Faculty of Engineering and the Built Environment

CIVL4660 Final Year Project - Semester 2

Experimental Investigation of the Effect of Pre-Soaking and Screening on the Mechanical Properties of Concrete Utilising Recycled Concrete Aggregate

[redacted]

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Executive Summary

Currently, recycled aggregates are only used in lower grade applications due to the major reason of their high porosity and consequently high water absorption. If recycled aggregates were remained untreated and then utilised in higher grade concrete applications, they would significantly weaken the concrete qualities, barely achieving a fraction of the required mechanical strength that is needed for the successful use of the concrete.

In this experimental study, the fresh and hardened mechanical properties of concrete have been investigated by substituting Natural Aggregate (NA) with Recycled Aggregate (RA). Due to the relatively high porosity and therefore high water absorption of RAs, surface treatment options have been considered to improve this and therefore ultimately improve the fresh and hardened mechanical properties of the concrete they are utilised in.

The surface treatment options that have been considered previously throughout past literature have been found to not be environmentally friendly and/or far too expensive to be industrially viable long term solutions. However, due to the lack of prior investigation into the combined effects of the RA surface treatment methods of pre-soaking and screening, the utilisation of these relatively environmentally friendly, cost effective and potentially industrially viable surface treatment methods has formed the basis of this experimental investigation.

It has been found in this study that the quality of the fresh and hardened mechanical properties of the concrete utilising RA were directly related to where the source of the RA materials came from. With the newer recycled aggregate material clearly exhibiting similar mechanical strength to the concrete control concrete sample, whereas the full 100% replacement of the older RA material did not achieve anywhere near the design values needed for satisfactory high grade use.

The combined effect of the surface treatment methods of pre-soaking and screening was found to be quite successful and to potentially be a sustainable industrially viable solution, however it is recommended that more study is undertaken into this specific field. As the very limited research that has been previously conducted has not allowed for very significant comparisons to be made between the results of this experimental investigation.

Acknowledgements

I'd like to pay special thanks to Dr. Patrick Tang for being willing to share with me his vast knowledge on recycled aggregates in concrete, and his overall guidance and support throughout this course. It has made this final year project one of the most interesting and enjoyable experiences I've had throughout my entire degree.

I'd also like to say a big thankyou especially to Dylan, Qian and Ian, for their unbelievable help with the hours and hours of extensive lab work we all had to endure together over this semester. I couldn't have asked for better people to do it with and couldn't have done it without you guys.

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1. Introduction

In the last decade there has been a massive growth in the development of concrete infrastructures all around the world. As a result of this increased demand, the construction industry has been consuming natural resources and conducting more reparation and demolition works than ever before in order to successfully meet the much larger needs of modern day construction. Therefore to accommodate for this increased consumption rate, more quarries have required to be implemented and due to the larger amounts of construction waste being generated, increased means of waste management have been needed, thus overall being at a negative impact on the environment. For these reasons, the incorporation of Recycled Aggregates (RA) into concrete products, particularly higher grade structural applications, would be a significant achievement not only from an industry point of view, but for the preservation of the environment as a whole.

1.1 Background

In order to maximise natural rock and promote environmental sustainability, RAs are mainly produced from recycled demolition materials which include recycled concrete, brick and masonry (Boral, 2019). RAs are generally a versatile material, although currently being only suitable for lower grade applications such as for use in low strength concrete, base and subbase for road pavement, asphalt production, structural fill and as drainage backfill material. This is due to the attached mortar and other surface additives that are commonly found on the surface of RA from their source of demolition, consequently exhibiting relatively high porosity, making concrete utilising RA not suitable for higher grade usage.

During the curing process of concrete utilising RA, higher amounts of water are absorbed into the surface of the aggregate, greatly increasing the moisture content of the RA as a result. This becomes a major issue when a specific water to cement ratio is wished to be achieved in concrete, as this ratio is of the upmost importance to achieve reliable strength values with higher grades of concrete. Due to the high water absorption of RA, the fresh and hardened mechanical properties of concrete utilising RA are detrimentally affected, with the workability of the concrete significantly decreased and the compressive and tensile strength of the hardened concrete demonstrating considerably lower limits than what would be achieved when utilising NA instead. (Abhiram & Saravanakumar, 2015)

It has been previously studied that the surface treatment of RA can be effective in nullifying the negative impacts that RA has on concrete when it's utilised as a replacement for NA. Ultimately improving the fresh and hardened mechanical properties of concrete and potentially successfully achieving the strength required for higher grade structural applications.

However, currently there are no industrially viable solutions to successfully utilise RA in concrete. Aggregate surface treatments such as silicate coatings, in particular lithium silicate, have been investigated and deemed impractical for industrial use, as they are far too expensive to implement and are not environmentally friendly as they cannot be readily and safely disposed of. Other RA surface treatments that have also been considered infeasible for industrial use are nitric dissolution, freeze thawing and thermal expansion.

The alternate RA surface treatments of pre-soaking and screening are therefore of very high interest for investigation, as there has been a very limited amount of research into the combination of these two surface treatments on the properties of concrete utilising RA.

1.2 Research Gap

Prior research has been conducted into various RA surface treatments trying to resolve the inevitably poor properties exhibited in concrete utilising RA. There is currently no industrially viable solution as to using RA, due to the reasons outlined in Section 1.1. For this reason, the influence of the combination of the surface treatment methods pre-soaking and screening on RA has been of extremely high interest for investigation.

This experimental investigation will therefore analyse the influence of this particular combination of RA surface treatment methods on the fresh and hardened mechanical properties of concrete utilising RA.

1.3 Project Overview

1.3.1 Project aims

The aims of this experimental investigation are to successfully investigate the effects of pre-soaking and screening on the mechanical properties of concrete utilising RA and to find an industrially viable method in which recycled concrete can actually be used in high grade structural applications.

1.3.2 Key objectives

The key objectives for this experimental investigation are:

- Investigate the influence of the complete replacement of recycled aggregate in concrete;
- Study the influence of the combination of pre-soaking and screening on the fresh properties of concrete utilising RA; and
- Study the influence of the combination of pre-soaking and screening on the mechanical properties of hardened concrete utilising RA.

1.3.3 Research significance

Through the investigation of the combined effect of pre-soaking and screening on RAs, it is intended that this research will help improve concrete material recyclability. Ultimately assisting in finding an environmentally friendly and industrially viable solution of overcoming the critically high water absorption exhibited by highly porous RAs. This research will showcase the workability and strengths that concrete utilising RAs can achieve, in order to potentially encourage their increased utilisation in higher grade structural concrete applications in the future.

1.3.4 Project scope

The scope of this experimental investigation is to analyse the impacts of the combined RA surface treatments of pre-soaking and screening on the fresh and hardened mechanical properties of concrete utilising RA. Providing sound recommendations regarding to these particular treatment methods being viable for industrial implementation.

1.4 Report Outline

Each of the sections of this report are outlined below:

- Section 2 – A literature review, introducing the reader to the context of RA and the surface treatments that have previously been investigated.
- Section 3 – A description of the methodology adopted to analyse the fresh and hardened mechanical properties of concrete utilising RA.
- Section 4 – Analysis and discussion of the results of the experimental investigation.
- Section 5 – Conclusion of the findings gathered throughout the investigation.
- Section 6 – Recommendations for the successful industrial implementation of RA.

2. Literature Review

2.1 Recycled Concrete Aggregate

2.1.1 Overview

Recycled Aggregates are obtained from the crushing and recycling of demolition waste materials, mainly concrete, although sometimes including bricks and masonry. This demolition waste is converted into a sellable RA product via a screening process that sieves the crushed materials into specified sizes (namely 10mm and 20mm), where they are then stockpiled for basic size and quality control. For RAs to be used as a new component of another concrete mixture, a thorough understanding of the properties of the aggregates is needed, as they greatly differ from the properties exhibited by NAs and are likely to be detrimental to the overall strength of the concrete.

The main difference of RA from NA is the quantity of cement mortar still maintained on the surface of the aggregate after it is obtained from the crushing of the recycled construction demolition materials. Figure 2.1.1 illustrates the typical cement mortar that is attached to the grains of RA (Malesev, et al., 2014).

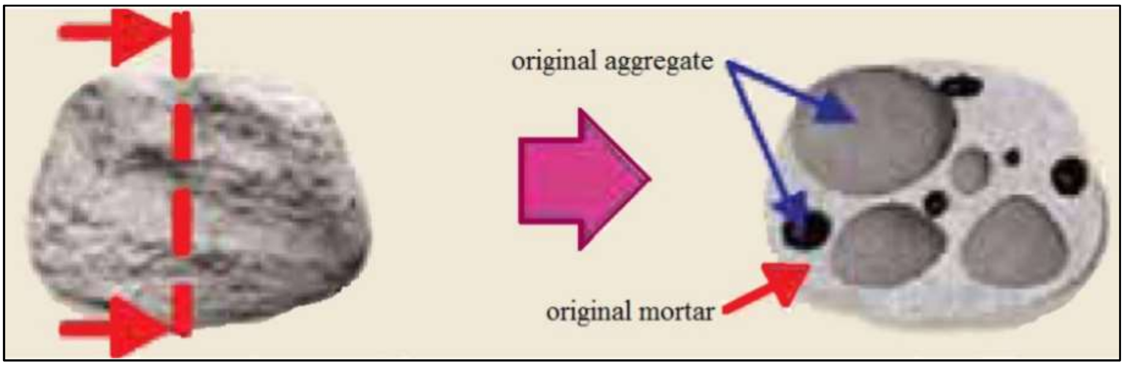

Figure 2.1.1 Typical cement mortar attached to RA grains

It can be seen from the gross depiction in Figure 2.1.1 that the original aggregates are surrounded by a matrix of highly porous cement mortar. Due to the methods undertaken to create RAs from recycled materials, this relative abundance of mortar varies widely depending on the location of where the construction waste materials were actually sourced. This variability adds to the unreliability and inconsistent performance of concrete when RA is utilised instead of NA.

2.1.2 Recycled coarse aggregate (RCA)

According to AS 2758.1, RCAs are defined as aggregates having a nominal size greater than or equal to 5mm (Standards Australia, 2014). Coarse aggregates generally take up around 40% of the total mass of a concrete mix.

RCAs are generally the major attributors to the high water absorption of RA as a whole, as most of the residual cement mortar attaches itself more easily to the larger coarse aggregates rather than the fine aggregates. This attribute has been previously found to greatly reduce the overall compressive and tensile strength of concrete utilising RA, as well as greatly decreasing the workability of the fresh concrete (Broadbent, 2017). Hence is the reason for the implementation of RA surface treatments, in order to try and resolve this major RCA issue.

2.1.3 Recycled fine aggregate (RFA)

RFAs are defined as having a nominal size less than 5mm (Standards Australia, 2014). Fine aggregates generally take up around 25% of the total mass of a concrete mix.

The major problem with RFAs are the way they are created, as RFAs are generally RCAs crushed to a much finer material. As a consequence of this, RFAs commonly consist of residual cement and fly ash particles which could potentially act as cementitious components to a concrete mix and increase the strength of the concrete. However as a result of this, the RFAs would therefore not satisfy their intended purpose of being a finer structural matrix for the additional cementitious material to bind to, thus remaining incredibly porous and being an overall detriment to the fresh and hardened mechanical properties of the recycled concrete.

It however has been previously found that the influence of the utilisation of RFA in concrete does not negatively impact the overall strength of the concrete, with the properties of recycled RFA concrete being similar to that of concrete utilising NA. It has also been found that the overall durability of RFAs are just as good as those exhibited by natural fine aggregates (Zega & Di Maio, 2011). Therefore, it could be said that the complete replacement of RFA into concrete could already potentially be a solution implemented in industry to successfully achieve higher grade structural concrete while also utilising otherwise wasted finer recycled materials.

2.1.4 Current applications and limitations

2.1.4.1 Applications

Recycled Aggregates are a very versatile material, currently being applied in a broad range of areas within the construction industry. However, they're only suitable for lower grade applications due to their high porosity, as discussed previously. Examples of the applications that RAs are being used for, according to Concrush, are:

- Drainage backfill material;
- Pipe bedding, side & haunch material;
- General fill material;
- Concrete slab, driveway and footpath bedding material;
- Pavement bedding material;
- Structural fill material; and
- Base and subbase for road pavement (Concrush, 2019).

2.1.4.2 Limitations

There are various limitations associated with RA when utilised in concrete. Mainly the workability of the fresh concrete and the compressive and tensile strength of the hardened concrete being significantly lower than that of concrete utilising NA at the same water to cement ratio, therefore restricting its usage to only lower grade non-structural applications, as outlined previously. The most effective method of improving the fresh and hardened mechanical properties of recycled concrete has been found to reduce the amount of mortar attached to the RA particles, currently achieved via the surface treatment method of screening.

Another potential solution for this limitation could be to implement a moisture correction to the concrete mix design, to possibly resolve the inconsistencies experienced with the water to cement ratios and ultimately improve both the workability and mechanical properties of concrete utilising RA.

2.1.5 Benefits

As outlined in Section 1, the growing construction industry and its increased usage of natural resources has been negatively impacting the environment. Mainly through the increased amount of quarries needing to be implemented and consequently, the amount of landfill sites required to accommodate for the increased construction demolition works.

The major benefit of RAs is that they have been proven to be environmentally friendly and very economically beneficial when utilised in concrete instead of NA, as they are essentially enabling the re-use of otherwise wasted materials into concrete applications, reducing the overall dependence on NA sources for modern day construction (Mack, et al., 2018). Thus having a positive influence on the environment.

Through just the partial utilisation of RA in concrete, it has also been found that the overall production cost can be saved by up to 60% and the total energy consumption saved by up to 58%. Resulting in the overall carbon footprint from production being reduced by up to 65% (Hossain, et al., 2016). Therefore it is of a great benefit to utilise RA in concrete applications.

2.2 Physical Properties of RA

2.2.1 Surface texture and shape of RA particles

In terms of morphological structure, RA is far less suitable than NA for use in concrete applications, as the excess old mortar and other surface additives commonly found on RAs are highly porous (Olorunsogo & Padayachee, 2002) and usually relatively less dense than the actual aggregate itself. These additives consequently make the shapes of the RA grains irregular and angular shaped, exhibiting cracked and thus porous surfaces. The prominence of these surface additives on the RAs is directly related to where the recycled waste was sourced from prior to production as well as how the aggregates were actually produced (the type of crusher, screening, sieving, grading and other processing procedures).

2.2.2 High water absorption

Water absorption is the characteristic by which RA differs the most from NA. The reason for this is that the additional cement mortar attached to RA is significantly porous and thus the water absorption experienced by RA is significantly larger. To successfully utilise RA within concrete products, the water absorption capacity of the RA must be known prior to the mixing of the concrete to ensure the appropriate water to cement ratio is achieved. Table 2.2.1 effectively compares RCA with NA, to better illustrate the differences in physical properties such as water absorption, specific gravity and bulk density between the two (Patil, et al., 2013).

Table 2.2.1 Physical properties of NA and RCA

No.	Physical Property	NA	RCA
1	Water Absorption (%)	1.56	6.4
2	Specific Gravity	2.63	2.3
3	Bulk Density (kg/m^3)	1469.8	1325.93

As can be seen, the water absorption is significantly higher in the RCA sample, at 6.4% which is quadruple that of the 1.56% experienced in the NA. However, the specific gravity and overall bulk density of the RCA are both lower than that of the NA. This large variation in water absorption capacity essentially means that RA cannot easily be used in industry, as the exact water absorption is not able to be effectively controlled by contractors and is thus unreliable to achieve the required water to cement ratios in higher grade concrete.

However, a potential way to resolve this issue (which is being investigated in this report) is to implement the surface treatment method of pre-soaking on the RA and then account for this additional water prior to mixing via a moisture correction. This would be done to ensure that the required water to cement ratio is ultimately maintained for each specific concrete mix.

2.3 Properties of Concrete Utilising RA

2.3.1 Fresh properties

2.3.1.1 Workability

The workability of concrete is the property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished (The Constructor - Civil Engineering Home, 2019). The water to cement ratio of concrete has a very significant effect on the workability of concrete, as they are directly proportional to one another, with an increase in water to cement ratio increasing the workability accordingly.

The poor characteristics of RA grains generally negatively impact the water to cement ratio and thus the workability of fresh recycled concrete. It has been found that the complete replacement of RA in concrete has a detrimental effect on the workability, whereas the replacement of up to 20% RFA has been proven to have no considerable effect on the workability (Kisku, et al., 2016).

The slump test is one of the most commonly used methods of measuring the basic workability of a concrete mix, and is therefore the method that was used during this experimental investigation for its ease of implementation. In a previous study, the slump measurements of NA concrete were found to be higher than that of 100% replaced RCA concrete which had the least slump. The low slump in the RCA100 concrete was deemed to be caused by the high absorption of water during the mixing process (Patil, et al., 2013).

2.3.1.2 Air content

The application of RAs in concrete has been found to have no considerable effect on the amount of air entrapped in fresh recycled concrete. Previous investigations have discovered that the amount of entrapped air is only up to a value of 1% in recycled concrete, which can be considered as negligible (Malesev, et al., 2014).

2.3.2 Hardened mechanical properties

2.3.2.1 Compressive strength

The compressive strength of concrete utilising RA is directly reliant on the quality of the RA and the amount of mortar still attached to the RA surface, which contributes to high water absorption and thus lower strength, as discussed previously. With the increased replacement of RA in concrete, generally the compression strength achieved is decreased. Recycled concrete also generally exhibits lower densities than naturally sourced concrete, from the porous nature of the RA, adding to the reasoning behind its poorer compressive strength.

It has been found that up to 50% replacement of RCA in concrete is satisfactory to confidently achieve a medium concrete grade of 30MPa (Patil, et al., 2013). Patil also found that the compressive strength of recycled concrete is directly related to the quality of where the aggregates are sourced from, meaning that it is entirely possible to achieve the required strength properties in recycled concrete for higher grade applications if the aggregates are sourced from decent quality construction materials.

2.3.2.2 Tensile strength

Tensile strength for recycled concrete does not significantly depend on the type and amount of applied RA in the concrete mix (Malesev, et al., 2014). But if a specific verdict were to be made, the increased implementation of RA in concrete was found to slightly decrease the tensile strength.

2.3.2.3 Tensile to compression strength ratio

The overall tensile to compressive strength ratios of various RA replacement amounts in recycled concrete have been found to be slightly lower than the ratios exhibited by concrete utilising NA (Malesev, et al., 2014).

2.4 Surface Treatment Methods for RA

Surface treatment methods are the most promising solution for improving the negative properties of RA to permit their successful utilisation in higher grades of concrete. Previous studies have investigated the effects of surface additive removal, lithium silicate coating, screening and pre-soaking methods on the properties of RA concrete. However as explained in Section 1.2, the combination of pre-soaking and screening has not been extensively investigated.

2.4.1 Surface additive removal

There are multiple RA surface additive removal methods that have been previously studied to effectively reduce the cement mortar content on RAs, with the most common methods being; mechanical beneficiation, thermal beneficiation and acid corrosion beneficiation.

2.4.1.1 Mechanical beneficiation

The mechanical beneficiation method essentially involves the surface additives on RAs being separated via both abrasive and impact forces applied on the RAs through either an eccentric shaft rotor or through mechanical grinding. The mechanical grinding method has been chosen as the preferred method for analysis in this literature review as it is the relatively more efficient of the two mechanical methods.

Mechanical grinding separates the additional cement mortar from the aggregates using a large drum containing iron balls and basically rotating the drum and tumbling the balls around to grind off the adhered mortar. Generally, the greater the amount of drum rotations, the greater the amount of mortar that is removed. However, with the greater the amount of rotations, there is the increased likelihood that some of the aggregates themselves will encounter surface cracking thus lowering the overall yield strength of the aggregates (Despotovic, 2016).

Mechanical grinding was also found to have multiple disadvantages, with the method consuming considerably high amounts of energy (therefore being very expensive) and creating a large amount of noise pollution, as well as creating a significant amount of hazardous fine cementitious dust as waste during the process. Therefore it can be seen how this method is deemed infeasible for broad industrial implementation.

However, the mechanical grinding method is relatively easy to implement and has been found to be generally more efficient than other treatment methods.

2.4.1.2 Thermal beneficiation

The thermal beneficiation method essentially involves the heating of the RAs to temperatures of around 400^{o}C, where the difference in the thermal expansion rate between the cement mortar and the aggregate is exploited, basically detaching the weaker cement mortar from the aggregate grains. The heated RA samples are then transferred to an abrasion apparatus and sieved to physically separate the RAs from the cement mortar. This treatment process is better illustrated in Figure 2.4.1 (Shima, et al., 2005).

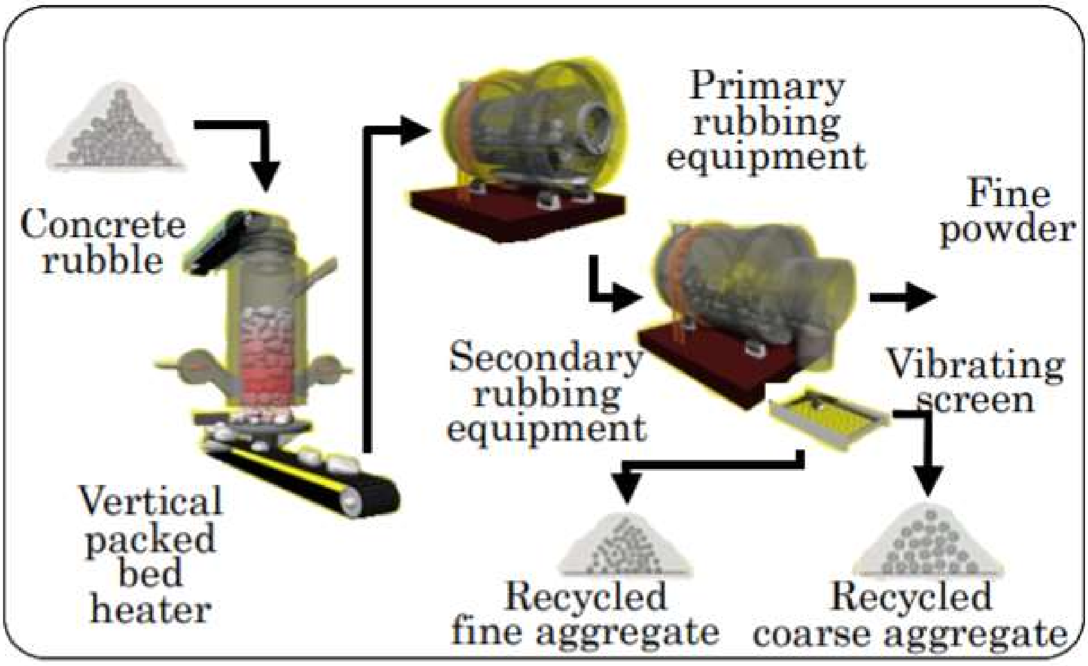

Figure 2.4.1 Thermal beneficiation process

The quality of RAs utilising thermal beneficiation treatment is significantly increased in comparison to other methods. However, it has been found that if the RAs are overheated, the RAs can potentially undergo degradation, resulting in an overall loss in mass of RA post treatment. Further disadvantages of this method include its even higher energy consumption and its very lengthy treatment durations, thus making it unsuitable for broad industrial implementation.

2.4.1.3 Acid corrosion beneficiation

The acid corrosion beneficiation method involves the exploitation of the very alkaline nature of cementitious materials, which are commonly adhered onto the surface of RAs, and separating them via the use of acidic corrosion. This is essentially achieved by soaking the RAs in a chosen acidic solution for approximately 24 hours to corrode the adhered cement mortar and detach it from the surface of the RAs. After which the RAs are then washed and submerged in water for a further 24 hours where they are then sieved to physically separate the corroded cement mortar from the aggregates. It has been found previously that hydrochloric acid (HCL) and sulphuric acid (H_2SO_4) are the most appropriate acidic solutions to remove the highest amounts of unnecessary cement mortar off the RA surfaces (Tam, et al., 2007).

This surface treatment method has been found to consist of various significant disadvantages which disapprove of its feasibility as a potential industrially implemented solution. The major disadvantage is that although increased acid concentration generally results in increased mortar removal, the higher the acid concentration comes the increased amount of chloride and/or sulphate by-products that are induced into the remaining RAs. From which as a result, negatively impact the durability of the final concrete product when the RAs are utilised as replacements for NAs. Due to the aggregates themselves reacting with these by-products, potentially lowering the yield strength of the individual RAs and/or potentially causing the premature corrosion of steel reinforcement, thus being detrimental to the durability of the recycled concrete as a whole.

Overall this treatment method has been found to be far too time consuming to be successfully used in industry, as well as being too expensive and not environmentally friendly. This method also poses large concerns for the health and safety of workers that have to handle these hazardous chemicals, if they were to be used commercially, therefore contributing to its further infeasibility as a treatment option.

2.4.2 Lithium silicate surface coating

Lithium silicate is a compound most commonly used as a sealant agent for concrete and has been determined through previous investigations to be one of the more favourable RA surface coating compounds. The lithium silicate surface treatment process generally consists of immersing the RAs in lithium silicate solution for a period of time, allowing the lithium silicate to soak into the relatively porous RAs and essentially induce a hydration reaction with the free calcium found within the adhered cement mortar on the RA surface. This reaction then creates an insoluble calcium silica hydrate solution which basically fills most of the RA pores, essentially decreasing the overall water absorption capacity exhibited by the RAs.

However, the lithium silicate surface coating method has been deemed to be not environmentally friendly and far too expensive to be successfully implemented in industry.

2.4.3 Screening

The surface treatment method of screening consists of the RAs being fed into a screening machine, shown in Figure 2.4.2, essentially undergoing different degrees of separation depending on the amount of times they're fed back into the machine.

Figure 2.4.2 Screening machine

The RA material is separated by passing through a vibrating 'screen box' which consists of various sized screens (meshes) which act like a sieve for the RA material to fall through. The different sized RAs are then transported along conveyor belts which lead to stockpiles of the different sized final products (Aggregate Screens & Crushers, 2019). To conduct more rounds of screening on the RA samples, the stockpiled material is simply fed back through the screening machine to attain twice (or more) screened RAs.

An investigation has been conducted by Concrush to see the amount of RA mass that is lost after different amounts of screening have been undertaken. The results for 4500kg of 10mm RA are shown in Table 2.4.1 (Concrush, 2019).

Table 2.4.1 Mass loss due to screening for 4500kg of 10mm RA

No. of Times Screened	Total Loss in Mass (kg)
0	0
1	350
2	250
3	150
4	50

As is illustrated in Table 2.4.1, for each time the RAs are screened there is a loss in mass. It can be seen that with the increased amount of times screened there is a slight decrease in the amount of mass lost. Where the question can be asked – Is screening four times really worth it for this minimal loss in mass?

Screening is already used in industry to achieve better mechanical properties for RAs utilised in lower grade concrete applications. Therefore in this experimental investigation the effect that the increased amount of screening has on a higher grade of concrete, when RAs are utilised instead of NAs, will be explored further.

2.4.4 Pre-soaking

Water absorption is much higher in RA, as has been discussed previously, greatly affecting the consistency of the water to cement ratio of concrete when RA is utilised instead of NA. Pre-soaking is a great surface treatment method to resolve this.

Pre-soaking involves the RAs being submersed in water for a specific amount of time prior to mixing. 3 to 5min has been found to be the optimal amount of time of submersion, as any longer than this and the water absorption of the RA plateaus out, as can be seen in Figure 2.4.3 (García-González, et al., 2014). Which is clearly not efficient for mass production, if pre-soaking were to be implemented in industry.

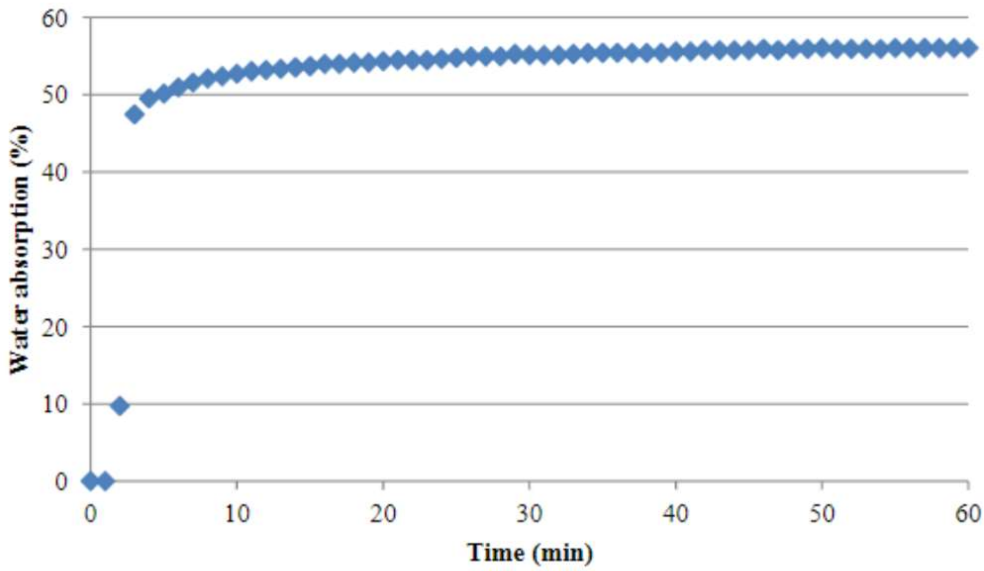

Figure 2.4.3 % of water absorption during first hour of pre-soaking

Pre-soaking the RAs essentially fills the voids created by the porous adhered cement mortar on the surface of the aggregates with water, so when being utilised in concrete, the RA's ability to absorb water is significantly decreased therefore allowing better control of the water to cement ratio to be achieved. However it should be noted that as a result of this surface treatment, if the same unchanged amount of water is added to the concrete mix, the water to cement ratio will be incorrect. Therefore it is essential that a moisture correction also be conducted during mixing, to effectively account for the excess water pre-soaked into the RAs, in order to achieve the required water to cement ratio for the mix.

Pre-soaking is one of the more effective, environmentally friendly and cost effective methods of RA surface treatment, hence why it is of great interest for further study. Especially its combined effect with the surface treatment of screening, which essentially forms the basis of this experimental investigation.

3. Methodology

3.1 Overview

For this experimental investigation, Concrush supplied the RCA and RFA samples, with the RCAs being only at a grade of 10mm (as 20mm RCA was not available for use). A particle size distribution (PSD) for each of the aggregates was conducted and aggregate crushing value tests were conducted on all of the coarse aggregates. Both fresh property and hardened mechanical property tests were also conducted on the concrete samples, with the fresh property tests including; air entrapment content and workability testing; and the hardened mechanical property tests including; compression strength testing and tensile strength testing.

3.2 Concrete Sample Preparation

3.2.1 Aggregates

Since 20mm RCA was not available for use, 10mm RCA was used to replace both the 10mm and 20mm NA in the concrete mixes. This was deemed absolutely necessary as it would provide the most accurate simulation of the effect that RA replacement has on the properties of concrete. Also, an initial PSD was conducted on the RAs, and it was found that the RFAs resembled the PSD exhibited from the natural coarse sand, but not the natural fine sand (see Section 4.1.1). Therefore when replacing with RFA in the concrete mix, it was deemed that only the natural coarse sand was necessary to be replaced as this would provide a more accurate simulation of RFA replacement.

3.2.2 Mix details

For this investigation, an unidentified commercial concrete supplier provided the concrete mix details for 1m^3 of high grade 50MPa concrete, which was used as the control mix comparison for all concrete testing. From these supplied mix proportions, it was noticed that fly ash was utilised in addition to cement to form the total cementitious material for the concrete mix, and water reducer was utilised as the preferred admixture to achieve the desired grade of 50MPa.

To achieve this high grade of 50MPa concrete, the water to cement ratio was specified to be held constant at 0.39 with the water reducer dosage rate at 350mL per 100kg of cement, and the slump to range between 80 to 100mm. The mix details for all 10 of the concrete mixes (0.041m^3) for this investigation are shown in Table 3.2.1.

Table 3.2.1 Mix details

No.	Mix Code	Cement (kg)	Fly Ash (kg)	20mm NA (kg)	10mm NA (kg)	RCA (kg)	Coarse Sand (kg)	Fine Sand (kg)	RFA (kg)	Water (kg)	Water Reducer (kg)
1	C	16.8	4.9	29.5	11.5	0.0	10.9	14.4	0.0	8.5	58.8
2	RCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8
3	RFA100	16.8	4.9	29.5	11.5	0.0	0.0	14.4	10.9	8.5	58.8
4	RCA100-RFA100	16.8	4.9	0.0	0.0	41.0	0.0	14.4	10.9	8.5	58.8
5	1SRCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8
6	2SRCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8
7	3SRCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8
8	4SRCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8
9	1SRCA100-RFA100	16.8	4.9	0.0	0.0	41.0	0.0	14.4	10.9	8.5	58.8
10	New1SRCA100	16.8	4.9	0.0	0.0	41.0	10.9	14.4	0.0	8.5	58.8

Glossary:

- C = Control
- RCA100 = 100% replaced RCA
- RFA100 = 100% replaced RFA
- RCA100-RFA100 = 100% replaced RCA & RFA
- #SRCA = No. of times RCA has been screened
- New1SRCA = Better quality 1SRCA from a higher quality waste source

Each mix supplies:

- 14 cylinders (9 for compressive strength, 3 for tensile strength, 1 for SEM, 1 for hardened concrete water absorption)
- 3 prisms (3 for shrinkage)
- 1 pot for the air entrainment device

3.2.3 Curing

The concrete samples were de-moulded 24 hours post casting and were immediately placed in a fog room for curing in accordance to AS1012.8.1, which is where they remained until they were required to be used for their specific form of concrete testing. The 14 typical concrete cylinders attained from each mix, post de-moulding, can be seen in Figure 3.2.1.

Figure 3.2.1 Concrete control mix cylinders

The standard dimensions of the concrete cylinders are 200mm in height and 100mm diameter.

3.2.4 RA pre-soaking

The RA pre-soaking method undertaken for this investigation essentially involved the submersing of the RAs in water for 3min, with them then poured out into a sieve to allow the excess water to drain off the aggregates. This process is illustrated below in Figure 3.2.2.

Figure 3.2.2 Pre-soaking process

As can be seen in Table 3.2.1, the amount of water used in each of the mixes is constant at 8.5kg, which is ultimately incorrect as pre-soaking introduces additional water, as previously discussed in Section 2.4.4. Therefore to achieve the desired water to cement ratio of 0.39 for each concrete mix, a moisture correction was conducted after pre-soaking to account for the increased moisture content exhibited by the RAs.

It is suggested by Standards Australia that saturated surface dry (SSD) should be achieved for all aggregates being used in concrete. SSD generally means that the aggregate itself is at a point where it cannot absorb any more water, thus SSD is the state at which all NAs are initially at and where RAs are ideally meant to be, prior to mixing. In order to achieve SSD for the RAs, the pre-soaking method as shown in Figure 3.2.2, was implemented to achieve a close enough state to SSD for the RAs.

3.3 Particle Size Distribution

PSDs of the RAs were undertaken in accordance with AS1141.11.1, using the sieve aperture sizes as outlined in Table 3.3.1.

Table 3.3.1 PSD sieve aperture sizes for each aggregate type

Aggregate Type	Mass Analysed (g)	Sieve Aperture Sizes (mm)
Fine Sand	309.34	2.36, 1.18, 0.425, 0.3, 0.15, 0.075
Coarse Sand	329.30	"
20mm NA	3237.00	26.5, 19.0, 13.2, 9.5, 6.7, 4.75, 2.36, 1.18
10mm NA	503.24	13.2, 9.5, 6.7, 4.25, 2.36, 1.18
RFA	300.46	2.36, 1.18, 0.425, 0.3, 0.15, 0.075
RCA	1893.40	9.5, 6.7, 4.25, 2.36, 1.18, 0.6, 0.425, 0.3, 0.15, 0.075
1SRCA	1937.60	"
2SRCA	1938.10	"
3SRCA	1943.70	"
4SRCA	1937.30	"
New1SRCA	502.80	13.2, 9.5, 6.7, 4.25, 2.36, 1.18

Using the sieve aperture sizes as outlined in Table 3.3.1, the percentage of mass passing through each of the sieves was calculated, to allow a PSD for each of the aggregate types to be created, shown in Section 4.1.1.

3.4 Aggregate Testing

3.4.1 Crushing value

3.4.1.1 Overview

In accordance with AS1141.21, a crushing value test was conducted on each of the course aggregates being used in this investigation. The crushing value of an aggregate is essentially the percentage of aggregate that passes through a sieve size of 2.36mm after applying a crushing force to the aggregate over a specified period of time.

3.4.1.2 Apparatus

A standard steel cylindrical measure, shown in Figure 3.4.1, was used to determine the mass of aggregate to be used for each crushing value test.

Figure 3.4.1 Standard steel cylindrical measure

A standard steel cylinder and plunger, as shown in Figure 3.4.2, were used to conduct the actual crushing value tests.

Figure 3.4.2 Standard steel cylinder and plunger

The universal testing machine (UTM), shown in Figure 3.4.3, was used to physically compress the cylinder and plunger to crush the aggregates within.

Figure 3.4.3 Universal testing machine

The UTM was used because it was able to very accurately apply the crushing force at a constant rate over the prescribed period of time. After the aggregates were finished being crushed, they were sieved, where the mass passing through the 2.36mm sieve was measured.

3.4.1.3 Procedure of portions for testing

The general procedure to determine the aggregate portions for testing is as follows:

1. Record the mass of the standard cylindrical measure.
2. Fill the standard cylindrical measure in thirds with the aggregate under analysis, compacting each third with 25 strokes of a steel tamping rod.
3. After the cylindrical measure is full and compact, scrape off the excess aggregate using the tamping rod as a straight edge.
4. Record the mass of the full standard cylindrical measure and deduce the mass (A) of the aggregate sample for testing.

3.4.1.4 Procedure for testing

The general procedure to determine the aggregate crushing value is as follows:

1. Pour the amount of aggregate, as determined in Section 3.4.1.3, straight into the steel cylinder for testing.
2. Level the surface of the aggregate and rest the plunger on top of the aggregates.
3. Place the cylinder and plunger into the UTM.
4. Apply a uniform compressive force of 40kN/min over a period of 10min to the sample.
5. Remove the sample after compression is completed. The process to achieve the final crushed aggregate product is illustrated in Figure 3.4.4.
6. Sieve the crushed material through a 2.36mm sieve and record the mass (B) that passed through the 2.36mm sieve.

Figure 3.4.4 Aggregate crushing process

3.4.1.5 Calculations

Equation 1 was used to calculate the aggregate crushing value:

Equation 1: Aggregate crushing value

$$Aggregate\ Crushing\ Value = \frac{B}{A} \cdot 100$$

Where; the aggregate crushing value is a %, B is the pre-crushed aggregate mass (g) and A is the aggregate mass that passed through the 2.36mm sieve (g).

To abide by Australian Standards, the aggregate crushing value procedure was repeated. In order for the average of the two determined values to be taken as the aggregate crushing value.

3.5 Fresh Concrete Properties Testing

3.5.1 Air Content

3.5.1.1 Overview

In accordance with AS1012.4.2, the entrapped air content of each of the concrete mixes was measured during this investigation. The air content of fresh concrete is essentially determined via a pressure gauge, which is used to measure the reduction in a pre-determined test pressure that is applied to the concrete.

3.5.1.2 Apparatus

The apparatus used to measure the entrapped air content was an air entrainment meter, shown in Figure 3.5.1.

Figure 3.5.1 Air entrainment meter

3.5.1.3 Procedure

The general procedure to determine the air content of the fresh concrete is as follows:

1. Fill the air entrainment pot with the freshly mixed concrete one third at a time, compacting the concrete with 25 strokes of a tampering rod after each third.
2. Once finished compacting the concrete, use a straight edge to level off the top of the pot and wipe clean the flanges of the pot to ensure a tight pressure seal is achieved.
3. Place on the lid of the air entrainment device and fill the space above the concrete with water, taking care to make sure all air is removed from the chamber.

4. Increase the pressure within the chamber until it corresponds exactly to the pre-determined test pressure.
5. Open the valve, wait 1min and record the pressure gauge value. This is the first determination air pressure.
6. Repeat Steps 3 to 5 by simply refilling the space with water to determine the second determination air pressure.
7. Average the two determination air pressures to calculate the apparent air pressure (A_1).

3.5.1.4 Calculations

Equation 2 was used to calculate the entrapped air content of the concrete:

Equation 2: Air content

$$A = A_1 - G$$

Where; A is the air content (%), A_1 is the apparent air content (%) and G is the aggregate correction factor (%) which is calculated in accordance with Section 9 of AS1012.4.2.

3.5.2 Workability

3.5.2.1 Overview

In accordance with AS1012.3.1, the workability of each of the concrete mixes was generally assessed via the conduction of a slump test.

3.5.2.2 Apparatus

A steel slump cone of standardised dimensions, shown in Figure 3.5.2, was used to conduct the slump tests.

Figure 3.5.2 Standard steel slump cone

3.5.2.3 Procedure

The general procedure to determine the slump and thus workability of the fresh concrete, is as follows:

1. Ensure the slump cone is made damp with water and positioned on a flat surface.
2. Whilst standing on the legs of the cone, fill the cone with concrete in one third layers, compacting each layer with 25 strokes of a tampering rod.
3. After completion of compaction use a straight edge to ensure the concrete is flush with the top of the slump cone.
4. Whilst maintaining firm downward pressure on the cone using its handles, step off the cone and slowly remove the cone in an upward motion.
5. Immediately measure the slump of the concrete using a ruler via measuring the difference between the height of the slump cone and the average height of the top surface of concrete.

3.6 Hardened Mechanical Concrete Properties Testing

3.6.1 Compressive strength

3.6.1.1 Overview

In accordance with AS1012.9, the compressive strength of each of the concrete mixes was measured at 7, 28 and 56 days of curing. The compressive strength of concrete is essentially used as a design value for engineers and designers to adhere to when utilising concrete in higher grade structural design.

3.6.1.2 Apparatus

The device used to conduct the compressive strength testing is the UTM, shown in Figure 3.4.3.

3.6.1.3 Procedure

The general procedure to determine the compressive strength of the concrete is as follows:

1. Place the concrete cylinder sample in the centre of the UTM and place the rubber capping on the rough end of the cylinder, shown in Figure 3.6.1.

Figure 3.6.1 Compressive strength testing - pre and post loading

2. Lower the compression plate flat onto the cylinder capping to achieve uniform bearing.
3. Apply a compressive force relatively slowly until failure, recording the peak force.
4. Unload and remove the concrete debris from the UTM.
5. Repeat Steps 1 to 4 for the remaining 2 cylinders for each specific duration of curing.

3.6.1.4 Calculations

Using the peak force recorded from the compressive testing and the surface area of the top of the concrete cylinders, the compressive strength of the concrete can be calculated using Equation 3.

Equation 3: Concrete compressive strength

$$f'c = \frac{P}{A}$$

Where; f'c is the concrete compressive strength (MPa), P is the peak force (N) and A is the surface area of the top of the concrete cylinder (2500π mm^2).

3.6.2 Tensile strength

3.6.2.1 Overview

In accordance with AS1012.10, the tensile strength of each of the concrete mixes was measured at 28 days of curing. Tensile strength is commonly determined via an indirect (splitting) tensile test which consists of applying a line pressure to the body of the concrete sample. Therefore this method of tensile testing was chosen to be used to determine the tensile strength of the concrete mixes.

3.6.2.2 Apparatus

The device used to conduct the indirect tensile strength testing is the UTM, shown in Figure 3.4.3. However with the cylinder to be positioned on its side, as explained in Section 3.6.2.3, with two thin wooden bearing strips placed underneath and on top of the sample to ensure a parallel line load is applied during testing.

3.6.2.3 Procedure

The general procedure to determine the tensile strength of the concrete is as follows:

1. Place the concrete cylinder sample flat on its side in the centre of the UTM and place the wooden bearing strips underneath and top of the sample, as shown in Figure 3.6.2.

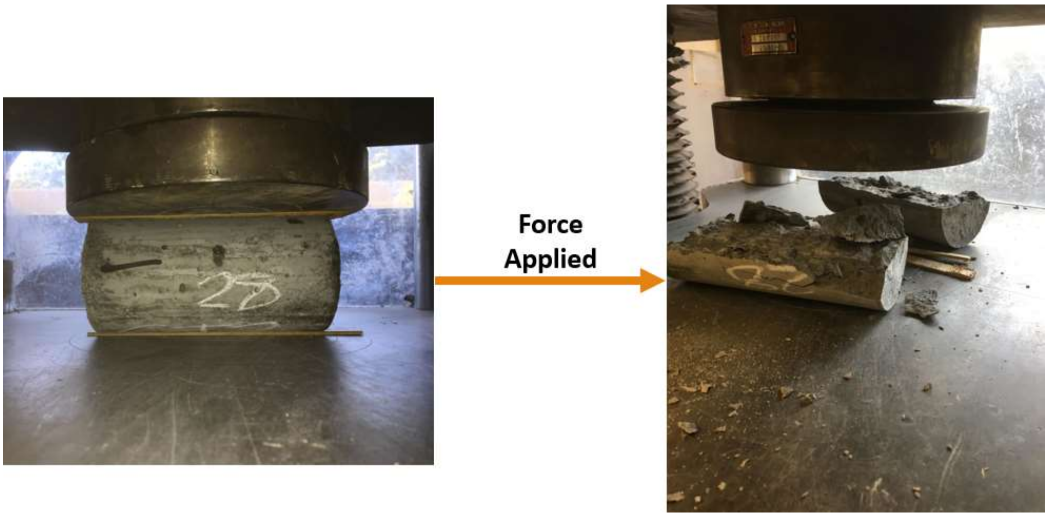

Figure 3.6.2 Indirect tensile strength testing - pre and post loading

2. Lower the compression plate flat onto the cylinder side to achieve uniform line bearing.
3. Apply a low compressive force relatively slowly until failure, recording the peak force.
4. Unload and remove the concrete debris from the UTM.
5. Repeat Steps 1 to 4 for the remaining 2 cylinders of 28 days of curing.

3.6.2.4 Calculations

Using the peak force recorded from the indirect testing and the dimensions of the concrete cylinders, the tensile strength of the concrete can be calculated using Equation 4.

Equation 4: Concrete tensile strength

$$T = \frac{2000P}{\pi LD}$$

Where; T is the concrete tensile strength (MPa), P is the peak force (kN), L is the length of the concrete cylinder (200mm) and D is the diameter of the concrete cylinder (100mm).

4. Results & Discussion

4.1 Aggregate Properties

4.1.1 Particle size distribution

In order to effectively relate the particle sizes of each of the aggregates used in this experimental investigation, a PSD was created for each aggregate and superimposed onto the same chart, shown in Figure 4.1.1, to allow for direct comparisons to be made between the aggregates.

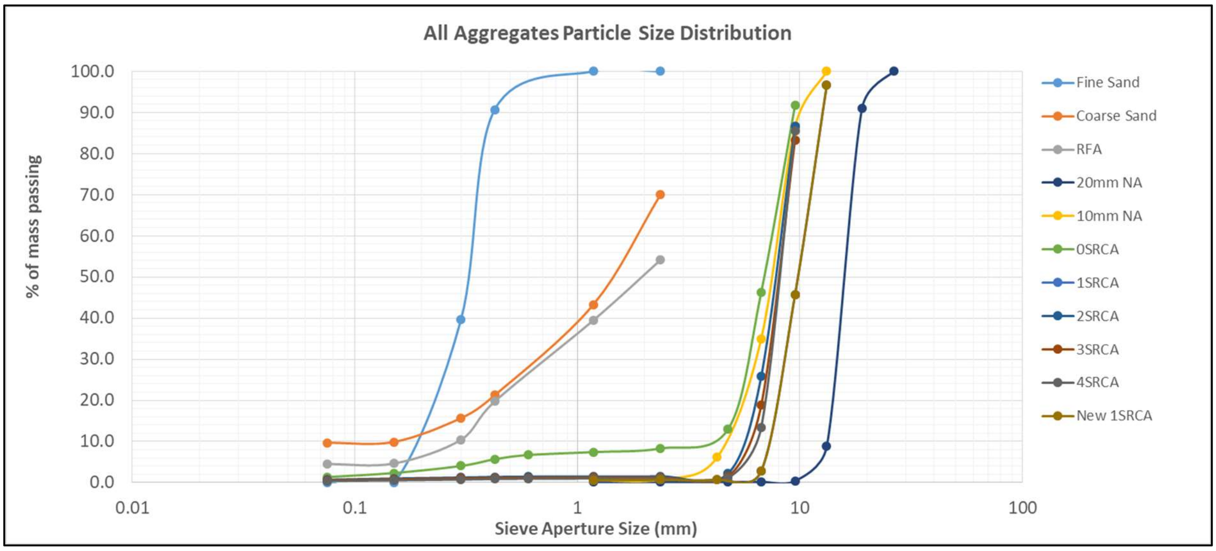

Figure 4.1.1 PSD for all aggregates

It can be seen from Figure 4.1.1 that the natural fine sand exhibits the ideal S-like pattern in its PSD, whereas the PSD for natural coarse sand and RFA are extremely similar. This similarity in PSD essentially governed the replacement amount of RFA utilised in the concrete samples, as it was deemed more accurate for testing to only replace the natural coarse sand with RFA instead of replacing both the natural coarse and fine sands.

Additionally, all the screened and unscreened 10mm RCA samples exhibited similar PSDs, where it can be depicted that the 0SRCA (RCA) contained a lot more fine particles (as the green curve is higher than the other curves) and the New1SRCA contained much better quality material (as the gold curve extends more to the right). It can also be seen from Figure 4.1.1 that the coarse aggregates, both recycled and natural, display similar PSDs as well. The 20mm NA PSD however, can be seen to be shifted slightly more to the right which is to be expected, as the majority of the 20mm NA is greater than 10mm therefore justifying why it reaches 100% of mass passing at the aperture size of 20mm.

The raw experimental data and calculations to create the PSDs can be found in Appendix A1.

4.1.2 Crushing value

The crushing value of an aggregate generally gives a very accurate representation of the amount of actual aggregate itself that physically crushes when a large load is applied. The aggregate crushing value results and their standard deviations (as error bars) are shown in Figure 4.1.2.

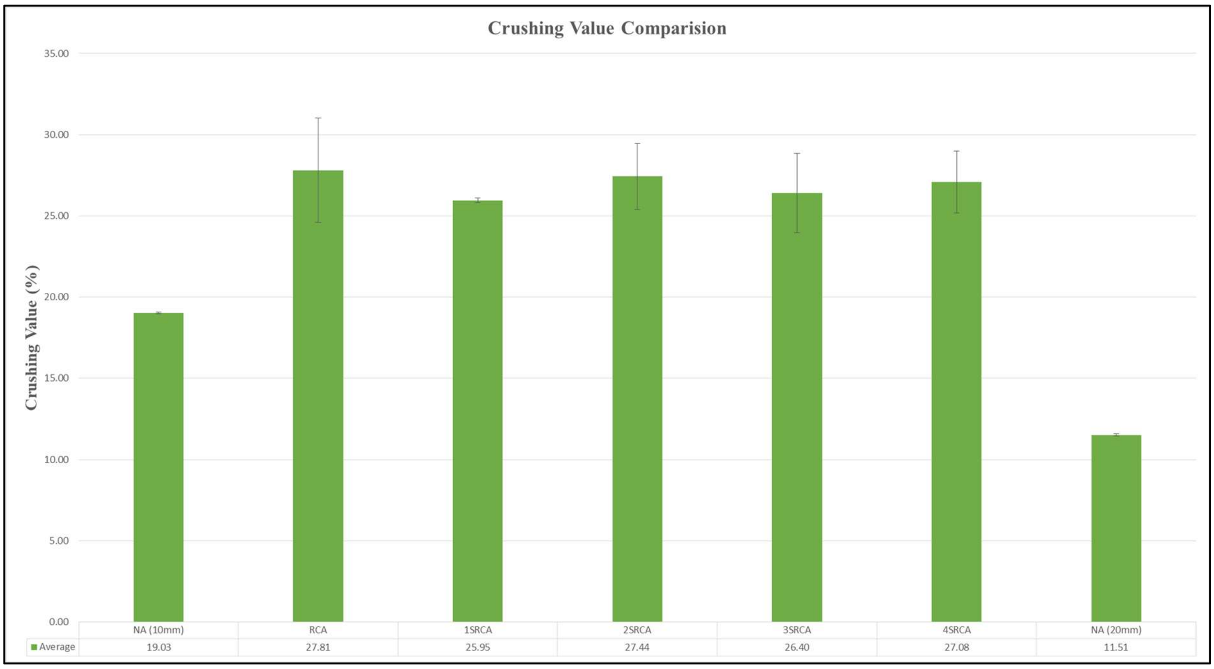

Figure 4.1.2 Crushing value for all coarse aggregates

From Figure 4.1.2 it can be clearly seen that there is a large difference between the crushing values of the RCAs and NAs, with the 10mm and 20mm NAs clearly being seen to be a lot stronger than the RCAs, as the higher the crushing value, essentially the weaker the aggregate. 20mm was found to be the strongest aggregate overall and the 0SRCA the weakest aggregate overall, which was generally to be expected. It can also be depicted that an increase in screening does not significantly affect the crushing value of the RCA, as there is no real trend amongst the screened RCA results.

In addition, utilising the full capabilities of the UTM, the crushing force applied to the aggregates was able to be plotted with respect to the position of the plunger and can be seen in Figure 4.1.3.

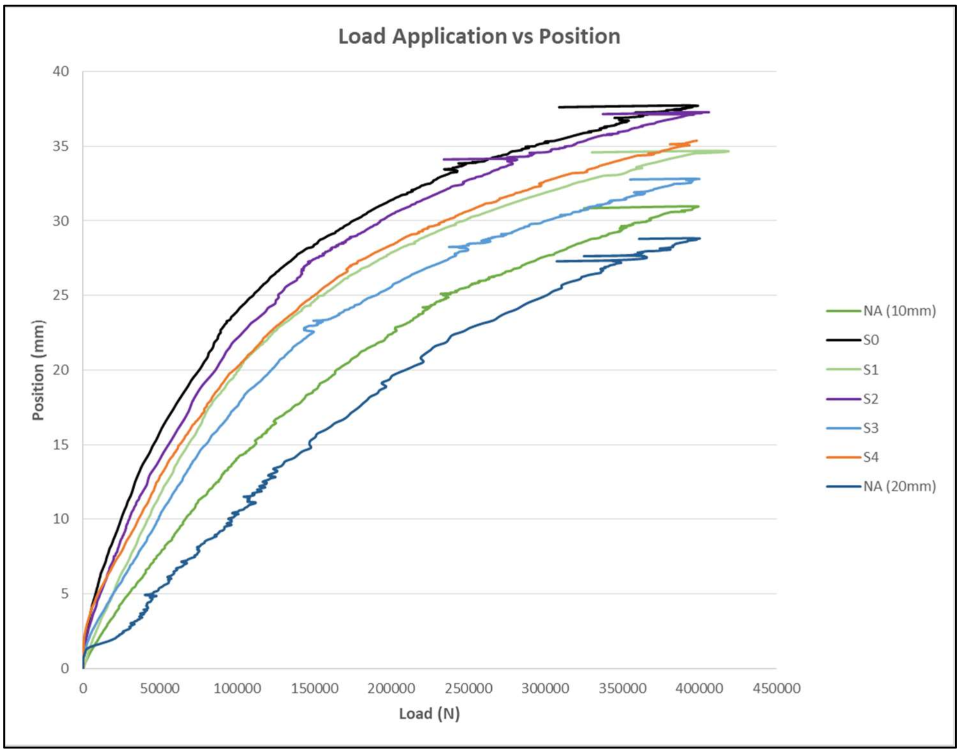

Figure 4.1.3 Applied load vs position

From this loading graph, it can be better distinguished that the unscreened RCA (0SRCA) is clearly the weakest aggregate as it displaced the most during the application of the load, whereas the strongest aggregate is clearly the 20mm NA which displaced the least during the application of the load. It still can't be depicted however the exact effect that screening has on the crushing value of RCA, but reasons for this could include; the sieving of the crushed fines post-crushing were inconsistent, or some fines may have been lost when transferring crushed materials from the steel test cylinder into the sieve.

The raw experimental data and calculations to determine the aggregate crushing values can be found in Appendix A2.

4.2 Fresh Concrete Properties

The fresh concrete properties were tested post mixing and prior to cylinder moulding, with these properties ultimately being a direct indicator as to how well the aggregates themselves have bonded with the cement constituents and thus, what the air content and workability of the concrete mix is like.

4.2.1 Air content

Using the methodology as outlined in Section 3.5.1, the entrapped air content of each of the concrete mixes was conducted, with the results as shown in Table 4.2.1.

Table 4.2.1 Air content of concrete mixes

Mix Code	A (%)
C	1.40
RCA100	1.60
RFA100	1.40
RCA100-RFA100	1.45
1SRCA100	1.60
2SRCA100	0.98
3SRCA100	0.83
4SRCA100	0.93
1SRCA100-RFA100	0.93
New1SRCA100	1.18

From these results it can be seen that the entrapped air content of the recycled concrete samples during investigation were found to have no noticeable trend in relation to the degree of RA replacement. With all concrete mixes achieving an air content measurement ranging between the small values of 0.8% to 1.6%. Therefore supporting the previous literature findings as discussed in Section 2.3.1.2, which essentially determined that no matter the RA replacement ratio within the concrete, the air content is relatively unaffected.

The raw experimental data and calculations to determine the concrete entrapped air content can be found in Appendix A3.

4.2.2 Workability

The workability of the concrete mixes was determined via a slump test, as outlined in Section 3.5.2, with the slump test measurement results shown in Table 4.2.2.

Table 4.2.2 Slump test measurements

Mix Code	Slump (mm)
C	80
RCA100	100
RFA100	100
RCA100-RFA100	100
1SRCA100	100
2SRCA100	100
3SRCA100	100
4SRCA100	100
1SRCA100-RFA100	100
New1SRCA100	100

From Table 4.2.2, all slump results were found to successfully be within the 80 to 100mm range as supplied by the unidentified commercial concrete supplier, with a consistent slump of 100mm achieved for all mixes except for the control mix, which achieved a slump of 80mm. From these results alone, it was not very clear on what effect the utilisation of RAs had on the fresh properties of concrete, however, photographs were taken of the mixes to compare with the control mix, and the RCA100 demonstrated some interesting physical properties. To better illustrate this, a comparison between the control mix and the RCA100 mix is shown in Figure 4.2.1.

Figure 4.2.1 Workability comparison between control and RCA100 samples

As can be seen in Figure 4.2.1 circled in red, there is a noticeable amount of concrete bleeding present in the RCA100 sample, which is not experienced in the control sample. This was determined to be because of the excess water in the mix being pushed to the surface of the concrete through the aid of the water reducer, whose effects on the concrete mix were slightly more noticeable in the RA concrete samples.

4.3 Hardened Mechanical Concrete Properties

4.3.1 Compressive strength

The 7, 28 and 56 day compressive strength values were calculated for 3 concrete samples of each duration of curing, for all 10 concrete mixes. With the average values being calculated and graphically represented, shown in Figure 4.3.1. The raw experimental data and calculations to determine the compressive strength of the concrete samples can be found in Appendix A4.

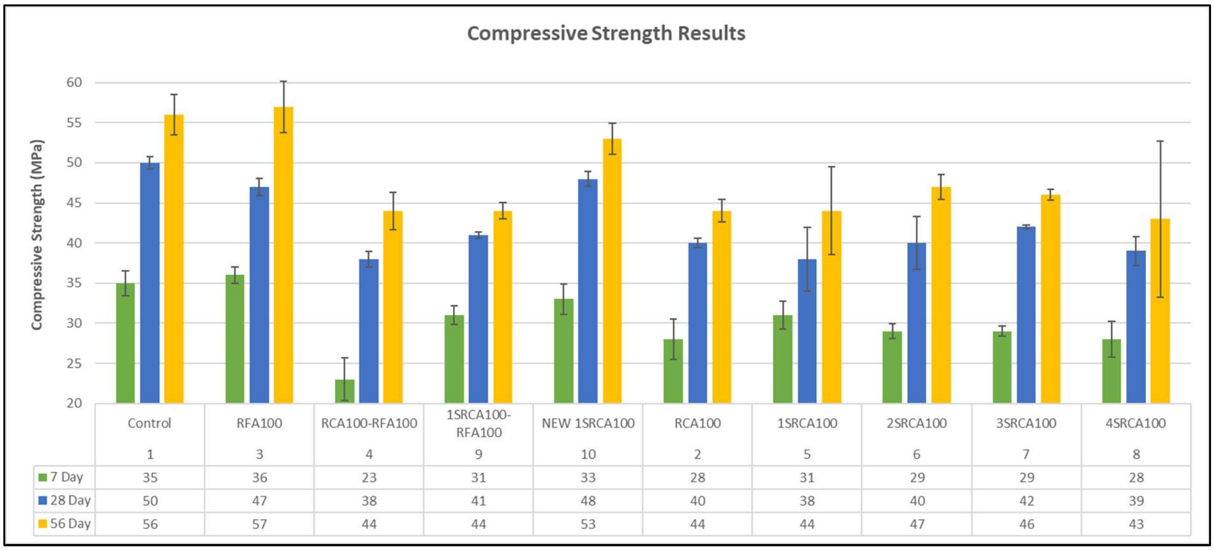

Figure 4.3.1 Compressive strength values of all concrete samples

From Figure 4.3.1 it can be seen that for every concrete mix there is a linear increase in compressive strength from 7 to 56 days, which is generally to be expected of concrete. The control mix and RFA100 mix were found to exhibit the highest compressive strengths, whereas the mix RCA100-RFA100, which was 100% replaced with RA, was found to exhibit the lowest overall compressive strength, with the 4SRCA100 mix not far behind it.

It can also be seen that the control mix was able to achieve the desired strength of 50MPa after the 28 day curing period, which was to be expected (as its exact mix proportions were supplied). However, no other concrete mix was able to successfully achieve this desired strength of 50MPa after 28 days (which is the most important curing duration, as this is what all concrete is designed for in engineering design). Except for the RFA and NewRCA100 mixes which were very close, achieving strengths of 47MPa and 48MPa respectively.

For a more direct comparison of the compressive strength results from the replacement of just RCA, an isolated view of Figure 4.3.1 was created for the control mix and RCA100 mix at 28 days, shown in Figure 4.3.2.

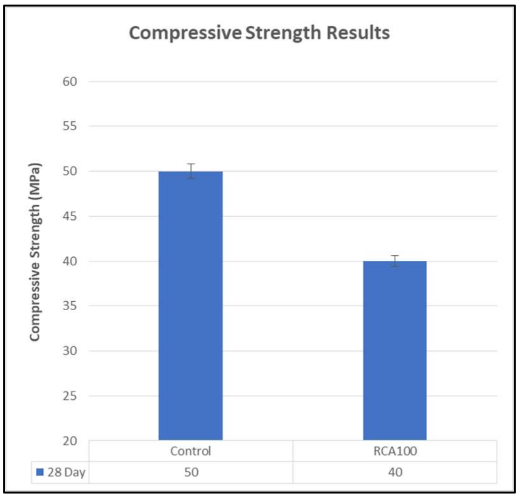

Figure 4.3.2 Effect of 100% RCA replacement on 28 day compressive strength

The effect of the 100% replacement of RCA in concrete can be clearly seen here, with the RCA100 mix being shown to only be able to achieve a maximum strength of 40MPa, which is well below the desired strength of 50MPa as exhibited by the control mix. Therefore deeming it as unacceptable.

However, when drawing the direct comparison between the control mix and the New1SRCA100 mix, shown in Figure 4.3.3, the very similar strengths that are achieved at 7, 28 and 56 days can be better visualised.

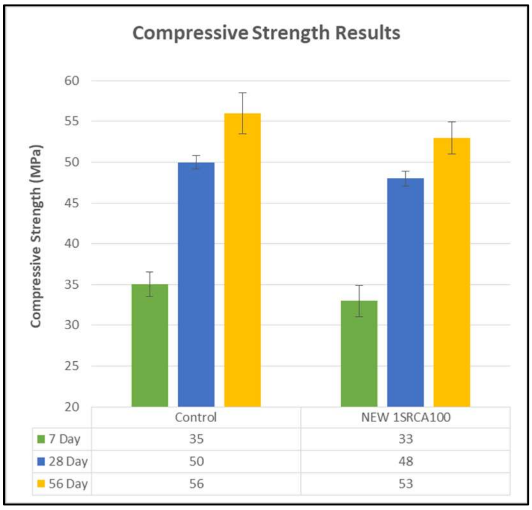

Figure 4.3.3 Effect of better quality RA on compressive strength

As can be seen in Figure 4.3.3, the New1SRCA mix almost achieves the desired 50MPa at 28 days and does in fact reach a higher strength of 53MPa after 56 days (but this is not industrially viable for use, as current engineering standards utilise the strength at 28 days for concrete design). However, one silver lining from these results is that there is a clear relation with the fact that the New1SRCA material was a newer recycled material and it achieved almost on par strengths with the control sample. The better quality material was likely sourced from a demolished highway or concrete structure, absent of the negative impacts of bricks, masonry, tiles and glass that the other RAs may have been consisted of.

For a more direct view of the implications of screening on the RAs, a localised comparison was made, shown in Figure 4.3.4.

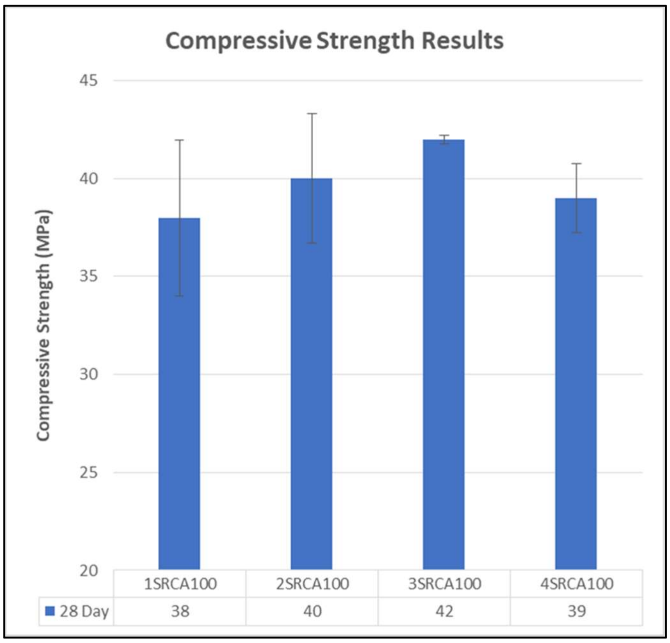

Figure 4.3.4 Effect of screening on 28 day compressive strength

From this comparison graph between the screened samples, none of the mixes were able achieve the desired 50MPa. However, it can be seen that screening does have a positive effect on the compressive strength of the recycled concrete at 28 days, up until an amount of 3 times screened, exhibiting a linear increase in strength when the amount of times screened is increased. Although, it is then noticed that the strength decreases drastically after being screened a 4th time, which suggests that the RAs become quite damaged after being excessively screened 4 times or more.

For a more direct view of the implications on the compressive strength of the complete replacement of RAs in concrete, a localised comparison was made, shown in Figure 4.3.5.

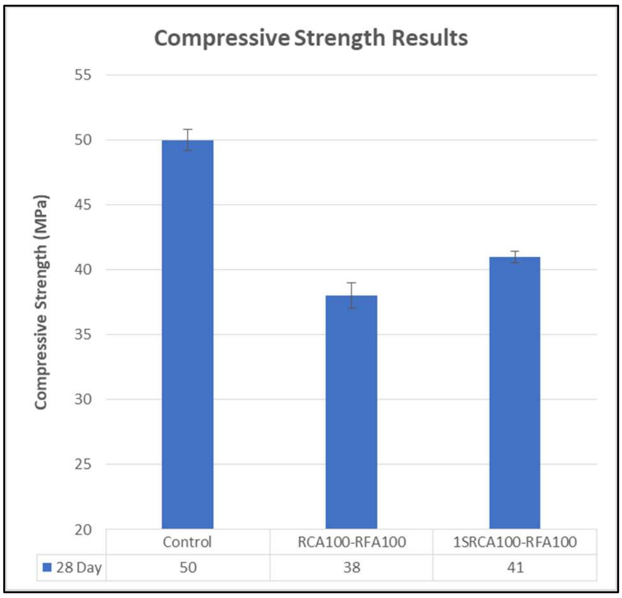

Figure 4.3.5 Effect of 100% replacement of RA on 28 day compressive strength

From Figure 4.3.5 it can be seen that both the 100% replaced RA samples achieved significantly lower compressive strengths than the control sample. However, it can be distinguished that screening the RCA once did in fact improve the compressive strength of the 100% recycled concrete.

4.3.2 Tensile strength

The 28 day tensile strength was calculated for 3 concrete samples of each of the 10 concrete mixes. With the values then being graphically represented, shown in Figure 4.3.6.

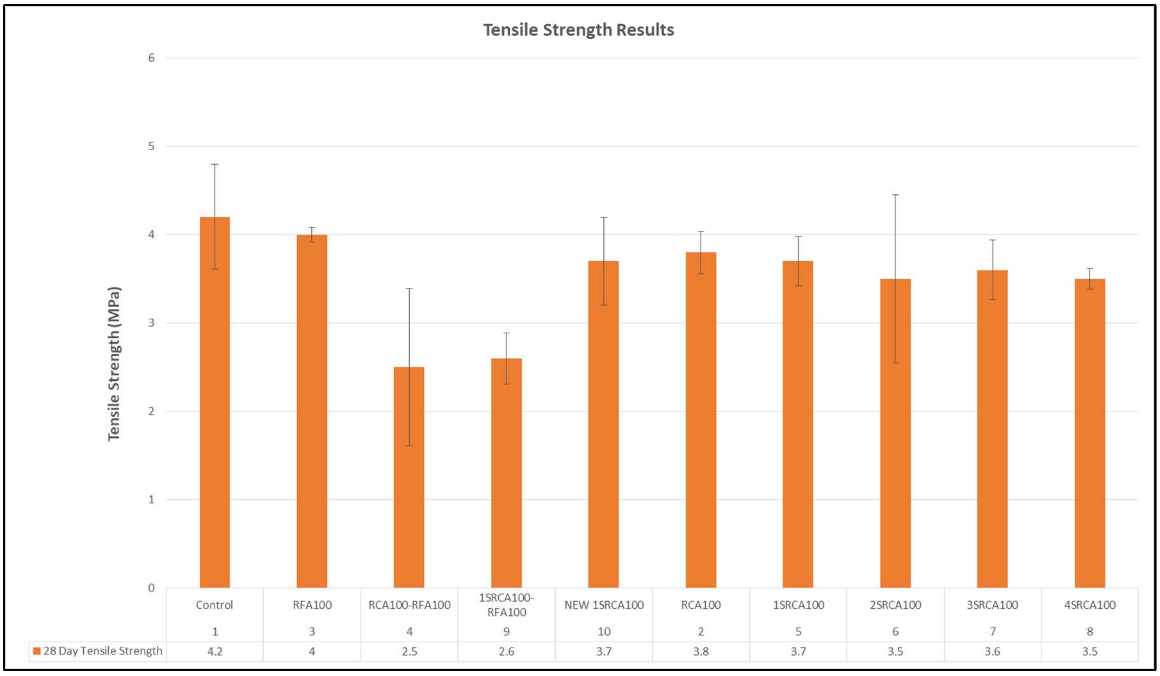

Figure 4.3.6 Tensile strength values of all concrete samples

From the tensile strength results calculated using the indirect method, shown in Figure 4.3.6, no real trend could be distinguished from the screened samples to analyse if screening actually improves concrete tensile strength. However, it could be readily depicted that with the complete replacement of both the RCAs and RFAs, there was a clear display of significantly lower tensile strength at around 1.5MPa lower than the other samples. Therefore agreeing with previous literature, as discussed in Section 2.3.2.2, in that the complete replacement of RAs do in fact lower the tensile strength of concrete.

The raw experimental data and calculations to determine the indirect tensile strength of the concrete samples can be found in Appendix A5.

4.3.3 Tensile to compression strength ratio

The ratios of tensile strength to compressive strength at 28 days were calculated and are shown in Table 4.3.1.

Table 4.3.1 Tensile to compression strength ratio results

Mix Code	28 day Compressive Strength (MPa)	28 day Tensile Strength (MPa)	Tensile to Compression Strength Ratio (%)
C	50	4.2	8.4
RFA100	47	4.0	8.5
RCA100-RFA100	38	2.5	6.6
1SRCA100-RFA100	41	2.6	6.3
New1SRCA100	48	3.7	7.7
RCA100	40	3.8	9.5
1SRCA100	38	3.7	9.7
2SRCA100	40	3.5	8.8
3SRCA100	42	3.6	8.6
4SRCA100	39	3.5	9.0

The typical range of values for the tensile to compression ratio is from 6% to 10%, therefore it can be seen from these results that all the ratios successfully fall within this range. However, there is some conjecture with the previous literature, outlined in Section 2.3.2.3, as the ratios of only the RCA replaced samples are in fact larger than that of the NA control mix. Whereas the 100% replaced RA mixes obey the literature and exhibit lower ratios. Thus, the only way to resolve this confusion would be to replicate more of the tests in this investigation to gain a higher reliability and accuracy with the compressive and tensile strength results.

5. Conclusions

This experimental investigation has effectively analysed the combination of the surface treatments of pre-soaking and screening on recycled aggregates, and the subsequent effect they have on the fresh and hardened mechanical properties of concrete, when utilised as a replacement for natural aggregates. Various concrete mixes were tested throughout this investigation, each containing different types of recycled aggregate components.

Pre-soaking the aggregates, along with an inherent moisture correction for each concrete mix, was found to be a very successful way of ensuring the water to cement ratio remained constant at a value of 0.39 during mixing. Pre-soaking also did not seem to greatly affect the air content or workability of the fresh concrete in any of the mixes.

It was found that with the 100% replacement of both recycled coarse and recycled fine aggregates in concrete, the completely recycled nature of the concrete aggregates was ultimately at a detriment to the workability of the fresh concrete and both the tensile strength, and more importantly, the compressive strength of the hardened concrete. The 100% recycled concrete was not able to achieve anywhere near the desired strength of 50MPa, which was the value of which needed to be reached to be able to be successfully implemented in industry, and thus for utilisation in higher grade structural concrete applications.

It was also found once the recycled coarse aggregates were screened more than 3 times, the screening process would then become a detriment to the strength of the individual aggregates, likely through surface fracturing. This was exemplified through the results comparison between the screened RCA samples, where the compressive strength after 3 times screened was at a peak 42MPa, but significantly reducing to 39MPa after being screened a 4^{th} time.

However, the major conclusion that could be made from this investigation, is that the better the quality of the recycled coarse aggregate, the increased potential that the concrete can reach the desired high grade strength of 50MPa. This is evident from the results of the New1SRCA sample, as a compressive strength of 48MPa was able to be achieved after 28 days (the optimal curing time used for engineering design), almost satisfying the required strength of 50MPa. It is believed that this high strength was directly a result of the better quality recycled materials the aggregates were sourced from.

Through performing this investigation, a deeper knowledge has been gathered in relation to the properties of recycled aggregates in concrete and their potential applications in industry.

6. Recommendations

Throughout this experimental investigation, it has been found found that the compressive strength of recycled concrete is directly related to the quality of where the recycled aggregates are sourced from, meaning it’s perfectly possible to achieve a concrete product that can be used in higher grade applications, if the recycled aggregates are sourced from better quality construction demolition waste.

For this to be successfully implemented in the future, it is recommended that recycled material quality measures be implemented at all recycled construction waste facilities (Concrush, etc.) to ensure the quality of recycled materials is upheld to the highest reliability, in order to be confidently and safely utilised in higher grade structural concrete design applications.

Also it is not recommended that the screening of recycled aggregates be conducted more than 3 times, as this is when the screening process then passes the point of structural benefit and starts to hinder the quality of the aggregate, potentially fracturing the surface and making the aggregate more susceptible to crushing, and thus failure when under compressive load.

It is recommended that the experimental investigation be conducted again, but this time, actually replacing the 20mm natural coarse aggregate with 20mm recycled coarse aggregate instead of using 10mm RCA as the replacement for all of the coarse aggregates. As this is what had to be done for this investigation due to a lack of available resources.

More study to be conducted into the combined effect of the RA surface treatments of pre-soaking and screening is recommended. As it would be very helpful for future study, to have relevant piece of past research to refer back to and compare results with, and to better help with effectively and efficiently discovering a potential industrially viable method of implementing recycled aggregates into high grade concrete applications.

7. References

- Abhiram, K. & Saravanakumar, P., 2015. Properties of recycled aggregate concrete containing hydrochloric acid treated recycled aggregates. *International Journal of ChemTech Research,* 8(1), pp. 72-78.

- Aggregate Screens & Crushers, 2019. *Screening.* [Online]
  Available at: http://www.aggregatescreens.com/screening.html

- Boral, 2019. *Recycled Aggregates.* [Online]
  Available at: https://www.boral.com.au/products/quarry-materials/recycled/recycled-aggregates

- Broadbent, N., 2017. *Investigation into the effect of lithium silicate surface treatment of recycled aggregates on the fresh and hardened properties of self-compacting concrete,* Newcastle: University of Newcastle.

- Concrush, 2019. *10mm and 20mm Recycled Concrete Aggregate.* [Online]
  Available at: http://www.concrush.com.au/site/products-and-applications

- Despotovic, I., 2016. *The improvement of recycled concrete aggregate - a review paper,* s.l.: Conference Proceedings International Conference.

- García-González, J. et al., 2014. Pre-Saturation Technique of the Recycled Aggregates: Solution to the Water Absorption Drawback in the Recycled Concrete Manufacture. *Open Access Materials,* pp. 6224-6236.

- Hossain, U., Poon, C. S., Lo, I. M. & Cheng, J. C., 2016. Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. *Resources, Conservation and Recycling,* pp. 67-77.

- Kisku, N. et al., 2016. A critical review and assessment for usage of recycled aggregate as sustainable construction material. *Construction and Building Materials,* pp. 721-740.

- Mack, J., Solberg, C. & Voigt, G., 2018. *Recycling concrete pavements,* s.l.: The Aberdeen Group.

- Malesev, M., Vlastimir, R. & Gordana, B., 2014. Properties of Recycled Aggregate Concrete. *Contemporary Materials,* pp. 239-249.

- Olorunsogo, F. & Padayachee, N., 2002. Performance of recycled aggregate concrete monitored by durability indexes. *Cement and Concrete Research,* pp. 179-185.

- Patil, S., Ingle, G. & Sathe, P., 2013. Recycled Coarse Aggregates. *International Journal of Advanced Technology in Civil Engineering,* 2(1), pp. 27-33.

- Shima, H., Tateyashiki, H., Matsuhashi, R. & Yoshida, Y., 2005. An Advanced Concrete Recycling Technology and its Applicability Assessment through Input-Output Analysis. *Journal of Advanced Concrete Technology,* 3(1), pp. 53-67.

- Standards Australia, 2014. *Aggregates and rock for engineering purposes - Part 1: Concrete aggregates,* s.l.: s.n.

- Tam, V., Tam, C. & Le, K., 2007. Removal of Cement Mortar Remains from Recycled Aggregate Using Pre-Soaking Approaches. *Resources, Conservation and Recycling,* pp. 82-101.

- The Constructor - Civil Engineering Home, 2019. *Workability of Concrete - Types and Effects on Concrete Strength.* [Online]
  Available at: https://theconstructor.org/concrete/workability-of-concrete-types-strength/11739/

- Zega, C. & Di Maio, A., 2011. Use of recycled fine aggregate in concretes with durable requirements. *Waste Management,* pp. 2336-2340.

Appendix A: Raw Data & Calculations

Appendix A1: Particle Size Distribution

Sieve Aperture Size (mm)	% Mass Passing										
	Fine Sand	Coarse Sand	20mm NA	10mm NA	RFA	0SRCA	1SRCA	2SRCA	3SRCA	4SRCA	New1SRCA
75											
53											
37.5											
26.5			100.0								
19			90.9								
13.2			8.8	100.0							96.6
9.5			0.4	86.5		91.6	86.8	86.8	83.2	85.4	45.6
6.7			0.2	35.0		46.3	25.9	25.9	18.8	13.5	2.8
4.75			0.2	6.2		13.0	2.4	2.4	1.5	1.2	0.7
2.36	100.0	70.0	0.2	0.8	54.1	8.3	1.8	1.8	1.3	1.0	0.7
1.18	100.0	43.3	0.2	0.6	39.5	7.4	1.7	1.7	1.2	1.0	0.6
0.6						6.7	1.6	1.6	1.2	1.0	
0.425	90.7	21.2			19.7	5.7	1.6	1.6	1.2	0.9	
0.3	39.7	15.7			10.4	4.1	1.5	1.5	1.0	0.8	
0.15	0.0	9.9			4.7	2.3	1.4	1.4	0.8	0.6	
0.075	0.0	9.7			4.5	1.4	0.8	0.8	0.6	0.4	
0	0.0	0.0			0.0	0.0	0.0	0.0	0.0	0.0	

Appendix A2: Crushing Value

First attempt

Weight of cylinder (g) 4525.1

	Weight of sample (g)	Mass of sample passing through sieve 2.36mm (g)	Crushing Value (%)
NA (10mm)	2628.6	499.3	19.0
S0	2258.9	679.3	30.1
S1	2547.9	658.6	25.8
S2	2220.9	641.2	28.9
S3	2563.9	632.8	24.7
S4	2209.9	628.2	28.4
NA(20mm)	2770.6	320.5	11.6

Second attempt

Weight of cylinder (g) 4525.1

	Weight of sample (g)	Mass of sample passing through sieve 2.36mm (g)	Crushing Value (%)
NA (10mm)	2702.1	515.3	19.1
S0	2595	662.9	25.5
S1	2486	647.7	26.1
S2	2557	664.8	26.0
S3	2297	645.9	28.1
S4	2511	646.0	25.7
NA(20mm)	2770.1	317.4	11.5

Crushing value test				
Samples	**Crushing value (%)**	**Crushing value (%)**	**Average**	**St. Dev.**
NA (10mm)	18.99	19.07	19.03	0.05335
RCA	30.07	25.55	27.81	3.20099
1SRCA	25.85	26.05	25.95	0.14507
2SRCA	28.87	26.00	27.44	2.03078
3SRCA	24.68	28.12	26.40	2.43113
4SRCA	28.43	25.73	27.08	1.90906
NA (20mm)	11.57	11.46	11.51	0.07766

Appendix A3: Air Content

		Apparent Air Content (Concrete Sample)			Volume of concrete sample (same as volume of measuring bowl) (L)	Volume of Concrete Produced per batch	Total mass of coarse aggregate in batch (20mm)	Total mass of coarse aggregate in batch (10mm)	Total mass of Recycled coarse aggregate in batch	Total mass of fine aggregate in batch (Coarse Sand)	Total mass of fine aggregate in batch (Fine Sand)	Total mass of Recycled fine aggregate in batch (Coarse Sand Equivalent)
No	Mix Code	A1 (First Determination)	A1 (Second Determination)	A1 Average	S (Litres, L)	B (m^3)	C_20_b (kg)	C_10_b (kg)	(kg)	F_Coarse_b (kg)	F_Fine_b (kg)	(kg)
1	Control	1.60%	1.60%	1.60%	7	0.041	29.52	11.48	0	10.865	14.35	0
2	RCA100	2.00%	2.00%	2.00%	7	0.041	0	0	41	10.865	14.35	0
3	RFA100	1.80%	1.80%	1.80%	7	0.041	29.52	11.48	0	0	14.35	10.865
4	RCA100-RFA100	2.20%	2.20%	2.20%	7	0.041	0	0	41	0	14.35	10.865
5	1SRCA100	2.20%	2.10%	2.15%	7	0.041	0	0	41	10.865	14.35	0
6	2SRCA100	1.75%	1.80%	1.78%	7	0.041	0	0	41	10.865	14.35	0
7	3SRCA100	1.80%	1.80%	1.80%	7	0.041	0	0	41	10.865	14.35	0
8	4SRCA100	1.80%	1.90%	1.85%	7	0.041	0	0	41	10.865	14.35	0
9	1SRCA100-RFA100	1.90%	1.80%	1.85%	7	0.041	0	0	41	0	14.35	10.865
10	NewRCA100	1.90%	1.85%	1.88%	7	0.041	0	0	41	10.865	14.35	0

		Mass of coarse aggregate in concrete sample (20mm)	Mass of coarse aggregate in concrete sample (10mm)	Mass of Recycled coarse aggregate in concrete sample	Mass of fine aggregate in concrete sample (Coarse Sand)	Mass of fine aggregate in concrete sample (Fine Sand)	Mass of Recycled fine aggregate in concrete sample (Coarse Sand Equivalent)	Aggregate Correction factor			Air Content
No	Mix Code	C_20_s (kg)	C_10_s (kg)	(kg)	F_Coarse_s (kg)	F_Fine_s (kg)	(kg)	G1 (First Determination)	G1 (Second Determination	G (%)	A (%)
1	Control	5.04	1.96	0	1.855	2.45	0	0.20%	0.20%	0.20%	1.40%
2	RCA100	0	0	7	1.855	2.45	0	0.40%	0.40%	0.40%	1.60%
3	RFA100	5.04	1.96	0	0	2.45	1.855	0.40%	0.40%	0.40%	1.40%
4	RCA100-RFA100	0	0	7	0	2.45	1.855	0.80%	0.70%	0.75%	1.45%
5	1SRCA100	0	0	7	1.855	2.45	0	0.50%	0.60%	0.55%	1.60%
6	2SRCA100	0	0	7	1.855	2.45	0	0.80%	0.80%	0.80%	0.98%
7	3SRCA100	0	0	7	1.855	2.45	0	0.95%	1.00%	0.98%	0.83%
8	4SRCA100	0	0	7	1.855	2.45	0	0.95%	0.90%	0.93%	0.93%
9	1SRCA100-RFA100	0	0	7	0	2.45	1.855	0.95%	0.90%	0.93%	0.93%
10	NewRCA100	0	0	7	1.855	2.45	0	0.75%	0.65%	0.70%	1.18%

Appendix A4: Compression Testing

				28 Day Test Compression									56 Day Test Compression								
		rounded Average	STDEV	Cylinder 1		Cylinder 2		Cylinder 3		average	rounded Average	STDEV	Cylinder 1		Cylinder 2		Cylinder 3		average	rounded Average	STDEV
Volume m3				**0.00157**		**0.00157**		**0.00157**					**0.00157**		**0.00157**		**0.00157**				
No	**Mix Code**			**kN**	**MPa**	**kN**	**MPa**	**kN**	**MPa**	**MPa**			**kN**	**MPa**	**kN**	**MPa**	**kN**	**MPa**	**MPa**		
Mass(kg)				3.789		3.678		3.662					3.655		3.655		3.628				
Density (kg/m3)		2300.0	1.9	2413.4		2342.7		2332.5		2362.8	2362.0	7.2	2328.0		2328.0		2310.8		2322.3	2322.0	9.9
1	Control	35.0	1.5	275.4	35.06501706	402.1	51.19696209	393.4	50.08924369	50.6	50.0	0.8	470.6	59.91865298	450	57.29577951	431.1	54.88935677	56.1	56.0	2.5
Mass(kg)				3.478		3.470		3.461					3.481		3.449		3.463				
Density		2206.0	6.8	2215.3		2210.2		2204.5		2210.0	2209.0	5.4	2217.2		2196.8		2205.7		2206.6	2206.0	10.2
2	RCA100	28.0	2.5	310.1	39.48315828	313.6	39.92879212	319.6	40.69273585	40.0	40.0	0.6	350.7	44.65251083	365.6	46.54963776	343.9	43.78670794	45.0	44.0	1.4
Mass(kg)				3.627		3.634		3.649					3.596		3.624		3.602				
Density		2295.0	6.6	2310.2		2314.6		2324.2		2316.3	2316.0	7.2	2290.4		2308.3		2294.3		2297.7	2297.0	9.4
3	RFA100	36.0	1.0	371.5	47.30084909	382.9	48.75234217	366.8	46.7024265	47.6	47.0	1.1	461.9	58.81093457	425.6	54.18907502	473.7	60.31335723	57.8	57.0	3.2
Mass(kg)				3.422		3.447		3.448					3.458		3.446		3.462				
Density		2116.0	87.5	2179.7		2195.5		2196.2		2190.5	2190.0	9.3	2202.5		2194.9		2205.1		2200.8	2200.0	5.3
4	RCA100-RFA100	23.0	2.6	292.4	37.22952429	307.7	39.17758079	298.1	37.95527083	38.1	38.0	1.0	361.1	45.97667996	361	45.96394756	329.6	41.96597539	44.6	44.0	2.3
Mass(kg)				3.500		3.532		3.501					3.584		3.489		3.501				
Density		2236.0	21.4	2229.3		2249.7		2229.9		2236.3	2236.0	11.6	2282.8		2222.3		2229.9		2245.0	2245.0	33.0
5	1SRCA100	31.0	1.7	334.2	42.55166559	289.9	36.9112144	274	34.88676353	38.1	38.0	4.0	390.3	49.69453943	363.2	46.24406026	306.3	38.99932726	45.0	44.0	5.5
Mass(kg)				3.490		3.515		3.497					3.503		3.525		3.493				
Density		2216.0	12.9	2222.9		2238.9		2227.4		2229.7	2229.0	8.2	2231.2		2245.2		2224.8		2233.8	2233.0	10.4
6	2SRCA100	29.0	0.9	292	37.17859471	342.9	43.65938399	326.2	41.53307395	40.8	40.0	3.3	365.9	46.58783494	385.3	49.05791966	363.1	46.23132787	47.3	47.0	1.5
Mass(kg)				3.494		3.465		3.480					3.459		3.474		3.485				
Density		2209.0	1.6	2225.5		2207.0		2216.6		2216.3	2216.0	9.2	2203.2		2212.7		2219.7		2211.9	2211.0	8.3
7	3SRCA100	29.0	0.6	338.8	43.13735578	337.9	43.02276422	335.6	42.72991912	43.0	42.0	0.2	359.4	45.76022924	369	46.9825392	360.6	45.91301798	46.2	46.0	0.7
Mass(kg)				3.498		3.489		3.482					3.497		3.519		3.483				
Density		2222.0	11.4	2228.0		2222.3		2217.8		2222.7	2222.0	5.1	2227.4		2241.4		2218.5		2229.1	2229.0	11.6
8	4SRCA100	28.0	2.2	316.2	40.2598344	318.6	40.5654119	293.4	37.35684824	39.4	39.0	1.8	256.4	32.64586193	398.1	50.68766628	377.4	48.05206042	43.8	43.0	9.7
Mass(kg)				3.454		3.466		3.456					3.458		3.515		3.470				
Density		2210.0	10.9	2200.0		2207.6		2201.3		2203.0	2202.0	4.1	2202.5		2238.9		2210.2		2217.2	2217.0	19.1
9	1SRCA100-RFA100	31.0	1.1	323.9	41.24022885	328.5	41.82591904	322.2	41.02377813	41.4	41.0	0.4	345	43.92676429	351	44.69070802	360.6	45.91301798	44.8	44.0	1.0
Mass(kg)				3.656		3.604		3.599					3.655		3.596		3.610				
Density		2308.0	54.8	2328.7		2295.5		2292.4		2305.5	2305.0	20.1	2328.0		2290.4		2299.4		2305.9	2305.0	19.6
10	NEW 1SRCA100	33.0	1.9	386.1	49.15977882	373.7	47.58096179	373.2	47.51729981	48.1	48.0	0.9	403.3	51.34975084	433.2	55.15673708	424.9	54.09994826	53.5	53.0	2.0

Appendix A5: Tensile Testing

		28 Day Test Tensile (Compression on side)								
		Cylinder 1		Cylinder 2		Cylinder 3		average	Rounded Average	STDEV
Volume m3		**0.00157**		**0.00157**		**0.00157**				
No	**Mix Code**	**kN**	**MPa**	**kN**	**MPa**	**kN**	**MPa**	**MPa**		
Mass(kg)		3.695		3.626		3.675				
Density (kg/m3)		2353.5		2309.6		2340.8		2334	2334	22.61
1	Control	146.6	4.67	136.5	4.34	110.4	3.51	4.2	4.2	0.59
Mass(kg)		3.460		3.501		3.481			0	
Density		2203.8		2229.9		2217.2		2216	2216	13.06
2	RCA100	128.1	4.08	121.4	3.86	113	3.60	3.8	3.8	0.24
Mass(kg)		3.736		3.678		3.614			0	
Density		2379.6		2342.7		2301.9		2341	2341	38.87
3	RFA100	130.1	4.14	125.5	3.99	125.7	4.00	4.0	4.0	0.08
Mass(kg)		3.441		3.459		3.430			0	
Density		2191.7		2203.2		2184.7		2193	2193	9.32
4	RCA100-RFA100	110.7	3.52	60	1.91	64.6	2.06	2.5	2.5	0.89
Mass(kg)		3.487		3.540		3.503			0	
Density		2221.0		2254.8		2231.2		2235	2235	17.32
5	1SRCA100	110.2	3.51	125	3.98	109.7	3.49	3.7	3.7	0.28
Mass(kg)		3.475		3.469		3.594			0	
Density		2213.4		2209.6		2289.2		2237	2237	44.90
6	2SRCA100	128.3	4.08	75.8	2.41	126.5	4.03	3.5	3.5	0.95
Mass(kg)		3.462		3.481		3.485			0	
Density		2205.1		2217.2		2219.7		2214	2214	7.83
7	3SRCA100	101.4	3.23	122.5	3.90	114	3.63	3.6	3.6	0.34
Mass(kg)		3.489		3.488		3.465			0	
Density		2222.3		2221.7		2207.0		2216	2216	8.65
8	4SRCA100	111.1	3.54	105.9	3.37	112.7	3.59	3.5	3.5	0.11
Mass(kg)		3.443		3.432		3.448			0	
Density		2193.0		2186.0		2196.2		2191	2191	5.21
9	1SRCA100-RFA100	76.9	2.45	91.4	2.91	74.7	2.38	2.6	2.6	0.29
Mass(kg)		3.607		3.586		3.573			0	
Density		2297.5		2284.1		2275.8		2285	2285	10.93
10	NEW 1SRCA100	126.3	4.02	99.1	3.15	125.6	4.00	3.7	3.7	0.49