are shown together in Figure 5.26. It can be seen that while the deflection at the point of ultimate loading varied between concrete types, if the compromised data relating to NA2 is not considered, the ultimate moments are not significantly different. Supporting the results of this investigation is the studies by Xiao et al. (2012) and Seara-Paz et al. (2018) who also noted no significant difference in yielding and ultimate moments with the inclusion of RA.

Figure 5.25: Failed Post Samples

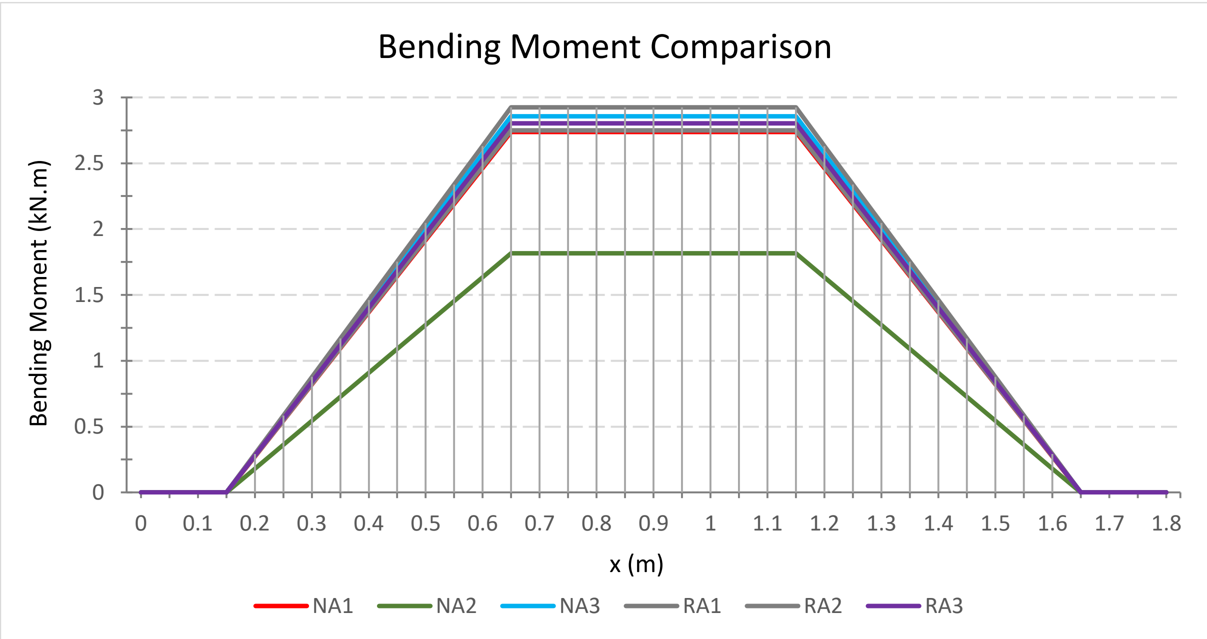

Figure 5.26: Bending Moment Comparison

5.5.4.1 NAC posts

After reaching the cracking moment, vertical cracks slowly developed upwards in the pure bending segment of the post. The number of cracks was limited and they did not propagate through each of the wire conduits. The cracks slowly widened with increasing load and a small number of shear cracks developed outside the pure bending segment as loading approached the ultimate load.

Failure of the post saw yielding of the reinforcing steel and the cracks in the pure bending segment rapidly enlarged with development of concrete crushing in the compression zone. Two of the posts underwent crushing near a loading point, while the other failed with mid-span crushing.

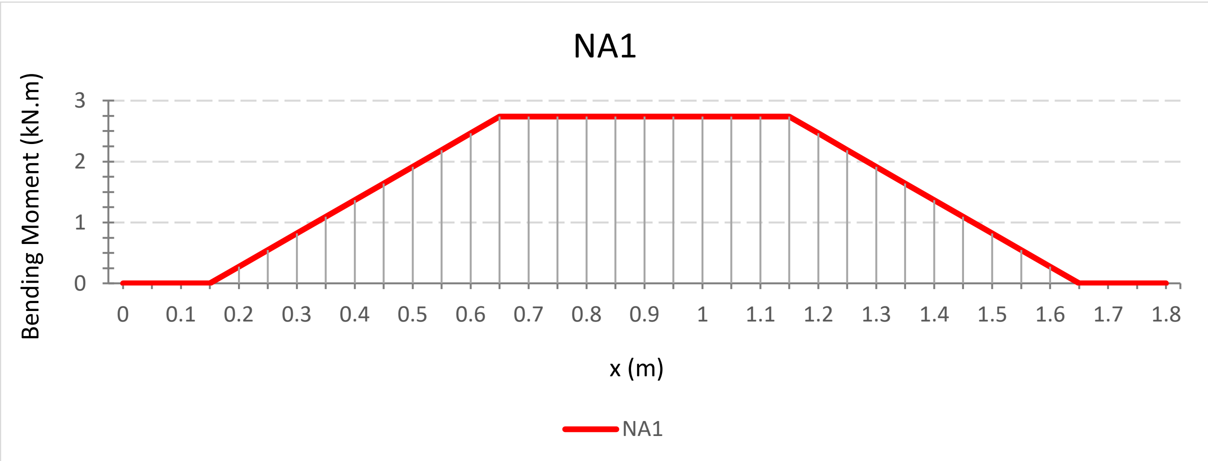

Figure 5.27: Bending Moment Diagram for Post NA1

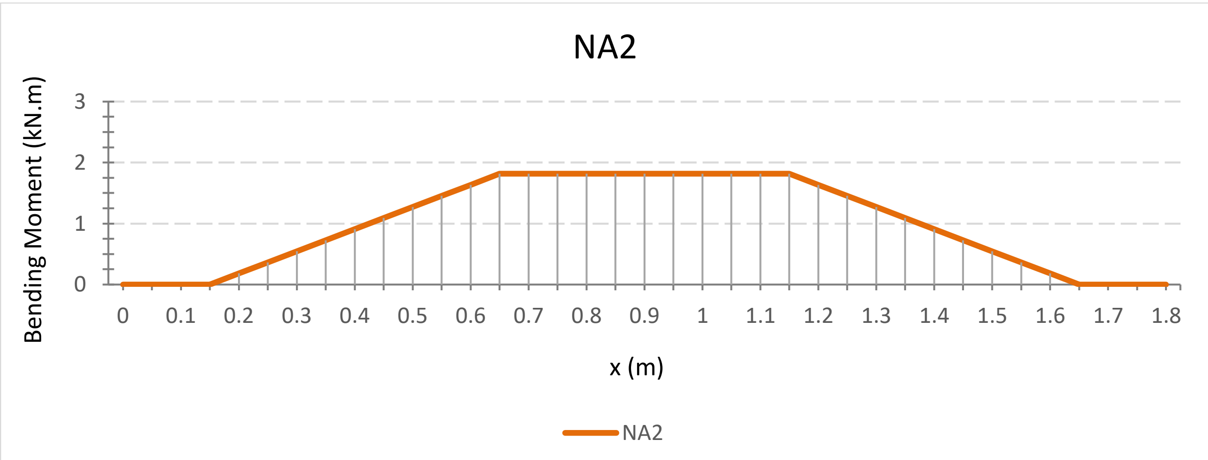

Figure 5.28: Bending Moment Diagram for Post NA2

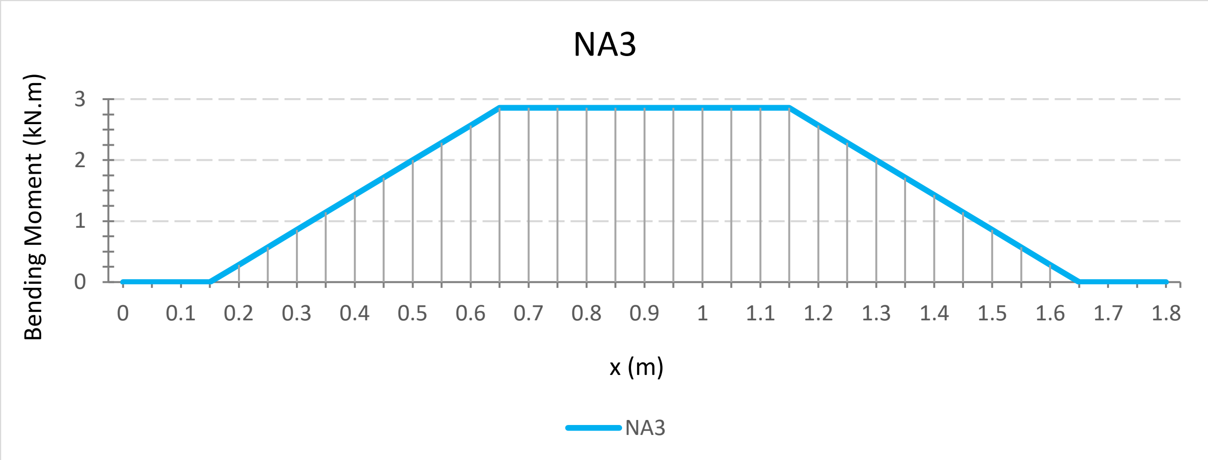

Figure 5.29: Bending Moment Diagram for Post NA1

5.5.4.2 RAC Posts

After the cracking moment was reached, vertical cracks propagated in the mid-span at the tensile edge of the beam. These cracks slowly developed upward as the loading increased and with further loading the crack widths slowly expanded.

When the load had reached approximately 45% of the beam's ultimate load, vertical cracks had appeared in the pure bending segment at almost every wire conduit. When the load reached about 60% of the ultimate load, the number of cracks stabilised. These cracks were fine and terminated below the neutral axis. As the load continued to increase, the cracks developed slowly, and some of the cracks began to branch out at the top of the crack.

The final stage was similar to the NAC posts, with failure of the reinforcement. At this stage, almost no new cracks appeared and the existing cracks widened relatively quickly. The beam was damaged and concrete crushing was evident in the upper compression edge.

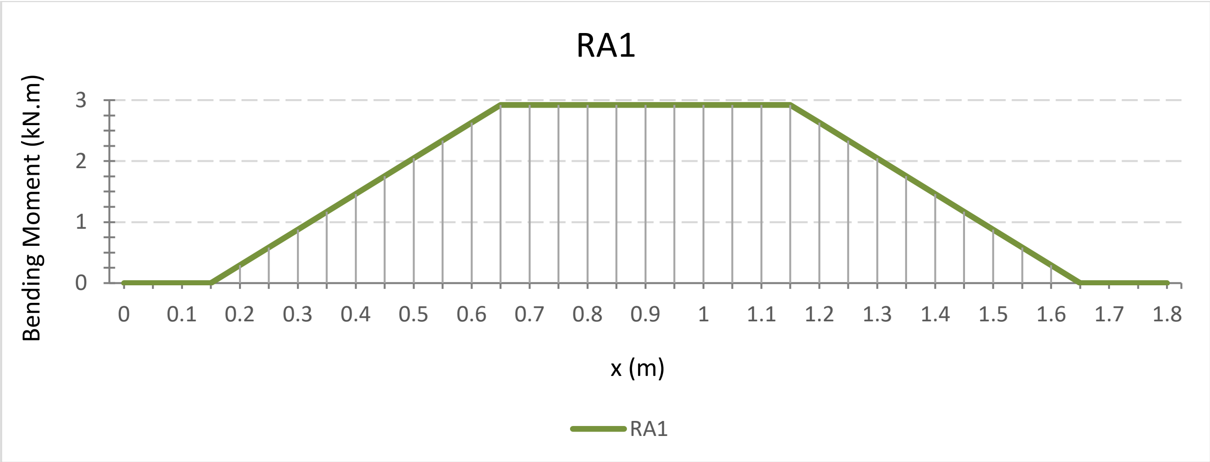

Figure 5.30: Bending Moment Diagram for Post RA1

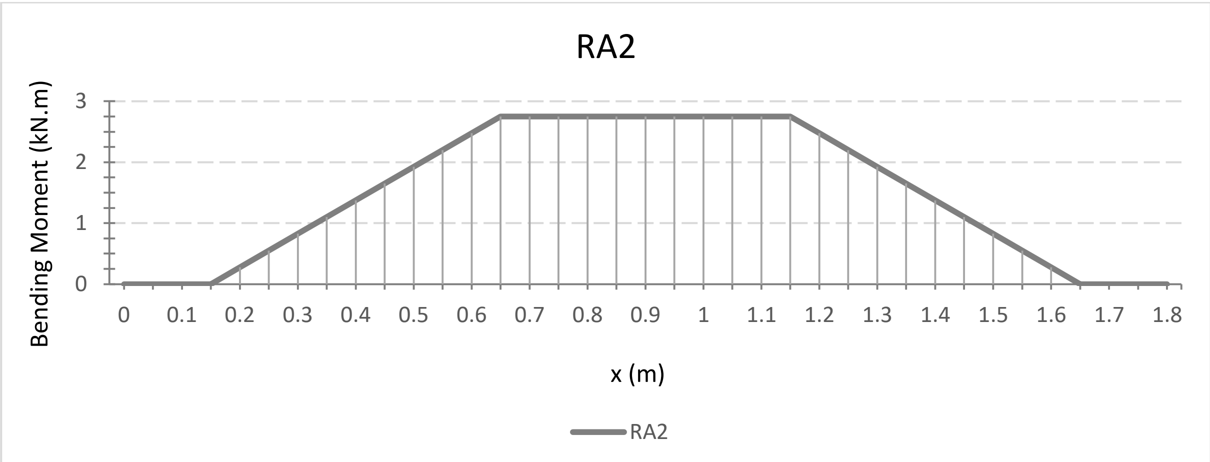

Figure 5.31: Bending Moment Diagram for Post RA2

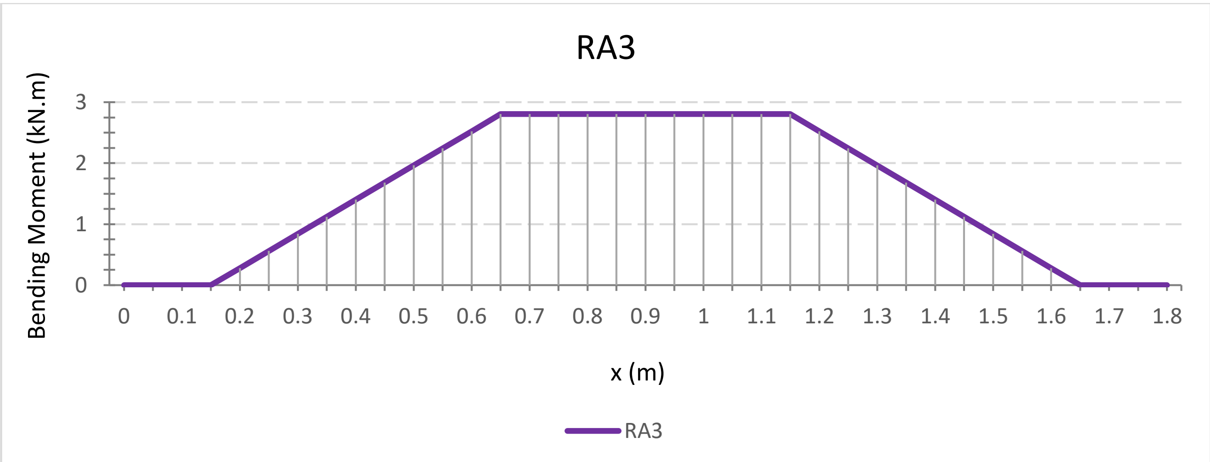

Figure 5.32: Bending Moment Diagram for Post RA3

Figure 5.33: Sample RA3 at M_{ult}

The similar performance of the RAC and NAC posts observed when comparing ultimate loads is in line with the findings of Xiao et al. (2012), who found no variance for up to 50% replacement, and Seara-Paz et al. (2018), who observed no significant differences. Seara-Paz et al. (2018) actually reported marginally higher M_{ult} in the case of 20% and 50% replacement with RA.

The researchers did not report using a particular mixing method in these studies and, similar to this project, the RA did not undergo any secondary treatment to improve its performance.

CHAPTER 6. CONCLUSIONS

6.1 Discussion

This research has investigated the performance of RAC, containing 30% replacement by weight of coarse aggregates, to allow a comparison to NAC, with a particular focus on the flexural strength of concrete fence posts made from the mixture. Based on the results the following conclusions have been drawn:

1. RA can be successfully used in fresh concrete to produce precast components such as fence posts. While the mechanical properties of RAC are generally of a lower standard than NAC, they are not substantially poorer as to prevent the used of RA, clean and free from impurities, in producing fresh concrete for these products. RA would benefit from the implementation of a classification system similar to that existing for NA to increase confidence in it as a construction material.

2. The compressive strength of concrete is not appreciably compromised by adding 30% RCA under the conditions studied. While the RAC reported a higher average compressive strength, the NAC mixture had a higher than desired slump value indicating that the effective w/c ratio was also higher thereby leading to a lower f_c' value.

3. Splitting tensile strength is approximately 10-11% lower with 30% replacement RA; however the reduction is not significant enough to preclude its use in the production of pretensioned concrete fence posts. In fact the very nature of the pretensioning placing the concrete into induced compression aids in concealing the minor tensile strength reduction.

4. Owing to the reinforcing pretensioned wires, both the NAC and RAC posts fail in a ductile manner. NAC posts exhibit larger deflections for a given loading and fail due to rupture of the reinforcement with rapid reduction in load and almost no deflection increase. The failure mode of RAC posts is slightly different, with a more gradual decline in load accompanied with a further increase in deflection. This is caused by bond slippage between the reinforcement and the concrete as a result of the additional ITZ within the RA.

5. 30% RA inclusion results in analogous ultimate loads under flexural testing although with lower deflections. 100% NA concrete posts displayed larger deformations for any given loading after the load exceeded the linear elastic limit. The RAC posts developed a larger number of flexural cracks than did the NAC versions resulting from the lower tensile strength..

6. RAC is more sensitive to curing conditions than NAC and requires adequate moisture to allow for hydration to progress to completion. A reduction of 32% in 38 day compressive strength is observed in RAC specimens subjected to steam/air curing compared to those cured under moist conditions. NAC also sees reduced compressive strength under steam/air curing although to a lesser degree of 16%.

7. Concrete fences posts fail due to flexural cracking when subjected to a lateral force applied in the mid-span. Multiple flexural cracks appear and widen with increased loading until failure associated with the reinforcing steel. Shear cracking is minimal and the cracks do not open to a significant degree.

Savings can be achieved through the use of mobile crushing plant to minimise transport costs and via cost saving on waste disposal. The cost of the RAC was approximately 70% cheaper than the basalt NAC. By replacing 30% of the coarse aggregate with RA the manufacturer realise cost savings of approximately 21%.

This project has added to the collective knowledge on the use of RA in the production of fresh concrete. The concrete posts produced using the RAC performed adequately under loading, exceeding the manufacturer's specification for withstanding a 4.9 kN laterally applied load. While the post company has not yet committed to utilising RA in the manufacture of their posts, this is due predominately to the challenge of sourcing clean RA free from other building waste contamination. The success of this project has allowed them to explore replacing a proportion of the current high grade aggregate they use, with a cheaper, lower grade aggregate to reduce costs.

6.2 Further Research

The following is a list of identified opportunities for further research in the field of RAC usage in the manufacture of pre-cast concrete components. The list has been derived from results of this study, along with the investigations conducted during the literature review, and is not to be considered exhaustive:

1. Evaluation of the permeability of RAC, and chloride penetration, to determine the effects on the pretensioning wires and the propensity for corrosion to develop. This would assist in considering the long term durability of the posts.

2. Investigate the optimised triple mix method proposed by Zhang et al. (2019). This method lead to improvements in compressive strength of 19% and if similar improvements in tensile strength can be realised this may increase the deflection characteristics of the posts under lateral loading.

3. Consider whether by-products from cleaning with acetic acid can financially offset the costs of treatment. Finding commercial markets for the by-products would encourage this method of treatment leading to cleaner RA and improved mechanical performance further driving confidence in the product.

4. Investigate the performance of RAC products over an extended timeframe. By observing and documenting the behaviour of RAC products over a period of 10-20 years or more, a better understanding of any changes in mechanical characteristics can be observed. This will aid in predicting a life span for products manufactured from RAC.

5. Produce further post samples using the RAC mixture and test their ability to withstand the driving forces they are subject to during installation. While this study has focussed predominately on the flexural strength of the posts mad using RAC, a key quality for success is being able to install the posts into the ground using an impact driver. This force drives the post into the ground, in a quick and economical manner, which is essential to ensure the product is financially viable.

6. Investigate the effects, and commercial viability, of steam curing followed by a period of moist curing, such as mist sprays or water immersion, for time periods of say 3, 7, 14 and 28 days. As this study has identified the sensitivity of RAC to proper curing conditions, this evaluation would assist in determining the curing regime that can deliver close to optimum results at an effective cost.

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Appendix A – Project Specification

ENG4111/4112 Research Project: Project Specification

For: Leigh Hollingworth

Title: Evaluation of the Performance of Recycled Concrete Aggregate in Fresh Concrete for Manufacturing Fence Posts

Major: Civil Engineering

Supervisors: Dr Weena Lokuge – USQ

Dr Vipul Patel – Latrobe University

Enrollment: ENG4111 – EXT S1, 2021

ENG4112 – EXT S2, 2021

Project Aim: To provide a comparison of the performance of recycled aggregate concrete (RAC) in an industrial application, and allow an evaluation to be made on the viability for commercial use.

Programme: Version 1, 17th March 2021

1. Conduct initial background research on the use of recycled aggregates in fresh concrete.
2. Carry out particle size distribution analysis on the control concrete mix to inform the RAC concrete mix design.
3. Develop a suitable concrete mix design to allow comparison with commercially made fence posts.
4. Manufacture two batches of fence posts; one using standard concrete as a control sample and the other batch using recycled concrete aggregate as partial replacement for coarse aggregate.
5. Collect and test sample cylinders from each batch of concrete for material testing to Australian Standards.
6. Carry out destructive beam testing in a laboratory setting.
7. Process and evaluate experimental data.

8. Provide initial analysis on suitability of recycled aggregate use in commercial fence post production.

If time and resources permit:

9. Conduct testing at 56 days to determine any changes to concrete and post characteristics.
10. Water cure and conduct beam testing on samples from each batch of posts for comparison with air cured samples.

APPENDIX B – RISK MANAGEMENT

The risk management process seeks to identify and mitigate incidents that may have detrimental impacts on the completion of the project. The purpose is to enable a proactive approach to be taken to avoid or minimise the impact of the risks should they come to fruition. The process involves progressing through the following steps:

1. Identify possible risks to the project.

2. Assessing the likelihood of each event occurring.

3. Estimate the effect of the impact on the project deliverables should an event occur.

4. Develop a response plan to avoid or mitigate the risk occurrence or level of impact.

5. Re-rate the risk and determine if it is now at an acceptable level.

A risk assessment has been carried out and considered foreseeable events that could impact this project; the results are contained in Table D-2.

Table D-1: Risk Assessment Matrix

Likelihood		Consequence				
		Insignificant (1) No injuries/ insignificant financial loss	**Minor (2)** First aid/ minimal financial loss	**Moderate (3)** Medical treatment/ Medium financial loss	**Major (4)** Hospitalisation/ large financial loss	**Catastrophic (5)** Death/massive financial loss
	Almost Certain (5) Often occurs	**Moderate (5)**	**High (10)**	**High (15)**	**Extreme(20)**	**Extreme (25)**
	Likely (4) Could easily happen	**Moderate (4)**	**Moderate (8)**	**High (12)**	**Extreme (18)**	**Extreme (20)**
	Possible (3) Could happen	**Low (3)**	**Moderate (6)**	**Moderate (9)**	**High (12)**	**High (15)**
	Unlikely (2) Known to have happened	**Low (2)**	**Moderate (4)**	**Moderate (6)**	**Moderate (8)**	**High (10)**
	Rare (1) Possible but unlikely	**Low (1)**	**Low (2)**	**Low (3)**	**Moderate (4)**	**Moderate (5)**

Table D-2: Risk Assessment

Risk Name	Likelihood	Consequences	Risk Level	Response	Likelihood	Consequences	New Risk Level
Foreign object in the eye.	Possible (3)	Major (4)	High (12)	Wear safety goggles when mixing concrete and testing samples.	Unlikely (2)	Moderate (3)	Moderate (6)
Inhaling cement dust.	Likely (4)	Catastrophic (5)	Catastrophic (20)	Wear an appropriate dust mask when handling cement powder.	Unlikely (2)	Minor (2)	Moderate (4)
Cuts and abrasions from handling aggregates.	Possible (3)	Minor (2)	Moderate (6)	Use a shovel or scoop to handle aggregates. Wear gloves.	Rare (1)	Insignificant (1)	Low (1)
Necessary materials are not readily available.	Possible (3)	Major (4)	High (12)	Secure supplies of all materials early in the project to allow time to find alternate sources in not available locally.	Rare (1)	Moderate (3)	Moderate (4)
Equipment necessary to carry out the project is not readily available.	Possible (3)	Major (4)	High (12)	Engage with relevant people to negotiate access to post manufacturing facility and laboratories early. Utilise support of project supervisor contacts if necessary.	Unlikely (2)	Moderate (3)	Moderate (6)
Contaminants in the RA impact on the RAC performance.	Likely (4)	Moderate (3)	High (12)	RA will be graded and any contaminants removed during this stage.	Rare (1)	Insignificant (1)	Low (1)
Object falling onto feet.	Possible (3)	Moderate (3)	Moderate (9)	Wear safety boots when carrying out field or lab work.	Possible (3)	Minor (2)	Moderate (6)
Crush injury when testing samples.	Unlikely (2)	Major (4)	Moderate (8)	Ensure safety cages are in place and people are clear of the machine prior to testing.	Rare (1)	Major (4)	Moderate (4)
Covid19 disrupts the project.	Possible (3)	Major (4)	High (12)	Negotiate laboratory access in regional area to attempt to avoid metropolitan lockdown and restrictions on movements.	Unlikely (2)	Moderate (3)	Moderate (6)

APPENDIX C – TESTING MACHINE RISK ASSESSMENTS

LA TROBE UNIVERSITY Safe Operating Procedure – Civil Engineering Laboratory

Instron 5980 Test Machine – Safe Operation Guide

Pre-checks:

Before operating the machine the following pre-checks are required to be performed:

1. Ensure you have been inducted to use the test machine and have completed the relevant risk assessments.
2. Inspect cables – check that all cables are properly connected, are not a trip hazard and inspect them for damage. Do not operate if there is any damage to cables – notify the facility manager.
3. Grips, fixtures and accessories – check that each of these are free of dirt, damage and deformation. Grips, fixtures and accessories should be kept clean and wiped down after use. Do not operate if there are any issues, notify the facility manager of any deformation or cleanliness issues.
4. Check the load frame is level – the load frame should be placed in such a position that the frame is sturdy and level. If you notice any problems with the frame contact the laboratory manager.
5. General housekeeping – inspect the work area around the machine and make sure it is clean, tidy and clear of any hazards.

After performing the above checks, correct any problems before operating the machine. For assistance please contact the facilities manager.

Risk Assessment

Hazard	Risk Matrix Rating	Safety Controls	Remaining Risk Rating
Electrical hazard Damaged electrical cables pose risk of electrocution.	Medium (Moderate, Unlikely)	Before turning the machine on, inspect the cables for damage and do not operate equipment if cables are found to be damaged. Switch off power to the system while doing any maintenance work or moving the machine.	Low
Crush Hazard The moving crosshead poses a risk of crushing. Falling heavy specimens and machine parts.	Low (Medium, Likely)	Users must keep clear of the test area when the machine is in motion. Take care when installing and removing specimens. Set the crosshead stop limits accordingly. Steel capped boots should be worn.	Low
Rotating machinery hazard	Low (Medium, Unlikely)	The machine has rotating ball-screws on either side of the load frame. The screws are covered to prevent risk, hence the machine should not be operated if the covers are damaged or absent. In addition, loose clothing and jewellery should be avoided and long hair should be kept tied back.	Low
Ejected particles/Flying debris hazard When the test specimen fails, it may eject particles.	Significant (Moderate, Possible)	Users and those in the test area should wear eye protection. Test area guards or covers should also be placed around the machine during operating when using hazardous test specimens. Make sure test specimen is installed correctly.	Low

Unexpected crosshead movement	Low (Medium, Unlikely)	The limit stops should be positioned accordingly before each test to protect the operator against any unexpected crosshead movement. The limits for the transducer should be set prior to operating.	Low
Pinch Points	Medium (Minimal, Likely)	To prevent pinching of fingers and skin, gloves should be worn when loading test pieces and installing the grips.	Low
Overloading	Medium (Minimal, Likely)	The tensile strength of the test specimen should not exceed the maximum loading capacity of the grips. The limits for the transducer should be set prior to operating.	Low
Slippage of specimen	Low (Minimal, Possible)	The specimen should be gripped by at least 75% of the available jaw face length. Always use serrated jaw faces. The crosshead limit stops prevent the upper and lower grips from colliding so as to not damage them. Ensure these are correctly positioned. In the event of an emergency, the emergency stop button should be used. The button will immediately stop the crosshead and should only be used because of an unsafe condition.	Low
Slips, Trips and Falls	Medium (Medium, Likely)	Ensure good housekeeping by keeping the floor around the work area of the machine clean. Remove tools and other items, secure loose cables and maintain general cleanliness of the floor area.	Low

Health & Safety Risk Matrix

The Consequence is the physical outcome of the hazard, including injury or illness to people and damage to equipment.

CONSEQUENCE	EXAMPLE
Catastrophic	Numerous fatalities, irrecoverable property damage and productivity
Major	Approximately one single fatality, major property damage if hazard is realised
Moderate	Serious non-fatal injury, permanent disability
Medium	Disabling but not permanent injury
Minimal	Minor abrasions, bruises, cuts, first aid type injury

The Likelihood can be described as follows:

LIKELIHOOD	EXAMPLE
Almost certain	Has happened, or could occur soon
Likely	Could easily happen
Possible	Could happen, and has either occurred before or could occur within a year or so
Unlikely	Has not been known to occur after many years of exposure
Rare	Exceptionally unlikely, even in the longer term

Risk Prioritisation Chart

DESCRIPTION	ACTION
HIGH to EXTREME	A high or extreme risk requires **immediate** action to control the hazard as detailed in the hierarchy of controls, or the activity involving the hazard must cease.
MEDIUM to SIGNIFICANT	A medium or significant risk should be immediately controlled in the first instance. If this is not possible, temporary controls should be implemented and a planned approach be taken to control the hazard.
LOW	A risk identified as low may be considered as acceptable and further reduction may not be necessary. However, if the risk can be resolved quickly and efficiently, control measures should be implemented and recorded.

Risk Rating Matrix

	Consequence				
Likelihood	Minimal	Medium	Moderate	Major	Catastrophic
Rare	Low	Low	Medium	Significant	Significant
Unlikely	Low	Low	Medium	Significant	High
Possible	Low	Medium	Significant	High	High
Likely	Medium	Medium	Significant	High	Extreme
Almost certain	Medium	Significant	High	Extreme	Extreme

Matest Compression Test Machine– Safe Operators Guide

Pre-checks:

Before operating the machine the following pre-checks are required to be performed:

1. Ensure all the components are in good working order and check there are no damaged or defective parts.
2. Ensure the area around the machine is clean and free of any trip or slip hazards.
3. Check the power lead for damage. Do not operate if power lead is damaged.

After performing the above checks, correct any problems before operating the machine. For assistance please contact the facilities manager.

Risk Assessment

Hazard	Risk Matrix Rating	Safety Controls	Remaining Risk Rating
Crush Hazard	Low (Medium, Likely)	Users must keep clear of the test area when the machine is in motion. Know the locations of the crush zones and take care when installing and removing specimens. Safety screens around the crushing zone are to be used when operating. In the event of an emergency press the red emergency stop button. Steel capped boots should be worn.	Low
Ejected particles/Flying debris hazard When the test specimen fails, it may eject particles.	Significant (Moderate, Possible)	Users and those in the test area should wear eye protection. The safety screens should be in place during testing. Make sure test specimen is installed correctly.	Low
Pinch Points	Medium (Minimal, Likely)	To prevent pinching of fingers and skin, gloves should be worn when loading test pieces. Be aware of potential pinch points.	Low
Slips, Trips and Falls	Medium (Medium, Likely)	Ensure good housekeeping by keeping the floor around the work area of the machine clean. Remove tools and other items, secure loose cables and maintain general cleanliness of the floor area.	Low
Manual Handling	Medium (Medium, Possible)	Never lift weights you are uncomfortable lifting. Avoid lifting in excess of 20kg alone,	Low

		seek assistance when lifting heavy items. Use the correct lifting method by bending the knees and lifting with the knees. Avoid using your back.	
Electric shock	Low (Medium, Unlikely)	Before operating the machine, inspect the power lead for damage. Never operate the machine if the lead is damaged.	Low

Health & Safety Risk Matrix

The Consequence is the physical outcome of the hazard, including injury or illness to people and damage to equipment.

CONSEQUENCE	EXAMPLE
Catastrophic	Numerous fatalities, irrecoverable property damage and productivity
Major	Approximately one single fatality, major property damage if hazard is realised
Moderate	Serious non-fatal injury, permanent disability
Medium	Disabling but not permanent injury
Minimal	Minor abrasions, bruises, cuts, first aid type injury.

The Likelihood can be described as follows:

LIKELIHOOD	EXAMPLE
Almost certain	Has happened, or could occur soon
Likely	Could easily happen
Possible	Could happen, and has either occurred before or could occur within a year or so
Unlikely	Has not been known to occur after many years of exposure
Rare	Exceptionally unlikely, even in the longer term

Risk Prioritisation Chart

DESCRIPTION	ACTION
HIGH to EXTREME	A high or extreme risk requires **immediate** action to control the hazard as detailed in the hierarchy of controls, or the activity involving the hazard must cease.
MEDIUM to SIGNIFICANT	A medium or significant risk should be immediately controlled in the first instance. If this is not possible, temporary controls should be implemented and a planned approach be taken to control the hazard.
LOW	A risk identified as low may be considered as acceptable and further reduction may not be necessary. However, if the risk can be resolved quickly and efficiently, control measures should be implemented and recorded.

Risk Rating Matrix

	Consequence				
Likelihood	Minimal	Medium	Moderate	Major	Catastrophic
Rare	Low	Low	Medium	Significant	Significant
Unlikely	Low	Low	Medium	Significant	High
Possible	Low	Medium	Significant	High	High
Likely	Medium	Medium	Significant	High	Extreme
Almost certain	Medium	Significant	High	Extreme	Extreme

APPENDIX D – MATERIAL TEST REPORT

Material Test Report

Report Number: S144-21-1
Issue Number: 1
Date Issued: 07/04/2021
Client: Allstone Quarries
Wimmera Highway, Newbridge Vic 3551
Contact: Kelvin Nicholson
Project Number: S144-21
Project Name: 10/14mm Aggregate
Project Location: Newbridge
Work Request: 458
Sample Number: 21-458A
Date Sampled: 07/04/2021
Dates Tested: 07/04/2021 - 07/04/2021
Sampling Method: AS 1141.3.1 9.4 - Sampling aided by power equipment - other than backblading method
Specification: 10/14 mm Aggregate
Sample Location: **Newbridge**
Material: Basalt
Material Source: East Face

ALLSTONE ASQ QUARRIES

Allstone Quaries Pty Ltd
Newbridge Laboratory
Wimmera Highway Newbridge Victoria 3551
Phone: (03) 5435 2092
Email: lab@asq.net.au

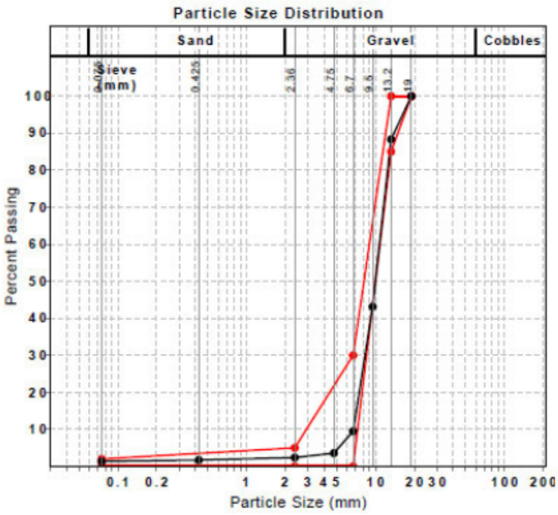
NATA WORLD RECOGNISED ACCREDITATION

Accredited for compliance with ISO/IEC 17025 - Testing

[redacted]

Approved Signatory: Nathan Catherwood
Laboratory Technician
NATA Accredited Laboratory Number: 16908

Particle Size Distribution (AS1141.11.1)						
Sample Washing	Sample was Washed					
Sieve	Passed %	Passing Limits		Retained %	Retained Limits	
19 mm	**100**	100	100	0		
13.2 mm	**88**	85	100	12		
9.5 mm	**43**			45		
6.7 mm	**9**	0	30	34		
4.75 mm	**4**			6		
2.36 mm	**2**	0	5	1		
0.425 mm	**2**			1		
0.075 mm	**1**	0	2	0		



Appendix E – Experimental Data

Table E-1: Compressive Strength Analysis Data

Sample	Weight (kg)	Height (mm)	Ave Diameter (mm)	Failure Load (kN)	Compressive Strength (MPa)
NA - 1	4.196	208.0	101.65	207.558	25.576
NA – 2	4.238	206.5	102.05	259.459	31.721
NA – 3	4.169	207.0	101.55	269.518	33.277
RA – 1	4.085	206.5	101.50	266.826	32.977
RA – 2	4.115	207.0	101.65	252.800	31.151
RA – 3	4.087	206.5	101.75	245.244	30.161
NAS – 1	4.097	206.5	101.85	208.409	25.580
NAS – 2	4.116	206.5	101.60	205.953	25.403
RAS – 1	3.997	207.5	101.70	145.412	17.901
RAS – 2	4.020	206.0	101.80	201.372	24.741

Table E-2: Splitting Tensile Strength Analysis Data

Sample	Weight (kg)	Height (mm)	Ave Diameter (mm)	Failure Load (kN)	Tensile Strength (MPa)
NA - 1	4.208	207.0	101.8	126.303	3.818
NA – 2	4.193	207.0	101.5	139.939	4.240
NA – 3	4.197	207.5	101.5	132.059	3.992
RA – 1	4.107	207.5	101.6	103.43	3.125
RA – 2	4.113	207.0	101.5	126.209	3.824
RA – 3	4.124	206.5	101.5	125.732	3.821

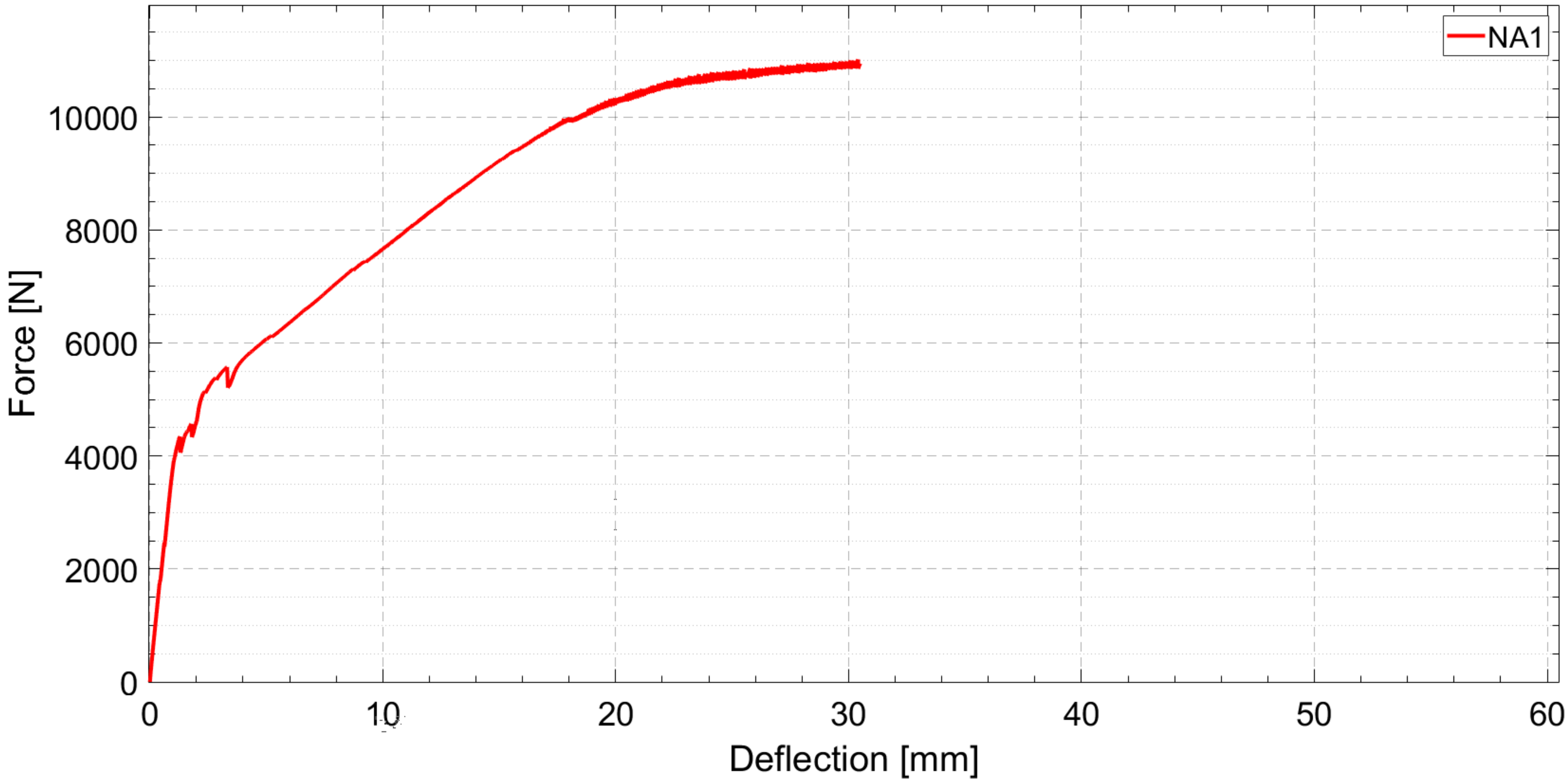


Figure E.1: NA1 Data Retrieved from the Test Machine

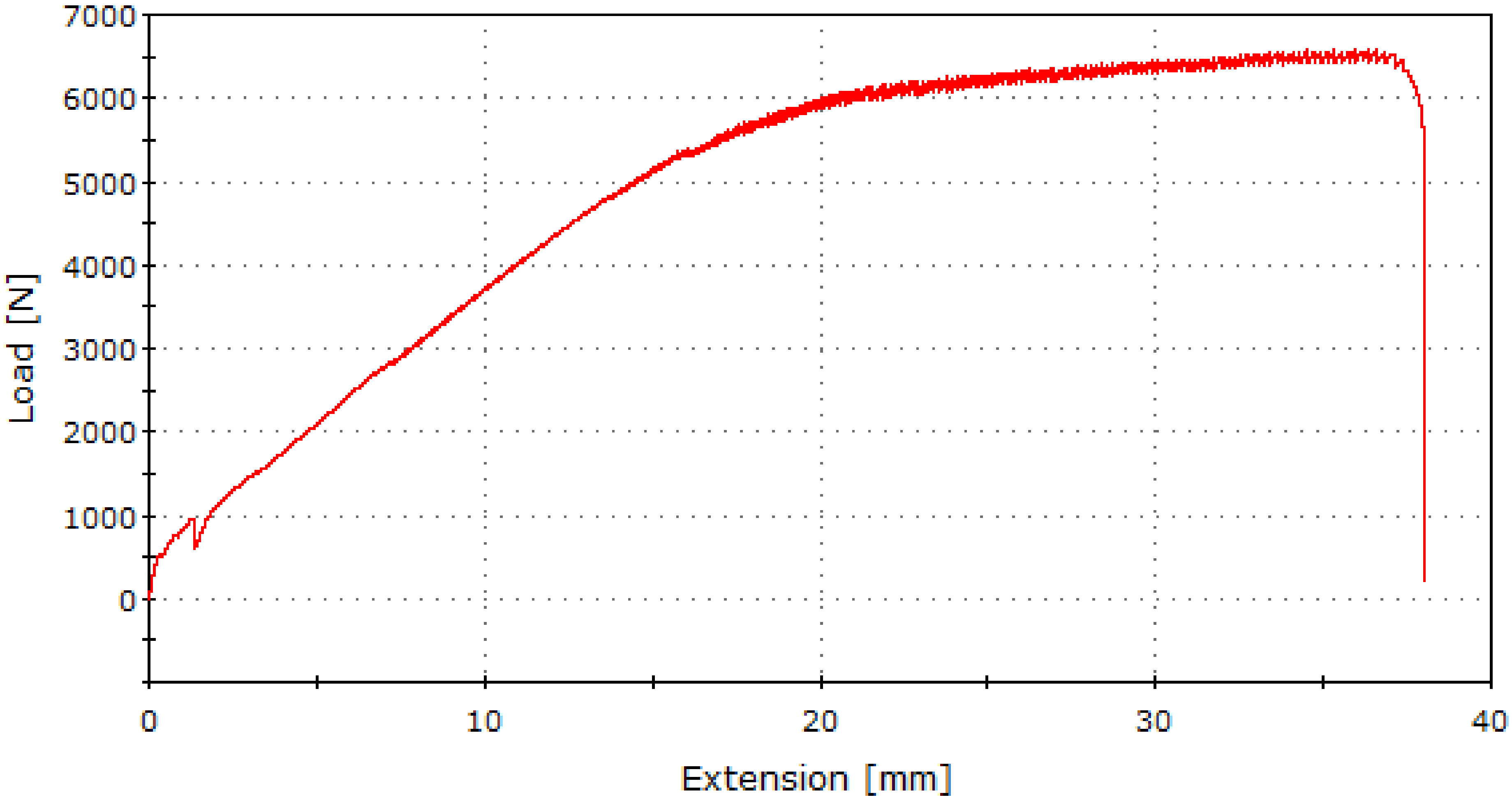


Figure E.2: NA1 Graph Retrieved from the Test Machine that was used for Data Digitisation

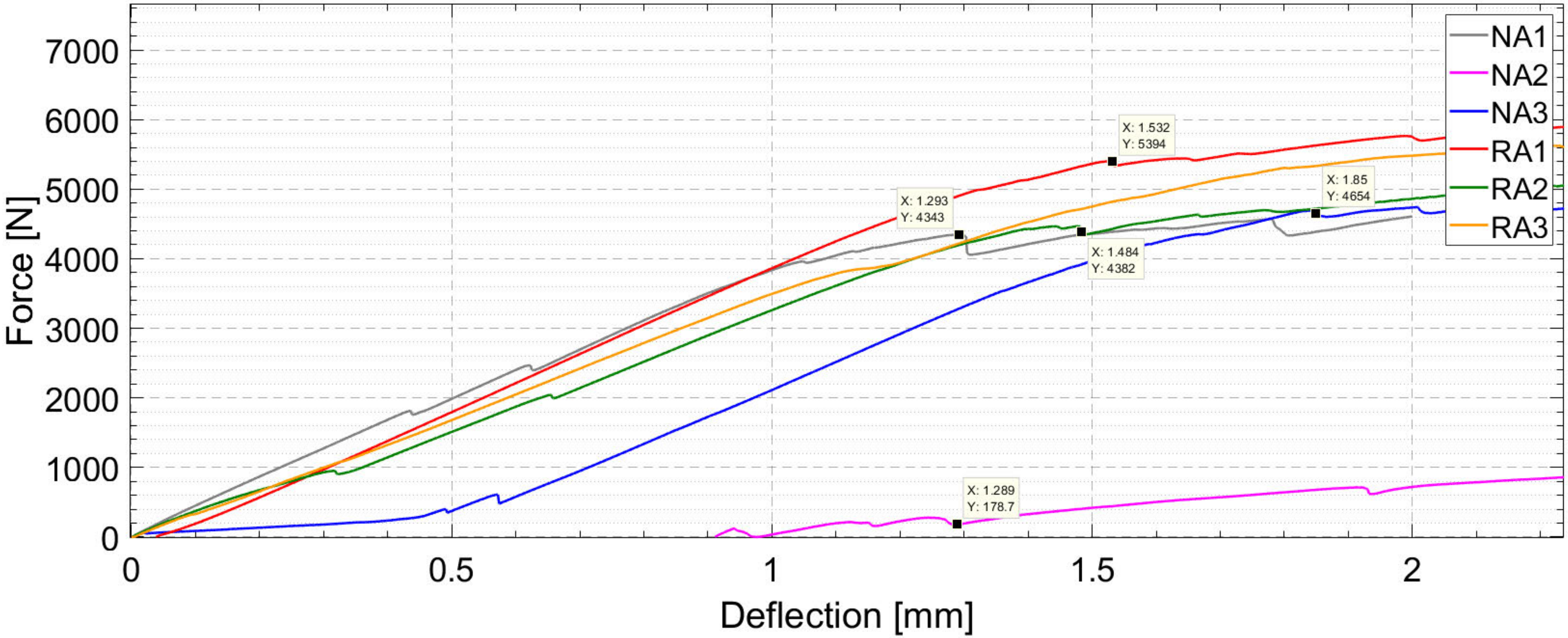


Figure E.3: Cracking Moment Data Points

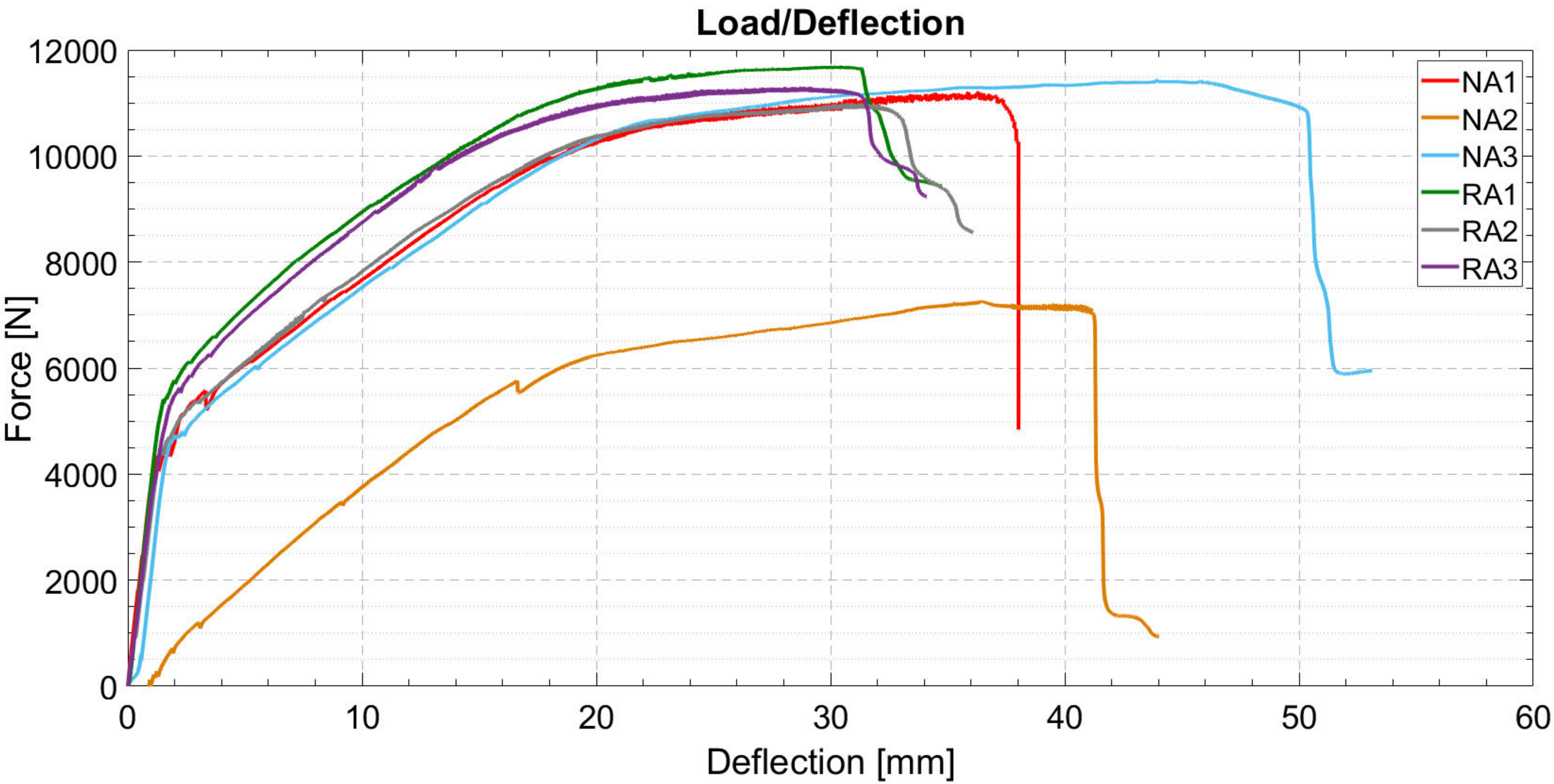


Figure E.4: Comparison of all Flexural Tests

Appendix F – Consequences and Ethics

This project seeks to improve the knowledge of the performance of recycled concrete and therefore provide another avenue for reuse of demolition material, diverting it from being deposited into landfill.

Successful testing results may lead to the concrete post manufacturer utilising a portion of RA within their standard concrete mixtures. Successful companies actively look at ways to reduce costs and improve their environmental credentials.

For economic viability it is likely that the concrete for recycling will need to be processed close to its point of use. This will lead to reduced number of heavy vehicle trips to transport materials which has benefits both for the road network through reduced fatigue but also environmental benefits through reduced emissions.

This may lead to an increase in mobile crushing plants and the associated noise and dust that accompanies the crushing process. As noted by Wijayasundara et al. (2017), the ultrafine particle produced from concrete crushing are considered more hazardous than those from NA production, which may lead to public health risks if processing plants are located near population centers.

Reducing quarry activities for the production of NA will result in less damage to the natural environment through clearing of vegetation and loss of habitat.

Engineers Australia's Code of Ethics (the Code) details the key values and principles that guide decision making within the engineering profession to help ensure that when a choice presents itself, a 'good' decision is made (Hartley 2010).

The Code outlines four key principles for engineering practice:

1. Demonstrate integrity.
2. Practise competently.
3. Exercise leadership.
4. Promote sustainability (Engineers Australia 2019).

While previous work conducted by other researchers has contributed to this project, it has been properly recognised and any results, conclusions and recommendations from this project are the result of author's own work. Testing has been carried out in controlled laboratory settings under the guidance of experienced professionals to ensure the veracity of the resulting data.

While the author is carrying out this project within their field of study, guidance has been sought from relevant professionals to assist in carrying out this project in so far as determining what testing to carry out, assisting with correct aggregate grading procedures and conducting specialised concrete testing. Collection and interpretation of data will be carried out by the author and any conclusions and/or recommendations drawn will be their own work.

This project seeks to identify a sustainable outcome considering both the environmental and economic benefits of using RA. The aim is that this will support the provision of sustainable building materials to help balance the needs of future generations, and at the same time reducing environmental impacts associated with quarrying natural aggregates.

While successful testing is desirable, this project has been carried out without bias and seeks only to objectively evaluate the performance of concrete utilising a replacement percentage of RA. Project integrity is paramount and the work throughout has been conducted in good faith and within the author's ability and knowledge base.

Appendix G — Project Plan

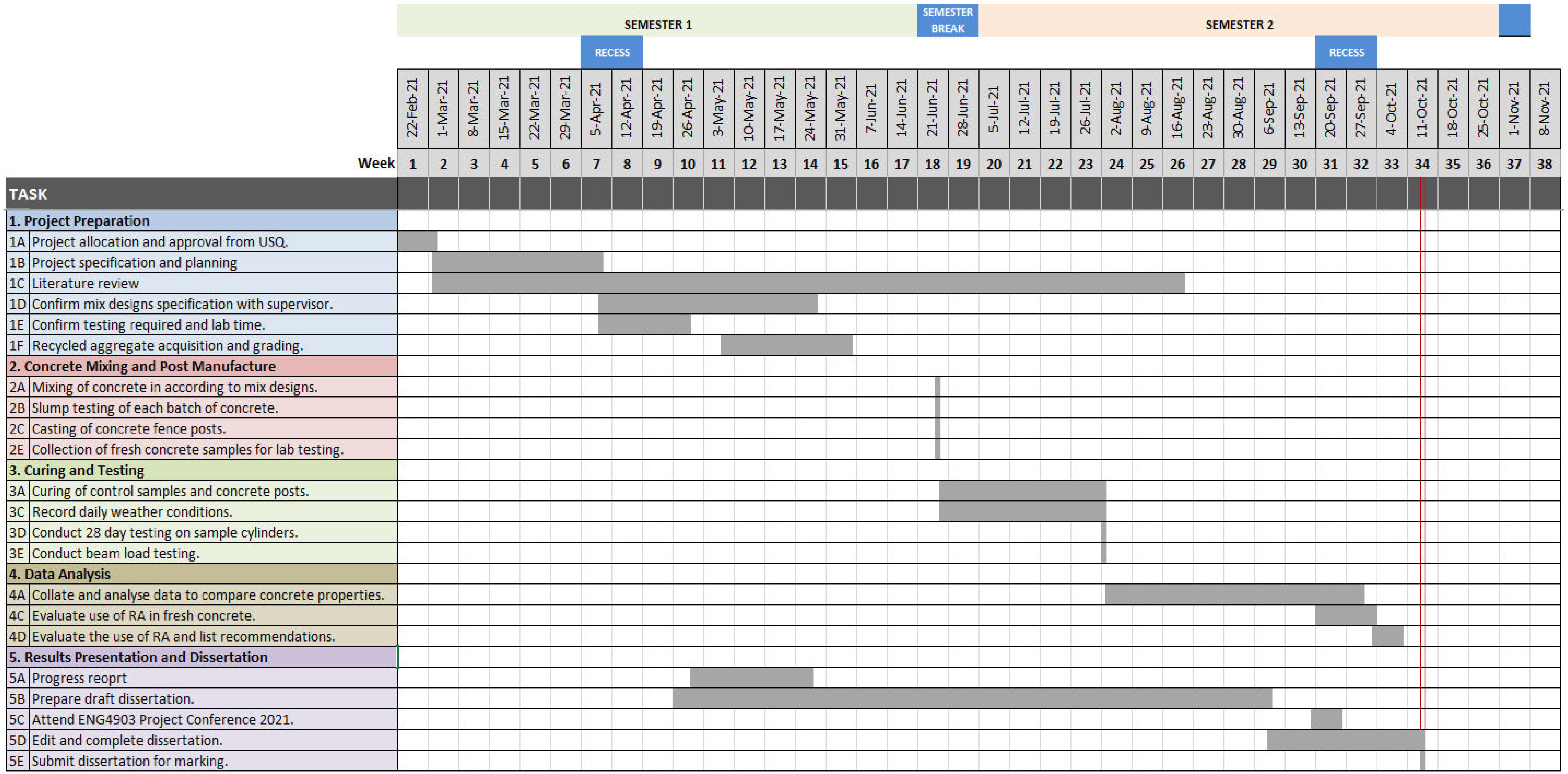


Figure G.1: Project Plan