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Research on Recycled Concrete Aggregates at NUS

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ABSTRACT: Sustainable concrete construction is critical to the economic development of infrastructures. The need and demand for infrastructure development is crucial to economic and social well-being of all nations. Of all the constituents in concrete coarse aggregate forms the biggest volume. As the reserve of aggregates is finite, the availability of suitable recycled concrete aggregate from demolition of concrete structures provides an alternate source to meet the increasing demand of new construction. Research on recycled concrete aggregate (RCA) at NUS was first conducted in the 1980's. In recent years, further studies cover two main areas. The first is on the technique to improve the quality of recycled coarse concrete aggregate by means of microwave treatment. The other is to develop a modified acid treatment method to fully remove all attached materials from RCA coarse particles. This provides a more reliable basis for determination of the mortar content in RCA thus achieving a more precise relationship between properties of RCA and mortar content. Results on the relationship between 24-hour water absorption, bulk density and Los Angeles abrasion resistance of RCA and mortar content show a higher regression coefficient compared to others in published literature.

Keywords: Recycled Aggregate, Mortar Content, Acid Treatment, Crushing, Concrete, Strength

1 INTRODUCTION

Sustainable concrete construction is critical to the economic development of infrastructures. The need and demand for infrastructure development is crucial to economic and social well-being of all nations. The current emphasis on sustainable concrete construction covers both new types of cement produced with lower carbon footprint and the three aims to reduce, reuse and recycled of materials. Research into applying the three aims in concrete construction include approaches for reducing the volume of concrete for the same structure (Tam et al, 2009), recovery of structural elements for reuse in a new structure based on the principle of design for deconstruction (IStructE, 2011) and the use of recycled concrete aggregates. Of all the constituents in concrete coarse aggregate forms the biggest volume. As the reserve of aggregates is finite, the availability of suitable recycled concrete aggregate from demolition of concrete structures provides an alternate source to meet the increasing demand of new construction. Research on recycled concrete aggregate (RCA) at NUS was first conducted in the 1980's. In recent years, further studies cover two main areas. The first is on the technique to improve the quality of recycled coarse concrete aggregate by means of microwave treatment. The other is to develop a modified acid treatment method to fully remove all attached materials from RCA coarse particles. This paper provides a brief summary of the studies conducted and highlights the findings that contribute to the better understanding of RCA and with some illustrations on the properties of concrete containing RCA. It is presented as initial studies conducted in the 1980,s and recent studies that have been completed. Further details related to these studies are given in the list of publications referred to in this paper.

2 INITIAL STUDIES

The studies in the 1980's were at a time when recycling of concrete aggregates was in its initial stage of development, before the established guidelines on the classification and use of recycled aggregates (BS EN 12620, 2002) and its use in concrete (BS 8500-2, 2006). The main objectives were to explore the feasibility of incorporating both coarse and fine recycled concrete aggregates in new concretes of similar or higher strength grades and methods to mitigate the effect of the reduction in strength of RCA concrete by addition of mineral admixtures. Laboratory prepared original concretes with granite coarse aggregate and natural sand of different strength levels were crushed to produce both the coarse and fine recycled concrete aggregate (RCA). The distinction between recycled aggregate (RA) and recycled concrete aggregate (RCA) is defined in BS 8500-1 (2006) as follows:

Recycled aggregate, (RA) – aggregate resulting from the reprocessing of inorganic material previously used in construction
Recycled concrete aggregate, (RCA) – recycled aggregate principally comprising crushed concrete

2.1 Properties of RCA

The presence of mortar in coarse RCA is acknowledged as the main factor lowering its quality when compared to natural aggregates (NA). Two commonly selected properties for coarse RCA to indicate the change from the original coarse aggregate are particle density (or specific gravity) and 24-hr absorption, others include Los Angeles abrasion value, crushing value and impact value. Typically the combined effects of these factors are assessed in terms of compressive strength of recycled aggregate concrete (RAC) containing either or both coarse and fine RCA. The results presented in this paper are for granite coarse aggregate only as this is the most common type available in Singapore.

Some of the results on RCA properties from these initial studies (Sri Ravindrarajrah et al, 1987, Tam et al, 1991) on selected properties of RCA are summarised in Table 1. In general, all tests on properties of aggregates and fresh and hardened concrete are in accordance with relevant Singapore standards which are based on corresponding British standards. More details on the parent concretes and method of processing as well as testing methods are available from these and other references listed (Sri Ravindrarajah and Tam, 1985, Ravindrarajah and Tam, 1987).

Since all the recycled aggregates are produced from crushing of laboratory specimens, they are expected to satisfy the requirements for RCA stated in BS EN 12620 (2002) amendment A1: 2008.

Although currently, guidance on the use of fine RCA is not yet available, BS 8500-2 (2006) in its "Commentary on fine RCA and fine RA" states clearly that "clean fine RCA is suitable for use in concrete. The results of the initial studies support this statement based on the tests on fresh and hardened concrete contained RCA, i.e. recycled aggregate concrete, RAC.

Table 1: Properties of natural and recycled concrete aggregates

Property	Granite	Natural sand	RCA Coarse	RCA Fine	Remarks
Specific gravity	2.67	2.61	2.49	2.32	1-yr old cube 60 MPa, (Sri Ravindra et al, 1987)
24-hr water absorption (%)	0.30	0.63	5.68	6.20	
Specific gravity	2.67	2.61	H – 2.44 M – 2.46 L – 2.44	2.32	Original concrete
24-hr water absorption (%)	0.3	0.6	H – 5.4 M – 4.5 L – 4.7	6.2	H: W/C = 0.51, A/C = 4.83 28d cube ≅ 42 MPa
Impact value (%)	14.6		H – 26.0 M – 27.6 L – 31.0		
Crushing value (%)	16.9		H – 28.7 M – 29.9 L – 33.5		M: W/C = 0.60, A/C = 5.92 28d cube ≅ 38 MPa
Los Angeles abrasion value (%)	18.1		H – 37.2 M – 40.8 L – 40.8		L: W/C = 0.73, A/C = 7.40 28d cube ≅ 30 MPa (Tam et al, 1991)

Based on the limited data available, only qualitative trends are considered. It is clear from the above that the reduction in quality of RCA is contributed by the presence of mortar in it, particularly in the case of coarse RCA. The components in fine RCA are difficult to separate and methods of quantifying them also need to be developed before guidance on the use of fine RCA can be developed.

2.2 Recycled Aggregate Concrete (RAC)

One way to assess the feasibility of using RCA in new concrete (RAC) is to compare the performance of concretes with and without RCA replacement of natural aggregates in terms of the properties of interest. Examples of such results from the initial studies at NUS are presented below. Only consistence and compressive strength results are presented in this paper. Other RAC properties including methods to mitigate the reduction in quality by adjusting concrete composition and addition of pozzolanic materials and details of the studies are given in Sri Ravindrarajah et al (1987) and Tam et al (1991). For a series of three mixes with the same water-cement ratio of 0.57 but with different combinations of fine and coarse aggregates consisting of crushed granite and natural sand and fine and coarse RCA, Figure 1 shows the effect of recycled fine and/or coarse concrete aggregates on loss of consistence (Vebe time) with elapsed time since mixing. All aggregates were batched in air-dried condition but additional batch water was provided to allow for absorption. Hence, initial consistence of all three mixes is similar. The much faster increase in Vebe time in mixes with recycled aggregate is contributed by their higher absorption. (Sri Ravindrarajah et al, 1987).

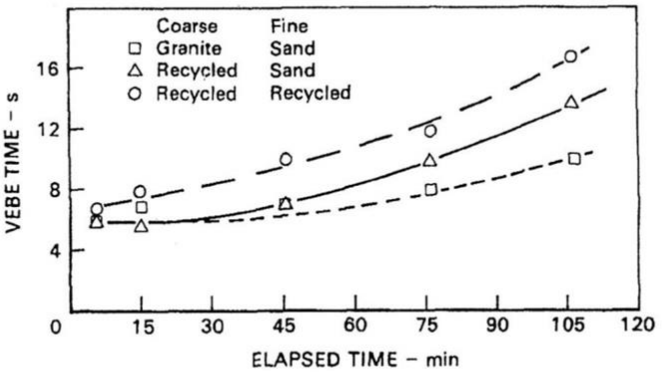

Figure 1: Effect of replacing natural aggregate with RCA aggregates on loss of consistence

The effect of aggregates on the development of compressive strength with age for curing under water or in laboratory environment for this series of concretes is presented in Figure 2 (Sri Ravindrarajah et al, 1987).

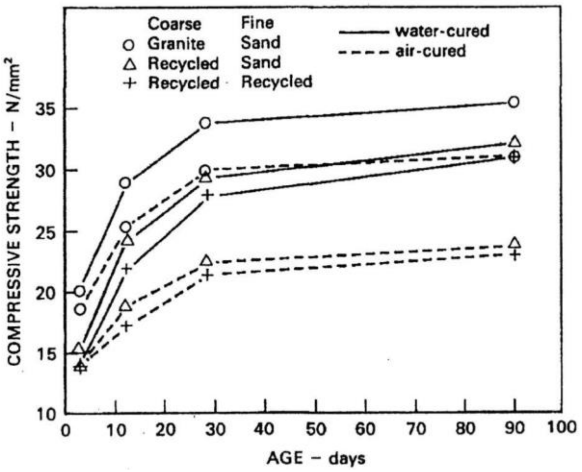

Figure 2: Development of compressive strength with age for combinations of aggregates

Another two series, each of five mixes, were prepared with similar cement and water contents over a range of water-cement ratios from 0.30 to 0.70 (at 0.10 intervals), one with granite and natural sand and the other with recycled fine and coarse aggregates. Only the mass of aggregates was adjusted to match their total volumetric fraction in the concretes. The relationships between compressive strength and water-cement ratio are similar for both series except that the one with RCA show similar reduction at both early (7 days) and later age (90 days). In general, the test results (Figure 3) showed that for the concretes made with both fine and coarse RCA showed about 10% reduction in compressive strength. It is of interest to note that influence of recycled coarse aggregate on strength is greater than that of the recycled fine aggregate in this study (Sri Ravindrarajah et al, 1985) and similar to the finding by Rasheeduzzafar and Khan (1984).

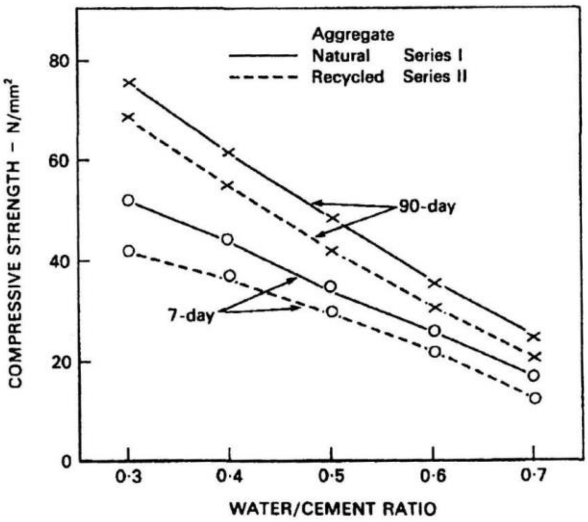

Figure 3: Relationship between compressive strength and water-cement ratio for concretes with both fine and coarse natural aggregates and RCA

More details and examples for other properties of concrete are presented in Ravindrarajah et al (1987) and Tam et al (1991). These include tensile strength, modulus of elasticity, drying shrinkage and creep test results. In all cases, there is a reduction in performance when RCA is incorporated into new concretes. However, by suitable adjustment of water-cement ratio and the addition of pozzolanic materials, particularly silica fume, the effects of RCA can be mitigated. These results indicate the feasibility of using both fine and coarse recycled concrete aggregate and potential approaches to mitigate the reduction in performance of RAC for which further development is necessary.

3 RECENT STUDIES

In recent years the interest for sustainable concrete construction has renewed strong interest to promote RCA as an alternate source of aggregates for structural concrete. Methods for enhancing the quality and yield of coarse RCA through the use of beneficiation processes and fine tuning of the RCA production process call for a better understanding of the overlapping interactions and effects of the various influencing parameters. The major parameters include the properties of the parent concrete such as the composition, strength level, maximum aggregate size, crushing procedure and particle size of the final

RCA. A brief summary of the studies conducted at NUS to gain a deeper understanding of the above matters is presented in this paper. Details on the development of the microwave beneficiation equipment and process, a new technique to completely remove mortar content from RCA together with other experimental details are given in Akbarnezhad et al (2011), Akbarnezhad et al (2012a), and Akbarnezhad et al (2012b).

3.1 Types of RCA

Coarse RCA particles often consist of one or more original aggregates covered partially or completely with mortar, generally referred to as "attached mortar". However, at particle size above 4 mm, small lumps of mortar alone have been found in coarse RCA. Hence, it is proposed that the three types of coarse RCA are classified as follows and illustrated in Figure 4:

Type I – particles with one or more original aggregates covered partially or completely with mortar and classified as Type 1A, if only a single original aggregate is present and Type 1B if more than one original aggregate is present.
Type II – particles consisting of only the mortar fraction of the parent concrete.

The commonly used term of "attached mortar" should strictly refer to Type I coarse RCA only. The more appropriate term to include both types of coarse RCA is "mortar content" which has been adopted in the NUS studies. For example, on average, 8-12 mm size fraction of RCA used in the concretes for this study RCA has a mortar content of 17%. This particular size range was selected because it has similar a mortar content close to the average for size fractions of 4-8 mm, 8-12 mm 12-16 mm and 16-20 mm (Akbarnezhad et al, 2011). In so doing, the effect of RCA size is removed in addition to having less variability between samples batched. This is to reduce the interaction of parameters in RCA, such as difference in mortar content and the amount of Type II RCA for different particle size.

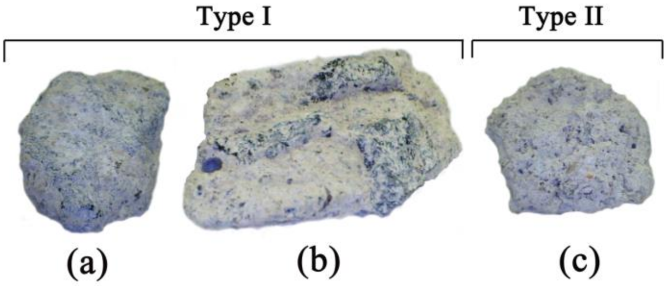

Figure 4: Types of RCA, (a) Type IA, (b) Type IB and (c) Type II

3.2 Microwave-assisted beneficiation

The method described in Akbarnezhad et al (2011) takes advantage of the difference in electromagnetic properties, water absorption capacity and higher tensile strength of natural aggregates compared to that of mortar to induce the breaking up and separation of attached mortar without damaging the natural aggregate (granite) in Type 1 RCA, In addition, Type II RCA is also broken up into much smaller particles (< 4mm). An example of an individual Type 1A coarse RCA particle before and after microwave treatment is shown in Figure 5. Detailed review of the treatment methods described in published literature are given in Akbarnezhad et al (2011), only a comparison of the efficiency of selected beneficiation methods is reproduced as Table 2. Percentage of mortar content by mass is based on total removal of mortar content from RCA by soaking in a 2 molar sulfuric acid for 5 days. Subsequently, a new acid treatment technique incorporating a rotary agitating process for total removal of mortar content was also developed which takes approximately 24 hours (Akbarnezhad et al, 2012a).

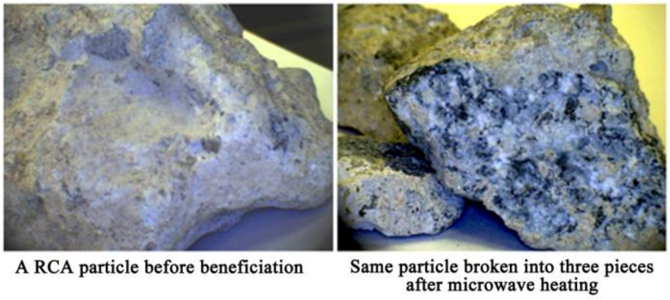

Figure 5: Surface of a RCA particle before and after microwave treatment (Akbarnezhad et al, 2011)

The microwave-assisted method adopted the RCA particles are heated to a much lower temperature (~ 140^{O}C for granite aggregate) and for a significantly shorter duration than needed for conventional heating. This is less likely to degrade the aggregate and with savings in time and energy consumption. It avoids the possible durability concern with acid soaking methods (attack on aggregate and residue sulfate).

For the adopted microwave-assisted beneficiation process, the RCA particles are heated to a much lower temperature (~ 140^{O}C for granite aggregate) and for a significantly shorter duration (seconds) than needed for conventional heating. This is less likely to degrade the aggregate and with savings in time and energy consumption. It avoids the possible durability concern with acid soaking methods – attack on aggregate and residue sulfate in RCA.

Table 2 – Properties of RCA before and after treatment using various beneficiation techniques

Beneficiation process			Process duration (hr)	Properties of RCA 24-hr water absorption (%)	Particle density (OD) (kg/m^3)	Mortar content (%) by mass
Before beneficiation				4.2	2370	47
Single-Stage Processes	Microwave Heating	Pre-saturated RCA	~ 0.02	2.8	2460	24
		Air dried RCA	~ 0.02	3.4	2430	32
	Conventional Heating	300 ^{O}C	2	4.1	2380	44
		500 ^{O}C	2	3.8	2390	41
	Mechanical Rubbing		~ 0.1	3.5	2410	34
	Acid Soaking	0.1 Molar sulphuric acid	20	4.1	2380	45
			120	4.1	2380	45
		0.5 Molar sulphuric acid	24	3.9	2390	41
			120	3.4	2420	33
		1 Molar sulphuric acid	24	3.5	2410	34
			120	1.6	2500	13
Combined Processes	Conventional Heating and Mechanical Rubbing	300 ^{O}C	~ 2.1	3.3	2430	31
		500 ^{O}C	~ 2.1	2.1	2480	21
	Microwave Heating and Mechanical Rubbing	Pre-saturated RCA	~ 0.12	1.1	2550	7

A series of concretes produced with RCA before and after the microwave-assisted beneficiation at 20%, 40%, 60%, 80% and 100% replacement of coarse aggregate by mass was tested. The composition of these concretes is the same as the reference concrete using natural aggregate and natural sand (cement 375 kg, water 167 kg, coarse aggregate 1072 kg, natural sand 736 kg). For both coarse RCA before and after microwave treatment, the replacement is percentage by mass. All aggregates were batched at over-dried condition with additional water based on 24-hr water absorption (10 minutes of soaking before addition of cement as around 90% of 24-hr water absorption taken up in 10 minutes). The results for cube compressive strength, flexural strength (modulus of rupture) and modulus of elasticity at 28 days are shown in Figures 6 to 8. They show the significant improvement in concrete properties for RCA aggregates after the microwave-assisted beneficiation process (MRCA).

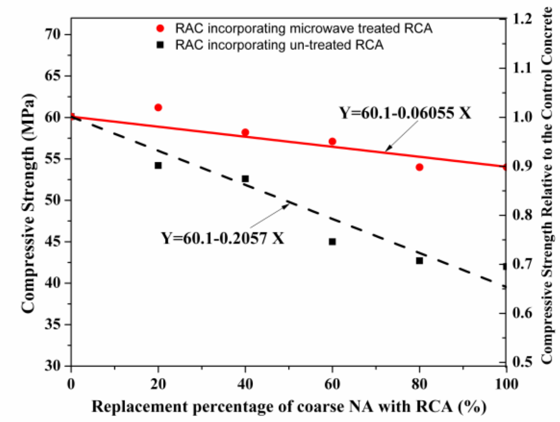

Figure 6: Effect of RCA/MRCA replacements (% by mass) on 28-day cube compressive strength

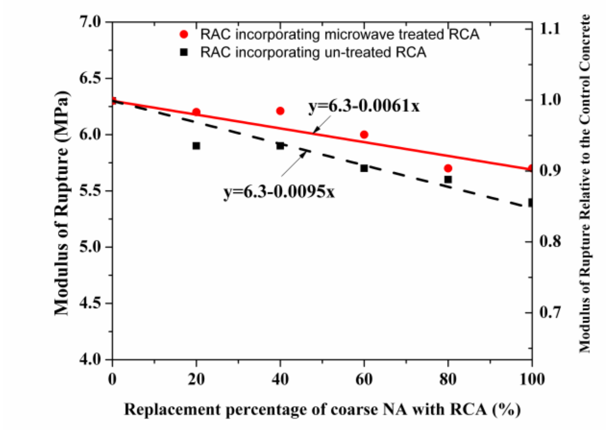

Figure 7: Effect of RCA/MRCA replacements (% by mass) on 28-day flexural strength

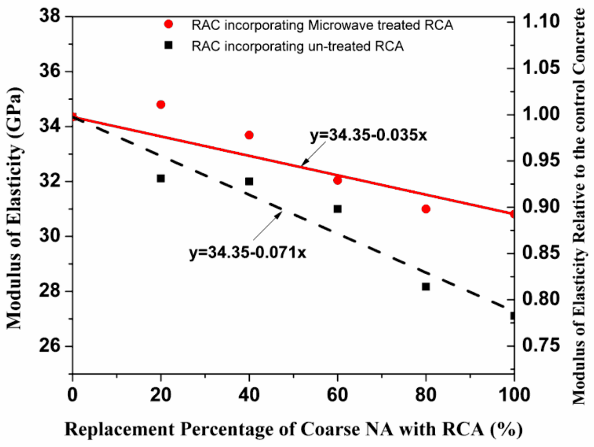

Figure 8: Effect of RCA/MRCA replacements (% by mass) on modulus of elasticity

3.3 Mortar Content

In order to develop a reliable relationship on the influence of mortar content, it is necessary to adopt an efficient and convenient technique to completely remove attached mortar and break down the mortar lumps in RCA to determine the mortar content. Akbarnezhad et al (2012a) has presented an acid treatment procedure to achieve complete removal of mortar in only 24 hours which is adopted for the test results presented in this paper (details of test procedure given in Akbarnezhad et al (2012a).

In determining the concrete compositions with RCA based on the concept of "equivalent mortar volume" proposed by Fathfazl et al (2009) and Abbas et al (2009), the amount of mortar in RCA should be taken into account. The behaviour of a composite material, such as concrete depends on the volumetric composition of the constituent materials rather than their proportions by mass (used in batching for production control). However, most test methods for determining mortar content provide results as percentage by mass of RCA. Hence, it is of interest to examine the relationship between percentage by mass and percentage by volume.

For a unit volume of coarse RCA with the volumetric percentage of mortar content = p_v %, the following relationships can be stated (Akbarnezhad et al, 2012a):

$$1 \text{ x } D_r = (1 - p_v/100) \text{ x } D_g + (p_v/100) \text{ x } D_m \quad (1)$$

where D_r = density of RCA, D_g = density of virgin aggregate in parent concrete, and D_m = density of mortar content in RCA (all in terms of kg/m^3). By rearranging the terms, the volumetric percentage of mortar content, p_v is given as:

$$p_v = 100 \text{ x } (D_g - D_r)/(D_g - D_m) \quad (2)$$

For a given parent concrete with known virgin aggregate and its coarse recycled concrete aggregate, the values of D_g and D_r can be experimentally determined. The value of D_m lies between the densities of a pure cement paste of water/cement ratio in the parent concrete (as a thin layer attached to original aggregates) to that of the mortar in the parent concrete (as lumps of mortar in Type II coarse RCA). It can be seen from Equation (2) that by assuming the value of D_m to be that of pure cement paste and that of mortar in the parent concrete, they indicate the upper bound and lower bound for the percentage of mortar content by volume, p_v respectively (density of the mortar being higher than that of the cement paste in the same parent concrete). By assuming that the value of D_m is equal to the value of the mortar fraction in the parent concrete, Equation 2 may be used to establish the relationship between mortar content in percentage by mass, p_m and percentage by volume, p_v as

$$p_m = p_v \text{ x } (D_m/D_r) \text{ or } p_v = p_m \text{ x } (D_r/D_m)$$

However, this approach provides a lower bound for estimating the mortar content by volume from mortar content by mass, usually determined in testing. The percentage by volume forms the basis for designing RCA based on the concept of "equivalent mortar volume" proposed by Fathfazl et al (2009) and Abbas et al (2009). Test results presented in Section 3.4 below indicate that for mortar content up to about 30% by mass, the value of D_m is close to the regression line for the density of the mortar fraction. Hence, the difference between percentage by volume and percentage by mass is small. The value for D_m varies with the amount of Type I and Type II RCA in a sample. In the case of Type IA particle, the attached material may vary from a thin layer cement paste to a layer of mortar of the same composition as the mortar fraction in the parent concrete. With RCA from a demolition site, even the parent concrete may be of different composition and strength levels. However, the proposed relationships provide an analytical approach to the understanding of the relationships between mortar content and important properties of RCA such as density and water absorption.

In order to verify the above relationships, 70 RCA samples of different mortar contents were produced from two parent concretes of compositions shown in Table 3 and prepared using natural coarse aggregate (granite) and natural fine sand. From these, bulk density (OD), 24-hr water absorption of the 8-12 mm size fraction and the Los Angeles abrasion loss of the RCA were determined. In addition, samples of the cement paste and mortar fraction of the two concretes were also prepared to determine their values of bulk density (OD) as summarised in Table 3.

From the test results of these coarse RCA the relationship between bulk density (OD) and mortar content by mass is as shown in Figures 9 and 10 for C30 and C60 respectively. For both parent concretes, the data tend to indicate a linear relationship which is also reported by De Juan et al (2009). The data for mortar content below 30% by mass are mostly close to the upper bound line, indicating that the mortar content has similar composition as the mortar fraction in the parent concrete.

Table 3 – Composition and properties of parent concretes and their components

Concrete designation	Constituents (kg/m^3)				Property
	Cement	Water	Natural sand	Coarse Aggregate	28-day compressive strength
C30	282	195	804	1072	27 MPa
C60	375	167	736	1072	63 MPa
Component					Bulk density (OD)
C30 paste	water-cement ratio = 0.69				1800 kg/m^3
C60 paste	water-cement ratio = 0.45				1910 kg/m^3
C30 mortar	water-cement ratio = 0.69, sand-cement ratio = 2.85				2100 kg/m^3
C60 mortar	water-cement ratio = 0.45, sand-cement ratio = 1.96				2180 kg/m^3

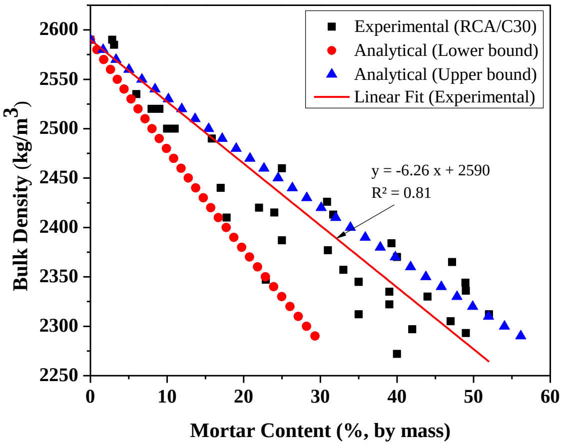

Figure 9: Comparison of analytical estimation and experimental results of mortar content for RCA obtained from C30 concrete

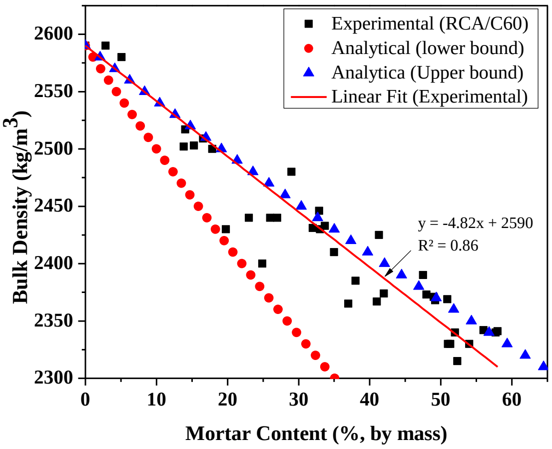

Figure 10: Comparison of analytical estimation and experimental results of mortar content for RCA obtained from C60 concrete

The difference in the slope for the two strength levels of parent concrete indicates the dependence of density on origin of parent concrete for the same percentage of mortar content by mass in RCA. It is noted that same constant is indicated for both cases as it represents the density of the natural coarse aggregate in the parent concrete.

Similarly, the relationships for 24-hr water absorption and Los Angeles abrasion loss are also close to linearity. The 24-hr water absorption relationship (Figure 11) also shows the influenced of the composition of the parent concrete. However, the relationship for Los Angeles abrasion loss (Figure 12) does not indicate such dependence. All the regression lines show R^2 values much higher than 0.5 to 0.6 from various sources as reported by De Juan et al (2009), thus demonstrating the improved reliability of the relationships based on more exact determination of mortar content and minimising the complex interaction of parameters in the experimental study.

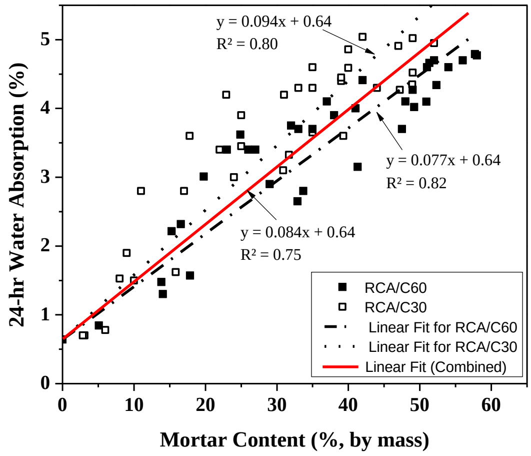

Figure 11: Relationship between 24-hr absorption and mortar content (% by mass) of RCA

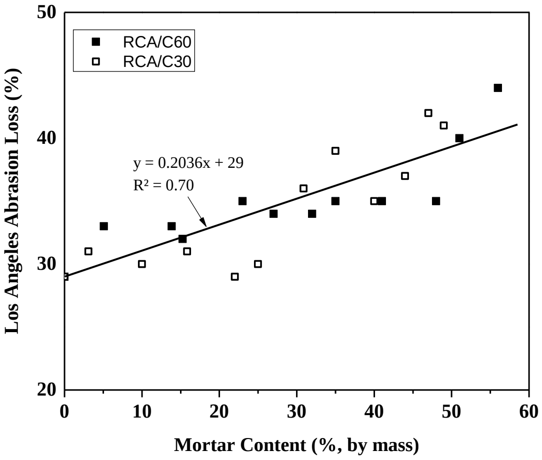

Figure 12: Relationship between Los Angeles abrasion loss and mortar content (% by mass) of RCA

4 EFFECTS OF PARENT CONCRETE PROPERTIES ON PROPERTIES OF RCA

The more important parameters that may affect quality and yield in RCA production include properties of parent concrete such as composition, compressive strength, types and grading of coarse aggregates, crushing equipment and procedures and size of the resultant RCA particles. The effects of these parameters overlap and interact with one another making it difficult to form firm conclusions for each individual parameter in isolation. The concomitant effects of some of these parameters were investigated by Akbarnezhad et al (2012b). Only the results for the concomitant effects of the compressive strength and size of the natural coarse aggregate (granite) in the parent concrete on bulk density, water absorption, Los Angeles loss of and compressive strength of RAC (RAC of 12 mm max. size and grading similar to that of natural coarse aggregate of 12 mm max. size in parent concretes) are presented in this paper. In addition, the effect of two different crushing procedures was also studied. The composition of parent concretes used to generate both RCA of 12 mm and 20 mm max. size (actual grading curves given in Akbarnezhad et al, 2012b) and their 28-day compressive strengths are as shown in Table 4.

Table 4 – Compositions and compressive strength of parent concretes used to produce RCA

	Concrete Class(Symbol for RCA Label)		
	C30(L)	C60(M)	C90(H)
Cement (kg/m^3)	282	375	480
Water (kg/m^3)	195	167	125
Superplasticizer (L/m^3)	0	2	15
Fine aggregate (kg/m^3)	804	736	758
Coarse aggregate (kg/m^3)			
Maximum. size 12 mm or 20 mm	1072	1072	1072
Average cube compressive strength (MPa)	27	63	88
(12 mm maximum size coarse aggregate)	29	61	85
(20 mm maximum size coarse aggregate)			

The types of coarse RCA generated from these parent concretes and their properties are tabulated in Table 5 where the first subscript for RCA indicates its maximum size (L for 12 mm and S for 12 mm), the second subscript indicates the concrete class of parent concrete (shown in Table 4, L for C30, M for C60 and H for C90) and the third subscript indicates the crushing procedure (1 for single stage with 25 mm jaw setting and 2 for two stages, first with 50 mm and second with 25 mm jaw setting).

4.1 Effect of compressive strength and maximum aggregate size in parent concrete

RCA produced from demolition of concrete structures may be of a wide range of parent concrete strengths. Hence, it is of interest to plot the results in Table 5 to note the effect of parent concrete strength on mortar content of different particle size of RCA generated from the three different strength levels (nominally, 30, 60 and 90 MPa) as shown in Figures 12 and 13 for maximum size of aggregate in parent concrete = 12 mm and 20 mm respectively. It can be noted that for both crushing procedure adopted, there is a general trend for all RCA size fractions to show higher mortar content for higher parent concrete strength. This may be attributed to the stronger bonding between mortar and aggregates as well as higher mortar strength in parent concrete of a higher strength. In the case of RCA of 12-20 mm size fraction, there is a tendency for RCA particles in parent concrete with maximum aggregate size of 12 mm to show a higher mortar content than the corresponding parent concrete with maximum aggregate size of 20 mm. RCA of 12-20 mm size fraction may be expected to consist of more Type IB particles as the maximum size aggregate in parent concrete is only 12 mm. The effect of these factors may lead to a greater scatter of mortar content when RCA is produced from a wide range of parent concrete strengths and of different maximum size aggregates from various demolition sites in other studies. The results also point to the benefit of more than a single stage of crushing to reduce the mortar content in production of RCA.

Table 5 – Properties of RCA generated from Parent Concretes

RCA Label	Mortar Content (% by mass)			Density (kg/m^3)			Water Absorption (% by mass)			Los Angeles Abrasion Loss* (%)
	4-8 mm	8-12 mm	12-20 mm	4-8 mm	8-12 mm	12-20 mm	4-8 mm	8-12 mm	12-20 mm	
RCA$_{LL1}$	41	46	24	2370	2365	2440	4.1	4.2	3.4	38
RCA$_{SL1}$	39	42	32	2375	2370	2430	3.9	4.1	3.9	35
RCA$_{LL2}$	37	29	12	2380	2450	2520	4.0	2.7	1.5	30
RCA$_{SL2}$	30	25	18	2430	2430	2500	3.8	3.7	2.4	29
RCA$_{LM1}$	54	51	38	2330	2330	2385	4.7	4.7	4.0	37
RCA$_{SM1}$	58	50	44	2340	2360	2365	4.9	4.4	4.2	39
RCA$_{LM2}$	52	23	26	2340	2440	2440	4.8	3.5	3.5	35
RCA$_{SM2}$	49	28	23	2370	2450	2430	4.4	2.7	3.7	36
RCA$_{LH1}$	62	43	47	2340	2375	2370	4.9	4.1	4.2	39
RCA$_{SH1}$	60	56	49	2335	2340	2360	5.1	4.8	4.4	38
RCA$_{LH2}$	42	38	27	2380	2385	2440	3.9	3.9	3.3	31
RCA$_{SH2}$	50	33	30	2370	2430	2430	4.2	3.8	3.8	34

* Test sample as per grading "C" specified in ASTM C131

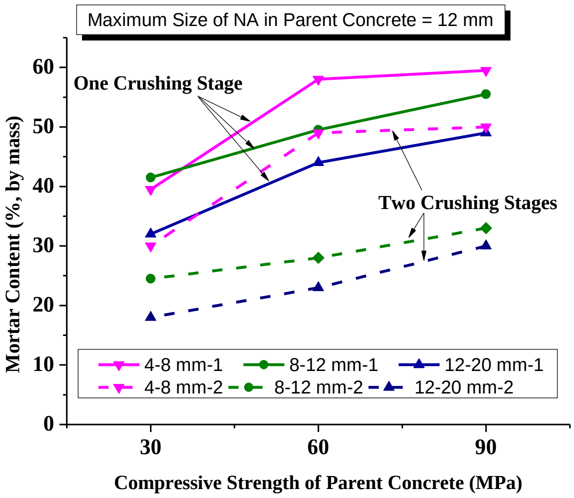

Figure 13: Effect of parent concrete strength (with 12 mm maximum aggregate) and crushing procedure on mortar content of RCA of different size fraction

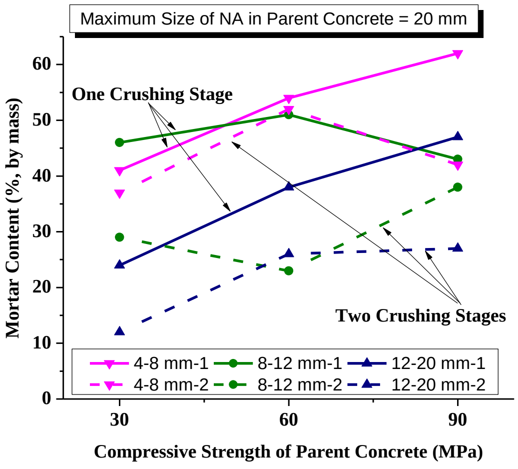

Figure 14: Effect of parent concrete strength (with 20 mm maximum aggregate) and crushing procedure on mortar content of RCA of different size fraction

5 CONCLUDING REMARKS

A series of controlled studies have been conducted, due to difficulties in isolating individual parameter and limited size and scope of the experimental programme, only tentative conclusions are possible on the effect of each independent parameter of major interest, such as strength of parent concrete, the maximum size of aggregate in parent concrete and the size of RCA particles generated (even from laboratory prepared concretes). However, the findings have enabled a better understanding of the role of mortar content of RCA on properties of RAC. Although not all the findings are presented in this paper, other properties of RCA and their effects on properties of RAC are reported in the references quoted, which contain greater details on the experimental programme and findings. Only some observed trends for RCA density and absorption are presented in this paper. Both density and water absorption values are good indicators of the quality of coarse RCA

A comparison of methods to enhance the quality of RCA is presented in Akbarnezhad et al, 2012a). A microwave-assisted beneficiation process was developed with the potential to provide an economic technique. In addition a new acid treatment technique for complete removal of mortar content in RCA was introduced which takes only around 24 hours for the process. This provides a potential practical approach to assess the mortar contend in RCA before incorporating it in the production of RAC.

It is recognised that further studies are needed to quantify and to ensure quality RCA is economically produced with the target to include both fine and coarse RCA in RAC. This enables RCA to be an alternate source of aggregates for concrete for sustainable concrete construction. A potential approach is to produce single-sized RCA (4 to 10 mm) in combination with single-size natural aggregate (10 to 20 mm) for better production control. It is expected that RCA will be around 30% to 40% of total coarse aggregate in concretes for which the effect on properties of RAC can be satisfactorily mitigated (Sri Ravindrarajah and Tam, 1985). This approach will not significantly change the total crushing cost in producing the coarse aggregates but with a much lower carbon footprint for sustainable concrete construction. The contribution of RCA as an alternate source of aggregates for concrete is feasible and further development to provide guidance on their appropriate use is recommended in future studies.

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