ACI CRC 18.517: Guideline Development for Use of Recycled Concrete Aggregates in New Concrete

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Chapter 1
INTRODUCTION

1.1 Executive Summary

The concrete design and construction industry has eagerly adopted sustainability initiatives over the last 20 years to help reduce its carbon footprint, improve economic sustainability, and ensure continued access to important natural resources that support the industry. Despite these advances recycled concrete aggregates (RCA) have been significantly underutilized even though they are becoming an increasingly available sustainable resource that can be used to reduce the amount of natural aggregates used in concrete. In areas where high quality aggregates are becoming scarce, and the cost to transport is increasing, the use of RCA can be both environmentally and economically advantageous. RCA's incorporation into concrete has been limited because of a lack of standardized guidance on creating mixture designs that will have predictable mechanical property and durability performance. This report outlines the current results of a project to develop those guidelines using a statistical analysis of existing literature.

This report includes a substantial coverage of recycled aggregate concrete (RAC) mechanical properties extracted from over 100 research articles that had been subjected to a thorough peer-review process. The data from those articles have been incorporated into a large database consisting of 932 compressive strength, 564 elastic modulus, 252 flexural strength, and 498 splitting tensile strength results of RCA. Performance of RAC systems has been preliminarily analyzed using non-linear regression analysis. Preliminary results presented in the report include an analysis of RCA replacement levels, aggregate properties, and gradation on overall mechanical property strengths. Then a statistical analysis was performed based on the factorial design concepts in order to understand the main effects of the factors that may influence the mechanical properties of RCA concrete systems and the generic trends when selected factors were changed within the pre-determined boundaries. Eventually, a robust and a computationally efficient methodology to generate RCA aggregates in concrete was developed by the authors, and the results on RCA mechanical properties (e.g., compressive strength and elastic modulus) have shown excellent agreements in comparison with the existing database analysis prepared for compressive strength and elastic modulus. Future iterations of these statistical analyses can be made with an expanded database as more information is available through continued research. The database has been made available online, and the authors hope to continue to update it over the coming years.

Overall, the RCA replacement ratio and the water-to-cement ratio had higher variabilities, while other factors such as mix proportioning parameters and aggregate properties had minor effects on the mechanical properties of RAC systems over the large dataset. Minimal strength loss was observed when RCA replacement levels increase above 20%. Results specifically focused on compressive strength, elastic modulus, flexural strength, and splitting tensile strength are presented. Aggregate-to-cement ratio and RCA replacement level were found to be the most significant factors that can cause major impact on RCA compressive strength at 95% confidence interval. Further, effective water-to-cement ratio was not significant at the 95% confidence level, yet, it showed a substantial main effect on the compressive strength response of RAC systems.

Durability properties of RCA have also been studied in this report. However, a major statistical analysis was not able to be completed due to the large variation of those testing methodologies used to quantify the durability properties. A substantial section of the report has been dedicated in the literature review on specific durability properties addressed in published journal articles. Durability properties on RCA such as shrinkage, creep, abrasion resistance, permeability, and freeze-thaw resistance were studied in this report and detailed in the literature review section.

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1.2 Project Scope

The scope of this report will focus on the creation of the database, current status of the literature review, and a preliminary statistical analysis of concrete mechanical properties of RAC systems through the use of the developed database. Additionally, the database created was used to validate a new computationally efficient method of analyzing RAC systems using randomly generated RCAs and finite element modeling of RAC. The four mechanical property factors; (1) compressive strength (f_c'), (2) modulus of elasticity (E_c), (3) flexural strength (f_r), and (4) splitting tensile strength (f_t) were chosen because they are the key parameters which directly govern the analysis and design criteria of reinforced concrete per ACI design codes[1,2]. With the current computational developments, the understanding of common trends in a large data set can be characterized by genetic programming[3], artificial neural networks[4–7], and linear, multi-linear, and non-linear regression analyses. Future work may want to consider the more advanced methods, however for the purposes of this report we have worked with more traditional statistical analysis techniques. This report compiles the datasets of more than 100 published articles that envelopes a wide range (i.e., from 1988 to 2018) of experimental results on above mentioned key parameters.

1.3 Project Significance on RCA

From the time where research interests started to expand after the World War II, there have been numerous efforts and studies that were performed to understand the material behavior of RCA as a supplementary material at full or partial replacement in lieu of the natural aggregates. However, due to the perception that a weaker material phase is attached to the natural aggregate (i.e. adhered mortar), a significant reluctance to use the materials in construction has been observed by the concrete suppliers, engineers, and owners[8]. Further, recycling of concrete demolition waste as recycled aggregates to partially or fully substitute natural aggregate has been recognized as an effective way to offset the shortage of natural aggregates, disposal of waste concrete, and related environmental issues[9,10].The goal of this work is to increase the utilization of recycled aggregates by providing advanced tools for concrete design using RCA that will support greater confidence in concrete quality of RAC systems.

1.4 Organization of Report

This report is organized into four chapters, including this brief introductory chapter. The major topics of each chapter are summarized below.

Chapter 2 provides a thorough background of the use of RCA aggregates in new concrete mixes and the variations of mechanical responses in concrete systems made of that. The main objective of this chapter is to provide a background on existing research findings that has been done by previous researchers on RCA. Further, a section is dedicated for RCA guidelines that have been adopted by different countries and agencies around the world who are producing RCA coarse aggregates.

Chapter 3 provides an illustrative project framework that was used to perform the database analysis, statistical analysis, and computational methodology to develop random aggregate structures for RAC systems to compare with the existing mechanical properties found in the database that was already created. This chapter contains detailed analysis procedures and statistical findings that may help in understanding the RCA material variability and how factors need to be manipulated to have a better RCA concrete performance. Eventually, a stepwise methodology was proposed to develop a mixture design procedure for RAC systems, and the it was used to determine concrete material proportions for a desired target compressive strength.

Chapter 4 provides a detailed summary of each task that was performed and elaborated in the previous chapter. Along with this, suggestions for next steps that can be done through ACI and ASTM documents for more standardized inclusion of RCA are proposed. Further recommendations for future work that needs to be addressed outside of the current project scope is also discussed in this chapter.

Chapter 2
LITERATURE REVIEW

2.1 General Information on Recycled Concrete Aggregates

Twenty-five billion tons of concrete is produced per year globally, which can result in a significant level of environmental impacts[11]. The fine and coarse aggregates generally occupy up to 60% to 75% of the concrete volume[12] (70% to 85% by mass) and thus, a large contribution in the environmental impact of concrete production is imposed by the mining, grading, and transporting of aggregates. Additionally, rapid industrialization and population growths have resulted in the increase of the demolition of older concrete structures to expand functional space and improve infrastructure worldwide. Therefore, using recycled concrete aggregate (RCA) as a supplementary material in new concrete systems (otherwise known as recycled aggregate concrete (RAC)) has now become a central focus in the material industry to enhance the sustainability of concrete production and to preserve natural resources[13–18]. Easy access to demolished materials can provide a sustainable stream of material that can partially replace natural aggregates for use in concrete. However, due to the lack of globally accepted technical guidance, long-term durability concerns, and the broad material variability of the aggregates sources, the usage of RAC systems has not been expansively practiced in concrete applications[8]. Existing consensus documentation such as European RILEM standards[19], Japanese Industrial Standards[20], German standards[21], ASTM C33[22], and the ACI 555 report[23] place certain limitations on the properties of the RCA for when they can be used in concrete. However, many of these limitations are based off of small sets of research, instead of driven from statistical analysis of large data sets.

As far as the concrete meso-structure is considered, the RAC system is a heterogeneous composite material consisting of natural aggregate, adhered mortar, cement mortar matrix, interfacial boundaries, and pores as shown in Fig. 1. When RCA materials from various sources are used in new concrete at full replacement levels in substitution of natural aggregates, the composite behavior of the that concrete system gets more complex than that of natural aggregate systems due to the high variety of material composition in RAC systems. RAC systems with partial replacement with virgin aggregates (i.e., source is different) further increases the material heterogeneity and consequently, it increases the complexity of the overall material behavior.

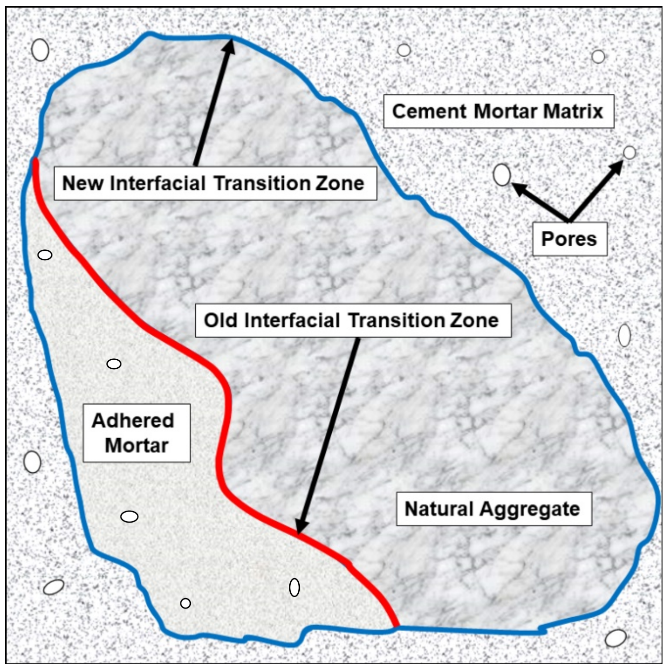


Fig. 1- Meso-scale material phases in RCA concrete systems

Strength properties of RAC systems depend on the mechanical properties of each material phase in the concrete, the impurity content[24–26] (e.g., brick, asphalt, plastic contents), and the morphological parameters such as angularity and roughness[27]. RCA quality can be quantified based on the production techniques which are being used to process RCA and various aggregate physical properties. The following subsection illustrates the existing findings of RCA qualitative indices to understand the diversity of the RCA material.

2.2 Qualitative Factors of RCA

2.2.1 Crushing and Grading Techniques

RCA is produced by crushing waste concrete with mechanically operated machines. RCA producers around the world utilize various mechanical devices to crush, process, and produce RCA. For example, both Russia and United States utilize specifically designed magnet separators and separating tables to divide reinforcement and lumber/plastic respectively, in which the bigger aggregates are being crushed by two primary and secondary impact crusher and sieved through a double screening device[28]. Such mechanical methods can improve not only the qualitative properties of the RCA final product with less-to-no physical impurities, but also ensure the consistency of the aggregate sizes for the use of different concrete applications. According to a comparative study on different recycling techniques around the world led by Xiao[29], it was identified that China used manpower to manually extract the large-scale impurity contents while continuously subjected to magnetic separation, screening and washing of RCA aggregates. Japan's recycling techniques adopted the same kind of aggregate separation where in addition, RCA were heated through a heating device at elevated temperatures (e.g. about 300ºC) to remove the weaker adhered mortar that might have attached on the natural aggregate. Weaker adhered mortar may exist due to the influence of the jaw-type crushing and there is a high possibility that micro-cracks could initiate from the crushing-action[30].

In Germany, recycling concrete plants use the same type of physical impurity separation method that Russia utilized, but the crushing mechanism is done using jaw-type crushers[28] like in Japan or China. Two types of crushing machines are shown in Fig. 2. Differing crushing operations could cause different impacts due to the crushing mechanism on the aggregate quality associated with the existence of micro-cracks (i.e., highly vulnerability for micro-cracks in jaw crushing process), many other countries use these two methods in producing RCA since both methods can efficiently break any type of hardened waste concrete material into smaller-sized particles. Therefore, further research into the physical characteristics of RCA after crushing is required, and further, aggregate qualitative testing needs to be performed to guarantee the applicability of recycled aggregates in general concrete aggregate purposes.

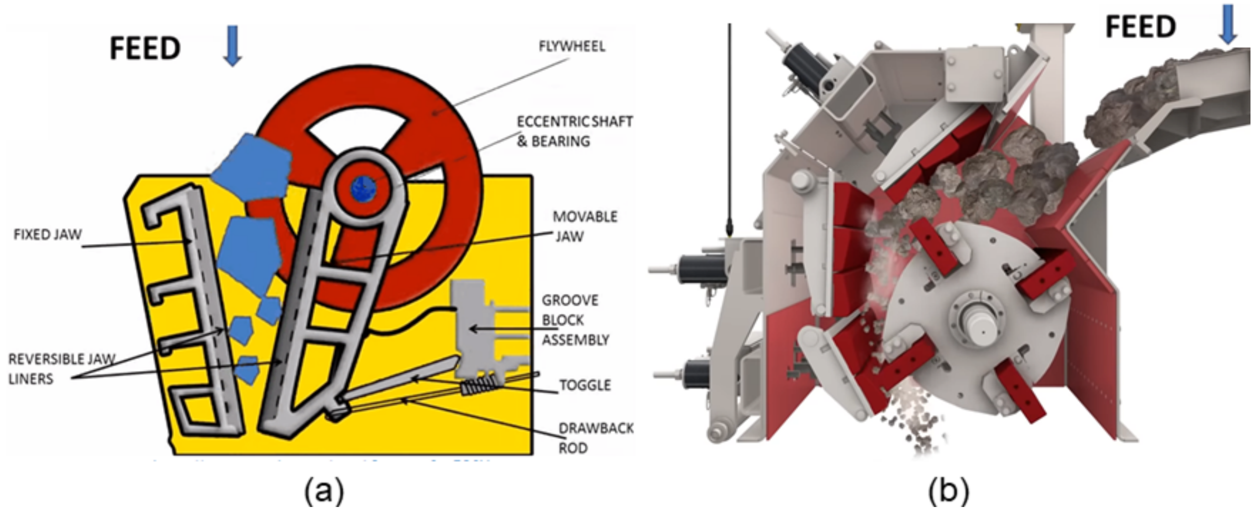


Fig. 2- RCA crusher types; (a) jaw-type crusher[31] (b) impact crusher[32]

2.2.2 Physical Properties of RCA

Unlike virgin aggregates, RCA particles are different because of the existence of adhered mortar that contributes to change the physical properties of RCA significantly. Therefore, the RCA quality depends on the physical properties that is governed by the individual material strengths of the material phases in RCA and the resistance against decaying or wearing mechanisms under external exposure conditions. Over the past several years, a series of investigations on the basic properties of RCA[24,33–40] have been carried out, and indicated that the different sources of waste concrete was the fundamental cause of randomness and variability of RCA properties.

2.2.2.1 Aggregate Gradation

The particle size distribution of aggregates, or gradation, is determined according to ASTM C136[41] in the United States, and similar methods worldwide. Although ASTM C136 is prescribed for natural aggregates, this same method is often used for assessing the gradation of RCA materials. Chen et al.[42] concluded that similar RCA gradation could be obtained similar to that of natural aggregates by using a crusher with the same maximum aggregate crushing size. Hansen[24] investigated that by using a jaw-type crusher in manufacturing RCA, could produce well-graded particle distribution ensuring a good packing density for a particular concrete mixture.

2.2.2.2 Density

The density of RCA can be calculated in the same way as for natural aggregates; i.e., for oven dry density, it is the oven dry mass of the total aggregates over a corresponding unit volume as shown in Equation 1.

$$Oven\ dry\ density = \frac{Oven\ dry\ solid\ mass}{Total\ volume\ of\ solid\ and\ pores} \tag{1}$$

Due to the inclusion of adhered mortar portion on RCA, which is porous in nature, the density of RCA particles is typically less than that of normal weight natural aggregates[43]. Aggregate density is a frequently used parameter for concrete mixture proportioning, and hence, the impact of adhered mortar on RCA density is an important factor. Table 1 reviews the previous research findings on RCA density. In general, the specific gravity of natural aggregate may vary between 2.5-2.8[44]. Based on the variability of those RCA relative densities, it was clear that the density of RCA particles was typically lower than natural aggregates[24] due to the attached mortar contents and the large variations of the derived source of RCA.

Table 1-Research findings on RCA density

Reference	Number of RCA sources	Relative density [oven dry]
Tam and Tam[34]	10	2.12~2.62
Buck[45]	4	2.36~2.59
Fathifazl[46]	2	2.31~2.42
Gokce et al.[47]	4	2.37~2.51
Abbas et al.[48]	2	2.31~4.2
Tu et al.[35]	1	2.35
Smith[49]	1	2.4

2.2.2.3 Porosity

RCA porosity has a high influence on the aggregate quality due to the presence of the adhered mortar phase with lower elastic modulus and toughness. An experimental study led by Abbas et al.[48] showed that the RCA porosity can be as high as 8.1-12.3 percent, calculated based on the data from the specific gravity tests[50]; whereas for natural aggregates, the porosity was as low as 0.9 for limestones, and 2.4 for river gravel aggregates. The high porosity may lead to stress concentration under external load and may result in the reduction of compressive strength of RAC compared to natural aggregate concrete systems[50].

2.2.2.4 Absorption Capacity

Due to the presence of high porosity in RCA particles, there is typically a higher absorption capacity compare to that of natural aggregates[43]. Due to such high absorption capacity, the water content of concrete mixtures using RCA has been found to be significantly increased. According to the ACI 555-01 report[23], the free water demand for RAC mixtures is 5% higher than that for natural aggregate concrete systems, when not using superplasticizers. However, the rate of absorption can influence fresh properties of concrete, and it may affect the shrinkage properties due to relative exchange of water from drying shrinkage during the hydration period. RCA particles in general, take a longer time to absorb moisture than natural aggregates during mixing period, and consequently, the aggregates may not be even in fully saturated state after the mixing period. Hence, it has been advised to presoak the RCA to compensate the slow water absorption rates before mixing[43].

A summary of research findings is shown in Table 2 and the range that the RCA absorption capacity varies (e.g., 0.57-11.6%) has been a significant focus when the quality of RCA is concerned. When higher RCA replacement levels are being used in new concrete, it has been observed that the water absorption rates have also increased proportionally[51–53].

Table 2- Research findings on RCA absorption capacity

Reference	Number of RCA sources	Absorption capacity [%]
Rahal[33]	1	3.47
Etxeberria et al.[54]	1	4.45
Movassaghi[55]	2	5.2~11.6
Gokce et al.[56]	2	3.19~5.58
Hansen and Narud[43]	3	5.7~6.0
Xiao and Falkner[57]	1	9.25
Tam and Tam[34]	10	0.57~8.74

2.2.2.5 Abrasion Resistance

Abrasion resistance is a measure of aggregate quality for coarse aggregates. The most common test for measuring the abrasion resistance of coarse aggregates is the Los Angeles abrasion test prescribed in ASTM C131[58] or Micro-Deval test in ASTM D6928[59]. This test method is performed for the mineral coarse aggregates that are smaller than 37.5 mm, and the test itself measures the degradation of the aggregates due to the combined actions including abrasion, impact, and grinding inside of a rotary steel drum with prescribed number of steel bearings. As the drum rotates, a thick steel plate is placed to pick up the well washed, oven dried aggregate sample (amounts depend upon the aggregate gradation) and the steel bearings to the topmost elevation inside the drum, and the content is released. Upon release, it creates an impact crushing effect on the aggregates due to the presence of heavy steel bearings. The contents are then continued to roll within the rotating drum subjecting the aggregates to abrasion and grinding until the steel plate holds the content for the next release. This process is continued for a prescribed number of cycles (i.e., number of cycles prescribed is 500 revolutions) depending on the frequency of the rotary drum (i.e., frequency is prescribed to be within 30-33 rpm), and eventually the aggregate sample is sieved over No. 12 mesh to measure the degradation as a percent mass loss.

However, the applicability of this method can be drastically limited for RCA, due to the inclusion of adhered mortar portions as a part of the RCA particles, and may be subjected to break off the adhered mortar easily at the interfacial transition zones. Therefore, it has been seen that the mass loss from the LA abrasion test were between 15-63% depending on the quality and the content of the adhered mortar attached to RCA particles[43,60,61]. Also, having a higher finer content in the attached mortar portion can lead to lower the abrasion resistance such that, the material can be easily susceptible for wearing and grinding action in the rotating drum[62]. Overall, considering the high mass loss of adhered mortar due to the brittleness and the low toughness, it is required to control some of the specifications prescribed in the ASTM C131 or implement new limitations based on the toughness (e.g. aggregate crushing index) of RCA source being selected. A summary of previous research on LA abrasion tests performed on RCA is presented in Table 3.

Table 3- Research findings on Los Angeles abrasion values of RCA

Reference	Number of RCA sources	mass loss [%]
Casuccio et al.[36]	2	34~39
Obla and Kim[63]	4	23.8~26
Hansen and Narud[43]	3	26.4~36.7
Tu et al.[35]	1	29.3
*De Juan and Gutierrez[53]	15	35~42
*Butler[64]	3	15.1~25

*Note: Asterisk (*) mark represents the studies performed under Micro-Deval apparatus.

2.2.2.6 Aggregate Crushing Index

Aggregate crushing index is a measure of aggregate strength under gradually applied compressive force. This property is a good indication of how RCA particles are in good quality or otherwise. A standard procedure can be found in British Standards: BS812:1990[65] to determine the aggregate crushing index. According to the standard, a well-washed, oven dried test specimen is compacted in three equal layers into a steel cylinder fitted with a freely moving plunger, where the specimen is subjected to a standard loading regime (e.g., 400 kN/10 mins +/- 30 sec) applied through it. The action crushes the aggregates to a degree which is dependent on the crushing resistance of the aggregates. The degree of aggregate crushing index is measured by sieving the crushed aggregates over a 2.36 mm sieve. The aggregate crushing index is determined by calculating the mass ratio between the original mass of the test specimen and the mass of the material passing the 2.36 mm sieve as a percent loss. The aggregate crushing index has no direct implication towards the overall strength of a concrete system made with RCA, as it could be influenced by the amount of adhered mortar content and the bond characteristics of RCA[27]. Therefore, this aggregate test is not a well-recommended procedure for RCA materials, as they are constantly weaker materials than natural/virgin aggregates. However, according to the standard specification given in BS 812:1990, Rahman et al.[66] extracted few limitations on the use of aggregate crushing index for different concrete applications made with RCA as follows.

- **Aggregate Crushing Index** < 25% → can be used in concrete for heavy duty floors

- 25% < **Aggregate Crushing Index** < 45% → can be used in concrete for wearing surfaces

- **Aggregate Crushing Index** > 45% → can be used for other secondary concrete applications

Previous research findings related to the aggregate crushing index of RCA are presented in Table 4.

Table 4- Research findings on RCA aggregate crushing indices

Reference	Number of RCA sources	Aggregate Crushing Index [%]
Katz[67]	1	24.3
Shayan and Xu[60]	1	24
Padmini et al.[37]	3	23~26
Hansen and Narud[43]	3	23.2~28.4
Sagoe-Crentsil et al.[68]	1	23.1

2.2.2.7 Soundness

Weathering resistance of aggregates are estimated by soundness testing through a repeated submersion in a sodium or magnesium sulfate solution, followed by oven drying to partially or completely dehydrate the salt precipitated in permeable pore spaces. Internal expansive forces upon rehydration through submerging the aggregates in the sulfate solution simulate the expansion of water under freezing. ASTM C88[69] is the standard practice for measuring the weathering resistance in aggregates. For coarse aggregates, a well washed, oven dried sample size (e.g., dried at 110+/- 5 ºC until constant mass is recorded) needs to be chosen depending on the maximum aggregate size (e.g., less than 100 mm) and the minimum aggregate size (e.g., larger than 4.75 mm) of the testing material (see section 7.3 of the Standard). Corresponding samples are fully immersed in a sulphate solution (i.e., either sodium or magnesium) for at least 16 to 18 hours. After the appropriate submersion time, the sample is removed from the solution and drained for extra 15 to 20 minutes and kept in a drying oven at 110+/- 5 ºC until a constant mass is recorded. The process of alternate immersion and drying is performed for several cycles (e.g. 5 cycles according to Roberts at al.[70]), then the aggregate samples are washed free from sulphate solution with barium chloride and running water, which is at 43+/- 6 ºC within the existing sample containers. The washed sample is then kept in a drying oven at 110+/- 5 ºC until a constant mass is recorded and finally, the loss in weight for each specific sieve size (see section 10.1.1) is computed as a percent mass loss. According to the standard specification, it is stated that extreme care should be exercised when using the type of the sulphate solution; accordingly, limits for percent loss allowed when magnesium sulphate is used are normally higher than limits when sodium sulphate is used. Regardless of which sulphate type is being used, due to the weak material phase attached to the natural aggregate (e.g. adhered mortar), research has shown that soundness testing may not be suitable for use with RCA. Hansen[24] found out that there were inconsistencies on the applicability of the test subjected for RCA, where it was reported that high contents of mass losses varied between 0.9 to 58.9%. Later, it was found and confirmed by Gokce et al.[47] and Abbas et al.[71] that the reason for such a high mass loss was due to the combination of washing and breaking off of the bond between the adhered mortar and the natural aggregate from the sulfate attack. The soundness testing method was designed for use with natural aggregates. The presence of adhered mortar, which will preferentially break off during the testing period tends to result in unusually high mass loss. Therefore, soundness testing is a severe testing methodology for RCA and does not represent a good quality measurement of the aggregates either.

2.2.2.8 Adhered Mortar Content

Currently, there is no standard procedure to evaluate the amount of adhered mortar content on RCA. Based on current literature, three methods are described, and the amounts of adhered mortar contents differ from each other due to the efficiency of the test method adopted for the evaluation. The amount of adhered mortar content is calculated based on the following expression given in Equation 2:

$$Adhered\ mortar\ content\ = \frac{Mass\ of\ RCA\ -\ Mass\ of\ RCA\ after\ removal\ of\ mortar}{Mass\ of\ RCA} \quad (2)$$

Nitric Acid Dissolution Method: The method was adapted from the work carried out by Movassaghi[55] and the test was done by immersing the aggregates in a 20% (by volume) nitric acid solution and heating the sample until the adhered mortar started to dissolve. This test was not recognized to be the best method to remove the attached mortar, due to the chemical degradation can be severely affected to those limestone aggregates and yield false quantifications. Also, the chemical attack is not 100% efficient in removing the entire adhered mortar phase off the natural aggregate due to the strong adherence between the two material phases. Further studies have shown that even with a cycle over 15-minute period in the Micro-Deval apparatus could not remove the attached mortar completely, owing to the stronger mortar-aggregate bond[72].It is possible that longer exposure at high concentrations of the acid could dissolve greater amounts of adhered mortar, yet, observations failed to confirm which aggregate experienced a higher dissolution of mortar[73]. Experimental findings have shown that nitric acid dissolution can contribute mass losses of 20% and 32% for two types of RCA[74].

Freeze and Thaw Method: This method is a combined breakdown of adhered mortar in RCA through mechanical stresses and chemical attack. The test procedure can be adopted by Abbas et al.[71] which is based on standardized guidelines provided in ASTM C88[69] and ASTM C666[75]. It was found that sodium sulphate was the most effective sulphate solution that can cause substantial disintegration of the adhered mortar[71]. Representative RCA sample is first oven dried until a constant mass is recorded at 105+/- 5 ºC and then the sample immersed in a 26% (by weight) sodium sulphate solution. While the sample is in the sulphate solution, it is subjected to five daily cycles of freezing and thawing consisting of 16 hours at -17 ºC followed by 18 hours at 80 ºC. After the final freeze-thaw, the aggregate sample is drained and washed as described in ASTM C88. Further hammering is allowed using a rubber mallet after the final freeze-thaw cycle for excess removal of adhered mortar. Finally, the aggregate sample is kept in an oven at 105+/- 5 ºC until a constant mass was reached, and the mass loss percent is measured after sieving the dry sample over a No. 4 sieve. The combined effects of mechanical and chemical attack have found to be extremely effective in removing higher adhered mortar contents (i.e., approximately 80-90% removal) upon inspection, compared to the nitric acid dissolution[72].

Thermal Expansion (Heat Treatment): The main mechanism of this method is to subject the RCA to a sudden temperature change where thermal stresses are generated upon cooling from an elevated temperature within a short period of time. This method is adopted from the work by Juan and Gutierrez[53]. At elevated temperatures more than 400 ºC, calcium hydroxide disintegrates upon subjecting to dehydration of cement mortar[76]. The test procedure is started by soaking the RCA sample under water for 24 hours and then, the sample is placed inside of a muffle furnace that can go up to an elevated temperature of at least 500 ºC for two hours. After keeping the sample for that long, the aggregate is then immediately transferred to a cold-water bath and sudden change of temperature can cause internal thermal stresses. While the aggregates are being cooled, the adhered mortar is turned into a brittle material and it can be easily removed by hand. Rubber hammers can be used for more contents of adhered mortar removal. Thereby, the remaining content is sieved over a No. 4 sieve and the material retained on the sieve is recorded as the initial mass and the adhered mortar particles are separated and weighed as adhered mortar mass. Upon inspection, heat treatment showed excellent adhered mortar removal capacity by showing nearly a 100% recovery[72].

The amount of adhered mortar content combined with the strength characteristics cumulatively affects the qualitative properties of RCA. In consideration of a typical RCA concrete, adhered mortar can exist between 25 to 65 percent by volume of aggregate content[43,46,53,55,71,72]. Depending on how RCA is produced; whether by using an impact crusher or a jaw-typed crusher, the adhered mortar content can be completely different due to the nature of the crushing action of those crusher types. For example, Etxerberria et al.[54] concluded that, an impact crushing process could yield higher percentage of RCA with minimum adhered mortar content, where those RCA particles were low in strength than the mortar produced in new concrete incorporating RCA. Research conducted on a variability study by Jayasuriya et al.[77] showed that, when the stiffness of the adhered mortar increases in RCA, the mean compressive strength of concrete made with those RCA was improved, and it indicated that, as the stiffness increased, the quality of RCA improved correspondingly.

2.3 RCA Specifications Adopted Around the World

Aggregate quality is a very important factor when strength-based and durability-based concrete productions are considered. There is a broad difference of waste concrete extracted through recycling from various RCA sources, and therefore, the analysis of the aggregate properties is significant. One main concern for using a classification method is due to the physical impurities that can influence the strength properties of concrete made with RCA. It was found that the strength of RCA concrete systems that had waste brick as impurities were 50% less than that of systems with only RCA[78]. Further, experimental work carried out by Peng et al.[79] concluded that, increased impurity content with waste brick decreased the overall RCA concrete strength by 15-25% than a control system consisted with only RCA particles. In addition to bricks, gypsum, asphalt, and wood chips can be of impurity contents that may hinder the elastic modulus of RCA concrete systems, and eventually, it may influence the strength of the concrete[25]. Therefore, it is clear that amounts of impurity contents need to be regulated when using RCA as coarse aggregates. Some countries, regions, or organizations around the worlds have proposed different methods of RCA classifications, and a brief summary is provided in the following subsection.

2.3.1 Hong Kong

The Hong Kong Civil Engineering Specifications started allowing for RCA in new concrete in 2001 after detailed laboratory investigations and plant trials[80]. Specification Works Bureau Technical Circular No.12/2002[81] "Specification facilitating the use of recycled aggregates" has two different applications for RCA used in concrete production; 1) for lower grade concrete applications, and 2) for higher grade concrete applications. For lower grade applications, concrete with 100% RCA is allowed, and recycled fine aggregates are not allowed to be used in the concrete, considering the risk associated with lower hardened and durability properties of concrete. The target strength is specified at 20 MPa and the concrete can be used in benches, stools, planter walls, concrete mass walls, and other minor concrete structures. For higher concrete grade applications that are less than 35 MPa strength requirements, the current specification allows a maximum of 20% replacement level of RCA excluding any type of concrete application related to water retaining structures. The specification requirements for RCA use in Hong Kong is shown in Table 5.

Table 5- RCA specification requirements prescribed in Hong Kong

Requirements	Limitation
Minimum dry particle density	2000 kg/m^3
Maximum water absorption	10%
Maximum content of wood and other materials less dense than water	0.5%
Maximum content of other foreign materials (e.g. metals, clay lumps, asphalt, glass, and tar, etc)	1%
Maximum content of sulphate	1%
Maximum contents of finer material (<4 mm)	5%
Maximum chloride content	0.05% (by mass of iron chloride of combined aggregate)
Flakiness index	40%

2.3.2 RILEM (European Union)

In 1998, RILEM published a specification for RCA particles[19] where this report addresses coarse recycled aggregates derived from three classes or categories. "Class I" was named for RCA obtained from masonry rubble, "Class II" was named for RCA obtained from waste concrete rubble, and "Class III" was named for a mixture of RCA and natural aggregates. Maximum allowance of RCA replacement from Class II was prescribed for 20% where no more than 10% of brick should be included as impurities. However, Class I and Class II can be used as 100% replacements. Table 6 represents the requirements adopted in RILEM specifications for each of those RCA classes. In addition, based on the RCA type, provisions for use as concrete aggregate along with a set of strength limits and durability compliance criteria are provided.

Table 6- RCA particle requirements prescribed in RILEM Standards

Requirement	Class I	Class II	Class III
Saturated dry density	1500 kg/m^3	2000 kg/m^3	2400 kg/m^3
Maximum content of material with SSD<2200 kg/m^3	-	10%	10%
Maximum content of material with SSD<1800 kg/m^3	10%	1%	1%
Maximum content of material with SSD<1000 kg/m^3	1%	0.5%	0.5%
Water absorption	20%	10%	3%
Maximum content of foreign materials (metals, glass, soft materials, bitumen)	5% (by volume)	1% (by volume)	1% (by volume)
Maximum content of metals	1% (by mass)	1% (by mass)	1% (by mass)
Maximum content of organic material	1% (by mass)	0.5% (by mass)	0.5% (by mass)
Maximum sulphate content	1% (by mass)	1% (by mass)	1% (by mass)

2.3.3 Japan

The Building Contractors Society of Japan has issued a document[82] that discusses about RCA classification. This document establishes a high/ lower limit for oven-dry density of RCA. The maximum design strength of RAC is determined by the type of recycled aggregates used which is controlled by the quality of the aggregates. Class L is considered as low-quality aggregates and, it is used for backfilling, filling, and levelling concrete as screed concrete. Class H is treated as high-quality aggregates and permits for normal concrete applications. The standard specifications for L and H classes of RCA are provided in JIS A 5023[83] and JIS A 5021[84] respectively. Table 7 illustrates the limitations of RCA usage in JIS A 5021[84]. Limitations presented in Table 7 are fairly comparable to those for conventional aggregates and, as a result, make the Japanese standard for high-quality coarse aggregates.

Table 7- RCA particle requirements prescribed in Japanese Standards JIS A 5021[84]

Requirements	Coarse Aggregate
Oven-dry density	≦2.5 g/cm^3
Water absorption	≦3%
LA abrasion	≦35%
Amount of material passing No. 200 sieve	≦1%
Chloride content	≦0.04%

2.3.4 China

Chinese specification has three categories for RCA classification based on their properties[85]. RCA requirements are listed in Table 8. The aggregate classes are defined based on the quality, quantified based on various aggregate properties such as chemical impurities, porosity, shape, and foreign materials attached. Class I maintains the highest quality to be utilized in structural applications whereas the Class III aggregates show low quality, which can only be used in non-structural concrete application.

Table 8- RCA particle requirements prescribed in Chinese Standards

Requirement	Class I	Class II	Class III
Water absorption	<3%	<5%	<8%
Apparent density	>2450 kg/m^3	>2350 kg/m^3	>2250 kg/m^3
Porosity	<47%	<50%	<53%
Content of clay by mass	<1%	<2%	<3%
Content of clay lumps by mass	<0.5%	<0.7%	<1.0%
Content of elongated and flaky particles	<10%		
Content of organic	Standard		
Sulfide and sulphate by mass	<2%		
Chloride by mass	<0.06%		
Other impurities	<1%		
Mass loss	<5%	<10%	<15%
Crushing Index	<12%	<20%	<30%

2.3.5 United States of America

The American Concrete Institute (ACI) does not have specific provisions in its current building code for concrete (ACI 318-14). However, guidance on use of RCA materials is mainly discussed by ACI technical committee 555 and their current state-of-the-art report[23]. In this report, impurity contents are discussed, and RCA specifications are provided in Table 9.

Table 9- RCA particle requirements prescribed in ACI 555-01R

Impurities	Lime plaster	Soil	Wood	Hydrated gypsum	Asphalt	Paint made vinyl acetate
Percentage of aggregate by volume	7%	5%	4%	3%	2%	0.2%

In ACI 221R[86], it has been specified that trial batches, extensive tests, chemical and petrographic analyses, and local performance records are of vital importance in the decisions regarding the use of RCA. The main reason that it requires thorough testing is because building rubble may contain deleterious amounts of brick, glass, gypsum, and any recycled concrete may contain reactive or poor-quality aggregates or high chloride contents. Aggregates made from municipal or industrial wastes (slags other than those from an iron blast furnace), recycled, or marginal materials may possess a number of undesirable physical and chemical qualities. Further, it explains that recycled materials should be specified and evaluated in accordance with ASTM C 33[22], except when the composition indicates the need for further specific requirements.

According to ASTM C33[22], when recycled fine aggregates are used for concrete subjected to abrasion, a gradation limits are allowed to increase from 0-3% to 0-5% passing of finer material than No. 200 sieve, considering more finer materials may exist due to the dust of fracture and clay contents. If the concrete is not subjected to abrasion, the gradation limits are further increased from 0-5% to 0-7%. Further, this specification advices to perform evaluations for environmental conditions such as, air quality, water quality, and storage by using appropriate local, state, and federal test methods in effect at the time of use. However, besides these information, ASTM C33 does not provide further provisions for classifying or guiding RCA usage on specific concrete applications.

AASHTO M80[87] permits the use of crushed concrete as aggregates, despite that it does not contain much provisions on RCA usage. It is noted that all crushed aggregates are required to satisfy the provisions of AASHTO M80. However, prior to the addition of this provision in AASHTO M80 standard, AASHTO M16[88] controlled the use of RCA in concrete. AASHTO MP16 mainly focused on aggregates used in non-structural applications. AASHTO MP16 categorized the RCA in three different classes; Class A, for aggregates subjected to severe exposure, Class B, for aggregates subjected to moderate exposure, and Class C for aggregates subjected to negligible exposure. Standard practice requirements for RCA in AASHTO MP16 is listed as shown in Table 10.

Table 10- Standard specification for RCA recommended in AASHTO MP 16

Requirements	Limitation
Maximum LA abrasion loss	50%
Soundness loss	12% (under sodium sulphate)
	18 (under magnesium sulphate
Amount of material passing No. 200 sieve	1.5%
Chlorite ion content	0.6 lb/yd^3 of concrete

2.3.6 Germany

German standards DIN 42226-100[89] was updated in 2002, and the standard allows the use of RCA in new concrete provided that it satisfies the requirements related to a particular aggregate class as shown in Table 11. Aggregates are categorized into four different types depending on the different levels of prescribed impurity levels due to various factors. The quality of the RCA types through Type 1 to Type 4 decreases and the applicability of these aggregates in structural concrete is limited. Therefore, it is recommended that Type 3 or higher RCA needs to be used in non-structural applications such as pavement, curbs, and pathways.

Table 11- RCA particle requirements prescribed in German standards

Requirement	Constituent by mass [%]			
	Type 1	Type 2	Type 3	Type 4
Concrete and natural aggregates	≥90	≥70	≦20	≥80
Clinker, no porous clay bricks	≦10	≦30	≥80	
Calcium silicate bricks			≦5	
Other mineral materials (e.g. porous brick, lightweight concrete, plaster, mortar, porous slag)	≦2	≦3	≦5	≦20
Asphalt	≦10	≦30	≦1	
Foreign substances (e.g. glass, plastic, metal, wood)	≦0.2	≦0.5	≦0.5	≦1
Oven dry density	≥2000 kg/m^3	≥2000 kg/m^3	≥1800 kg/m^3	≥1500 kg/m^3
Maximum water absorption (in 10 mins)	10%	15%	20%	No limit

2.3.7 Canada

The current limited use of RCA in Canada is not only related to its properties or performance, but also due to ambiguous characterization of the product in national, provincial, or municipal material standards and building codes. The Canadian Standards Association (CSA), for example, addresses RCA very loosely. A note to clause 4.2.3.1 in CSA A23.1-0990, advises particular attention be paid to deleterious substances, durability characteristics, potential alkali-aggregate reactivity, workability characteristics, and physical properties. Additionally, it states testing frequency may need to be increased to daily, depending on the RCA source and variability. However, CSA allows use of RCA as long as the resulting product meets its performance standards. The recent version of this Canadian Standard, published in 2014, included an Annex that describes the production and properties of aggregates produced from recycled concrete for use in hydraulic cement concrete was added.

2.4 Mechanical Properties of Recycled Concrete Aggregate Systems

RCA can be used as a partial or full replacement level in combination with or instead of natural aggregates in new concrete. A considerable amount of experimental research has been carried out to examine the mechanical behavior of RAC systems. In general, many researchers have noted that mechanical properties such as compressive strength, elastic modulus, tensile strength, and flexural strength of concrete systems made with RCA are not as high as concrete made with natural aggregates. However, it is unclear whether this was an inherent material deficiency, or because many early researchers added water to the mixtures to maintain workability in RCA mixtures. More recently, it has been found that through a careful material selection and mixture proportioning can meet or exceed the properties of concrete made with regular natural aggregates[54,77,91]. The following sections provide a brief overview of previous research on mechanical properties of RAC. Further analysis of this work will be provided in later sections.

2.4.1 Compressive Strength

Overall, the compressive strength is affected by a wide range of factors such as; water-to-cement ratio, type of cement, addition of admixtures, aggregate size and shape, moisture condition under curing, temperature, loading rate while testing etc. However, majority of the findings have concluded that the compressive strength of concrete made with RCA is typically lower than that of concrete made with natural aggregates by about 0% to 30%. The primary cause of such a drop was found to be due to the replacement ratio and the adopted water-to-cement ratio[25,54,92,93].

Similar compressive strengths were obtained by lowering the effective water-to cement ratio in the mixture design[37], and by increasing the cement content used[68]. The idea of increasing the cement content was to fill the porous area on the RCA particles with cement fines to increase the bond between the aggregate and the cement mortar matrix. Despite of this method yields similar RCA strength performance; it might not be as economical as expected. Higher compressive strengths properties have also made by using RCA extracted from high strength parent concrete sources[25,30]. The database of this project analyses a broad extend of those experimental findings on RCA compressive strength and a statistical analysis has been presented in Chapter 3.

2.4.2 Elastic modulus

Elastic modulus of concrete represents the elastic behavior of the material under an axial load. Since the RCA concrete system is composed of five heterogeneous materials, the elastic modulus is mainly governed by the equivalent stiffness of the composite material. Due to the inclusion of adhered mortar content, which is a weak, porous material phase, the elastic modulus of RAC systems has not shown promising results compared to natural aggregate concrete systems. Therefore, it has been found that the RCA elastic modulus is controlled by the density of the RCA aggregate[44,94]. In addition to the density of the aggregate, as the maximum aggregate size was reduced, the elastic modulus further reduced due to the combined effects of the increased surrounding area of the cement mortar paste in the concrete and the increased adhered mortar content in the system[37]. In general, it has been seen that the elastic modulus was decreased by about 5% to 20% than compared to a concrete system made with natural aggreagtes[25,37,67,95].

2.4.3 Tensile Strength

The tensile strength of concrete varies between 8% and 15% of the compressive strength. Majority of the literature findings showed that the tensile strength of RAC systems were lower than that of natural aggregate concrete systems[24,37,96]. Safiuddin et al.[97] conducted an experiment that turned out to have a similar tensile strength for both concrete systems made with natural aggregate and RCA. Etxeberria[54] showed that the splitting tensile strength of RAC systems were higher than the controlled natural aggregate systems. These finding were attributed by the absorption capacity of the adhered mortar on the

RCA particles that contributed to lower the effective water-to-cement ratio in the mixture, and the new interfacial transition zone with a stronger bond between the aggregate and the cement paste around it.

2.4.4 Flexural Strength

Flexural strength or modulus of rupture is an important hardened property when concrete used for pavements or slabs on grade. Abou-Zeid et al.[98] found that the flexural strength of recycled aggregate concrete systems were similar or slightly less than the systems made with natural aggregates. This was attributed to a superior bond between the RCA and the cement binder due to the rough surface and angularity of the aggregate, and it is presumed to be due to some sort of a reaction between the RCA and the surrounding cement paste.

2.5 Durability Properties of Recycled Concrete Aggregate Systems

When concrete has good durability, it is better able to withstand chemical attacks, actions due to abrasion or weathering, surface scaling, or other methods of deterioration. Despite of the fact that there is not enough research out in the literature for RAC systems' long-term durability properties, specific studies have been studied in this report addressing major durability issues that can be mostly relevant for RCA concrete systems.

2.5.1 Shrinkage and Creep

As discussed, significant portions of an RCA particles are composed of porous adhered mortar phase. Due to the high absorption capacities in RCA, relative movements of pore water in the capillary pores can be expected during hydration process. Hansen[24] reported that drying shrinkage can go up to 50% more than that of natural aggregate concrete systems. Having a higher paste content (i.e., adhered mortar and cement paste matrix in RAC systems) has been found to be less dimensionally stable than natural aggregate[44]. Due to the increased old mortar content, the drying shrinkage of RAC systems increased with the increasing RCA replacement level[99,100]. An investigation was experimentally tested by Adams et al.[101] on the cracking susceptibility of RAC systems during drying shrinkage. It was demonstrated that the use of RCA can significantly reduce the cracking risk of concrete against drying shrinkage and higher concrete performances (e.g., compressive strength, tensile strength, elastic modulus) were achieved when residual mortar content was less than 20%. Computationally, the cracking propensity was examined with the increase of adhered mortar content for a constant aggregate geometry by Jayasuriya et al.[102] where the study showed that the cracking potential alleviated as the adhered mortar was increased from 0% to 100% attributed by the stiffness compatibility of the materials at higher adhered mortar contents.

Creep in RCA concrete systems can be exacerbated due to the increase of replacement levels of RCA[99,103]. Further, Gomez-Soberon[103] found that even with 15% increment of RCA replacement can result 24% higher creep compared to a natural aggregate concrete system. Creep is more common in RCA due to the two-phased material nature of the aggregate with one phase (i.e., natural aggregate) is strong enough for internal deformation in the cement paste where the other phase (i.e., adhered mortar) is less restraint against shrinkage.

2.5.2 Abrasion Resistance

Abrasion resistance in RCA concrete systems are performed on a horizontal concrete surface by subjecting to an abrasive force exposed to several cycles where abrasion depth is measured as an indicator to assess how resistant the concrete is. Since the test is too severe on RCA related concretes due to the variability of adhered mortar strengths, the results have not been consistently reported in the literature. Dhir et al.[104] found that RAC systems with 50% replacement ratio showed similar performance in abrasion resistance compared to natural aggregate systems. When RCA replacement level was increased to 100%, the abrasion depth increased by 34% than natural aggregate concrete system[104]. Experimental attempts on RCA concrete system's abrasion resistance were made by Limbachiya et al.[105] and the results were uncorrelatable between the replacement level and the abrasion depth. A 30% RCA replacement initiated an abrasion depth of 0.81 mm, and when the RCA replacement level was increased to 50%, the abrasion depth reduced to 0.69 mm. Surprisingly, when the RCA replacement level was increased to 100% the abrasion depth was 0.79 mm. The primary reason for these inconsistencies is due to the material property variability in RCA aggregates where weaker adhered mortar phases essentially can be easily worn out during the force cycle.

2.5.3 Permeability

Permeability can increase the risk of concrete deterioration due to the intrusion of deleterious substances such as carbon dioxide, chloride, sulphate, and even moisture. Due to the porous material phase in RCA, the concrete made with RCA has a substantial porosity compared to natural aggerate concrete. Limbachiya et al.[105] used three RCA replacement levels including 30%, 50%,100%, and it showed that the carbonation effects on those RAC systems performed negligible, better, and best respectively. Similarly, Levy and Helene[51] showed the same carbonation trends with improved performance with the increased RCA replacement levels. Contradictorily, Sagoe-Crentsil et al.[68] showed the RAC systems with 100% replacement with natural aggregates were worst in carbonation performance. Partly, in support of this research finding by Sagoe-Crentsil et al.[68], Dhir et al.[104] confirmed that RCA replacements of more than 50% showed worst performance and vice versa for RCA replacement levels less than 50%.

Shayan and Xu[60] concluded that RAC systems are very good in resisting the chloride penetration when silica fume was used as a supplementary cementing material and help prevent corrosion happening over time through making a dense concrete material. Otsuki et al.[106] reported that chloride penetration showed an increase in RAC systems than natural aggregate concrete systems, but not at a significant level.

Sulphate attack on RAC systems can lead to initiate cracking, spalling, and loss of concrete integrity upon delayed ettringite formation. Since RAC systems has a wide network of interfacial transition zone (i.e., old and new), internal concrete pressure due to the formation of ettringite may easily deteriorate the concrete system. It was found by Limbachiya et al.[105] that, when the RCA replacement level was increased, the tested mortar bars were subjected to severe exposure to sulphate attack. Dhir et al.[104] showed that the mortar bar expansions were quite the same as was seen in natural aggregate concrete systems up to 30% of RCA replacement level, and, at 100% RCA replacement level, mortar bar expansion was about 68% than that was observed in natural aggregate concrete system mortar bars.

2.5.4 Freeze and Thaw Resistance

Researchers have found that cracking upon freezing and thawing may be more likely when saturated aggregates are used in the concrete[44]. However, it is reported that the freeze and thaw damage resistance of RAC systems is similar to that for natural aggregate systems[45,56,104,105]. Air entrainment plays a significant role in freeze and thaw resistance for concrete with RCA, and even with small amounts of non-air entrained RCA showed a substantial loss of freeze thaw resistance[56]. Therefore, it is advised to choose proper air entrainment depending on the severity of the freeze thaw exposure, and also use RCA that come from concrete that was previously air entrained, while balancing the porosity of the RAC system without compromising the compressive strength of the concrete.

Chapter 3
PROJECT OUTCOMES

3.1 Project Objective

Due to the heterogeneity of concrete systems and disparity in types of systems used, no large-scale empirical results can be drawn from these specific articles. Hence, recycled aggregate concrete (RAC) systems may exhibit broad performance diversity by adopting countless types of parent concretes as recycled concrete aggregate (RCA) with larger material property varieties and inefficient mixing approaches that can eventually pertain higher variabilities in RCA concrete mechanical performances. Current standards for developing concrete mixtures were developed through the use of statistically driven analysis of empirical results from various concrete mixtures[3]. This same approach should be used for creating guidelines for the use of RCA.

The main goal of this study is to use statistical analysis tools to use existing data to create RAC performance predictions using given inputs. The study adopted a large-scale database analysis, and used to understand the common trends related to following mechanical properties of RAC systems:

- Compressive strength (f_c')
- Elastic modulus (E_c)
- Flexural strength (f_r)
- Splitting tensile strength (f_t)

3.2 Data Collection Process

To establish a database system on RCA properties, a large scope of experimental studies was reviewed during the data collection phase. Articles are chosen based on the abstracts provided and the information contained. A thorough cross section of articles has been searched for, in order to ensure that the international research community is well represented. Multiple international databases such as Google Scholar, Web of Science, American Society of Civil Engineers, ASTM International, Elsevier, SCOPUS as well as selected individual journals were used to locate data for this work. Articles were read, catalogued, and summarized. Data was then extracted from the articles and entered into the database. The research team also ensured that the data in one article was not simply a replicate of data in a second article, but was new research that was not already existing in the database (i.e. data from the same sample set used for multiple articles, or data presented in review articles, was not included).

Keywords related to the current topic were very useful to obtain the most relevant data from those articles. Then, the results were reviewed and entered into the database. Data derived from computational analyses were not recorded, as the research team decided to limit the scope to experimental data only. Additionally, RAC systems that used recycled fine aggregates were not included in order to limit the number of variables that were examined . A flow diagram of the article selection and review process can be observed in Fig. 3. Data extraction was done in two different ways. If data was presented in tabular format, the data was entered directly into database as reported in the article. Graphical data is processed through a program called Plot Digitizer[107] which takes scanned graphical images and reads data points off of the graph. Once extracted, the data is then entered into the database.

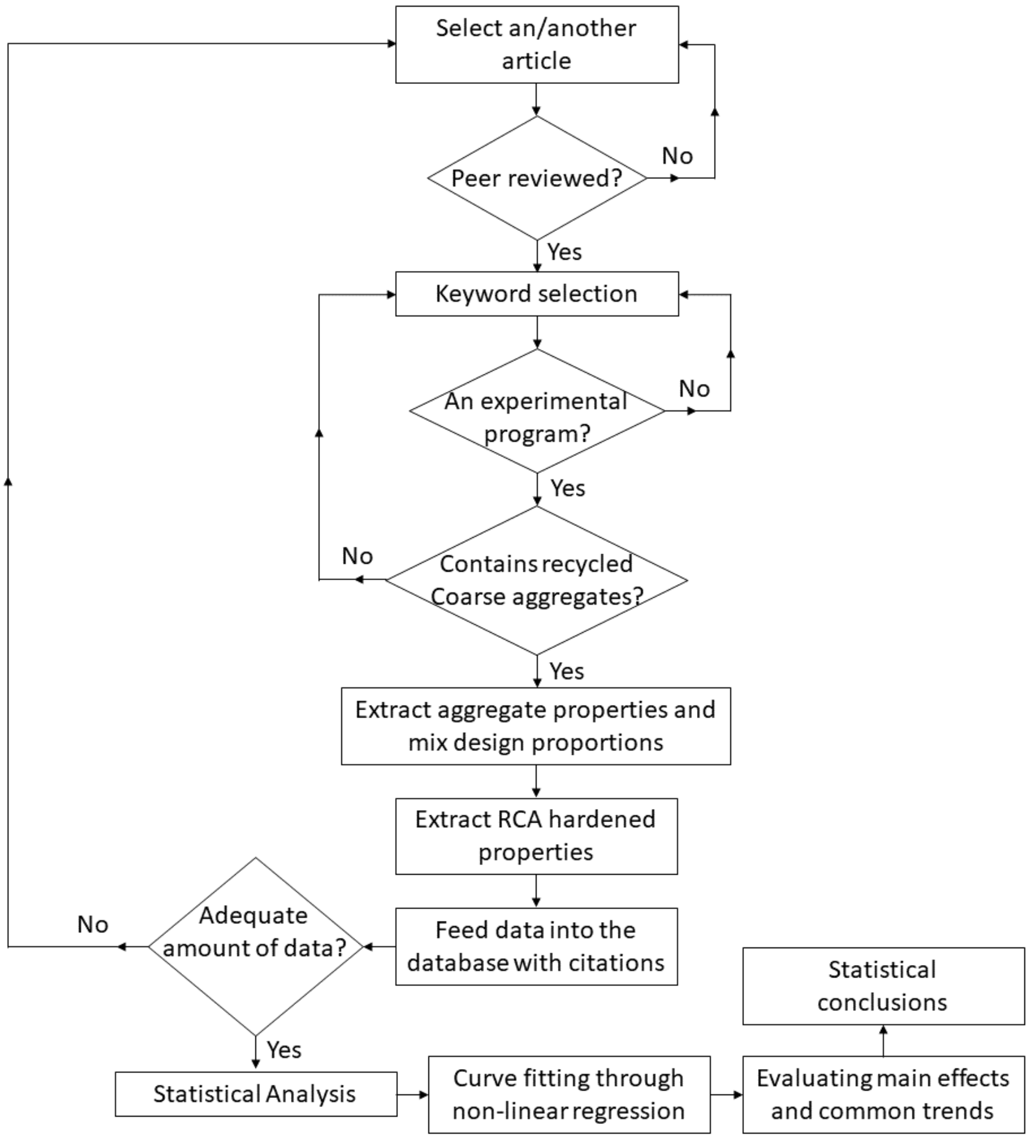


Fig. 3- Review process of the database creation from start to end

3.3 Database Creation

The access to the current RCA concrete database is provided at the end of the report. About 2250 mechanical property data on RCA concrete compressive strength (932 samples), elastic modulus (564 samples), flexural strength (252 samples), and splitting tensile strength (498 samples) results were obtained through the extensive literature investigation. The experimental results on compressive strength in the database was sub-divided into two categories: 1) cylindrical specimen and 2) cubic specimen strengths. For evaluating the elastic modulus and the splitting tensile strength of RAC systems, only data from tests using cylindrical specimens were considered, whereas the flexural strengths of RAC systems were obtained through beam testing. Due to the large variabilities across the experimental procedures that various authors have adopted, the specimen sizes (i.e. 4 in x 8 in cylinders or 8 in x 12 in cylinders) are different from one experiment to the other, but were considered together in the same grouping. The database includes the specimen types and the corresponding sizes accordingly.

There are many factors that can affect the performance of mechanical properties in RAC systems depending on the materials and the mixing approach that had been used in the experiments. Therefore, the data contains the following factors for each mechanical property that was carried out with individual mixtures:

- Replacement level (based on mass replacement)
- Effective water-to-cement ratio (either as reported, or calculated based on documentation in the paper. If effective/not-effective was not provided, the reported w/c ratio was assumed to be the effective water-to-cement ratio)
- Total aggregate-to-cement ratio
- Maximum aggregate size (RCA and natural aggregate)
- RCA water absorption capacity
- Natural aggregate water absorption capacity
- Slump
- Specimen type tested for the hardened properties.

3.4 Analysis and Results

Despite of the large variabilities in the dataset, an efficient way of representing the mechanical properties of RCA was identified, where the RCA replacement level was broken into small class widths containing 0%, 1-20%, 21-40%, 41-60%, 61-80%, and 100%, and the mechanical properties were exhibited against the effective water-to-cement ratios. Concrete systems with RCA replacements between 81-99% had only one data (e.g. 90%) in the database, and since the scarcity of data may lead to false interpretations on a wide range of RCA replacement of such, that particular data was omitted in the statistical analysis. This approach was reasonable, as other factors related to aggregate properties and the mix proportioning parameters did not change noticeably over the dataset. Additionally, the effective water-to-cement ratio is the key parameter that governs the strength properties of concrete systems, and thus, it was chosen as the explanatory variable in the analysis. The predictor variables were set to the RCA mechanical properties for cylinder compressive strength, cube compressive strength, elastic modulus, flexural strength, and splitting tensile strength.

3.4.1 Variation of Compressive Strength

Data that was included in the database comprised of 28-day compressive strength results for all the testing specimens. In order to see the effects of RCA replacement level on the 28-day compressive strength of RAC systems, a special class boundary scheme was adopted as 0%, 1-10%, 11-20%, 21-30%, 31-40%, 41-50%, 51-60%, 61-70%, 71-80%, 81-90%, and 100%. Replacement levels were based on mass replacement of aggregates, using only a single source of RCA material. Tight class boundaries were selected to observe the continuous trends of compressive strength over the RCA replacement levels, in case of sudden variations might be undetected at high class widths. Additionally, there was significantly more data available representing the replacement ratios when considering compressive strength only. For other mechanical properties, the amount of data restricted the reliability of smaller class size findings.

In Fig. 4 it can be observed that up to 20% of RCA replacement contributed in increasing the mean compressive strength by 14.6% (e.g., 44.7 MPa to 51.2 MPa) of RAC systems. Further, 11-20% RCA replacement level class width produced the best compressive strength performance considering the overall compressive strengths of the RAC systems analyzed throughout the database. It was noticeable that the mean compressive strength exhibited three local peak strength values at 11-20%, 41-50%, and 100% regardless of the overall strength evolution over the RCA replacement. This is attributed to the aggregate interaction between the adhered mortar and the cement paste contributing a good stiffness compatibility of the RAC system. The aggregate interaction can be influenced by the material properties, material morphologies, and spatial distribution of aggregate geometries inside the body of concrete. When RCA replacement is increased, not only is the RCA stiffness compatibility increased (i.e., owing to high adhered mortar content), but also the amount of roughness area which is associated with the RCA aggregate texture is increased. Due to this reason, it can be explained as to why, at 11-20% RCA replacement levels, the hardened strength properties performed well. Contradictorily, when RCA replacement levels are increased, the existence of widespread ITZ regions (i.e., both new and old ITZ are treated as the weakest link in the concrete) are increased which are oriented in random directions of the aggregate geometry. It has been numerically observed by Jayasuriya et al.[108] that the damage of RAC systems were expedited when old ITZ geometries were aligned in the same direction of the loading plane while testing the uniaxial compressive strength. Therefore, due to the existence of a large distribution of ITZ phases and depending on their geometric orientations, the compressive strengths can be drastically limited, and correspondingly, similar trends were observed with lower performance at 1-10%, 21-30%,31-40%, 51-60%, 61-70, and 71-80% RCA replacements while other replacement showed local peaks of compressive strengths.

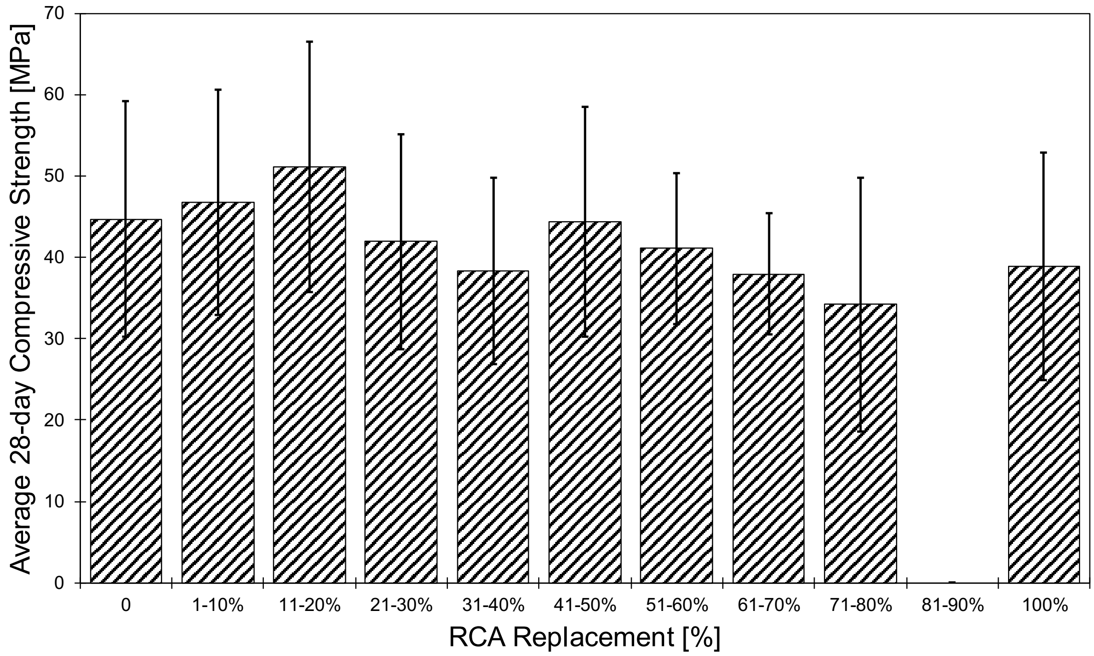


Fig. 4- Mean compressive strength variation of RAC systems over RCA replacement levels

The average compressive strength of each specimen type corresponding to individual replacement level was obtained and the statistical trends showed that the cube compressive strength was always higher than the cylinder strength. The data was subdivided into two categories where both cube and cylinder strengths were plotted against each other and it was seen that the general trends were the same as observed as before throughout the RCA replacement level class widths, despite of the difference between the cube and cylinder strengths. The strength fluctuation is shown in Fig. 5, displaying compressive strengths for both cube and cylinder specimens.

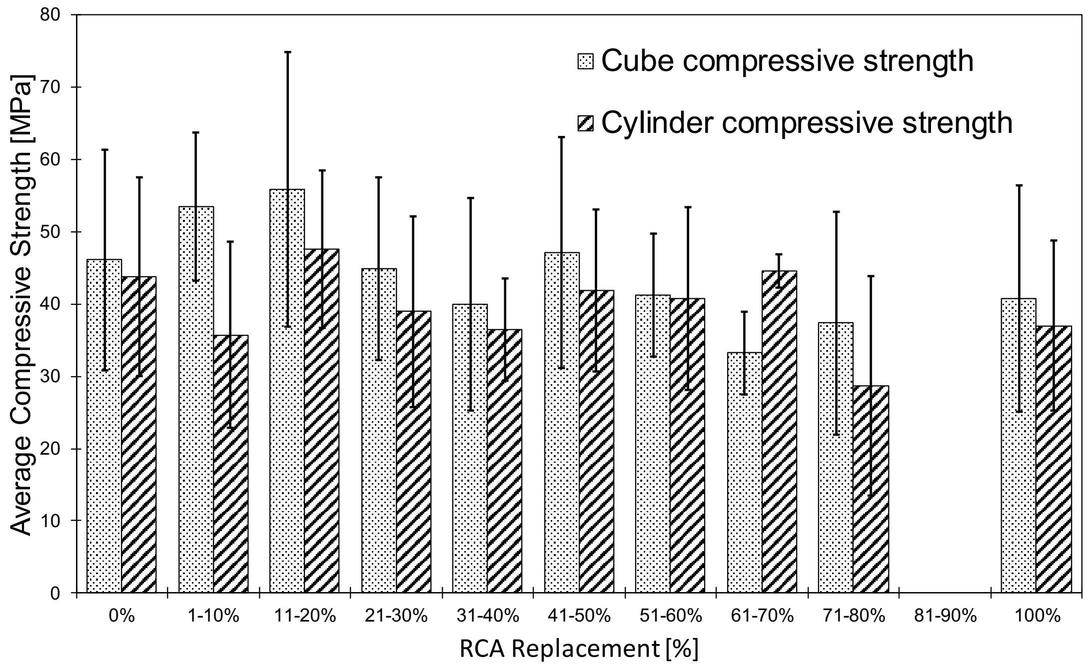


Fig. 5- Comparison of compressive strength cast from two different specimen types

Overall, the mean compressive strength of RAC systems against the effective water-to-cement ratio obtained in the database is represented in Fig. 6 using scattered plots at 0%, 1-20%, 21-40%, 41-60%, 61-80%, and 100% RCA replacement levels. RCA replacement levels between 81-99% had only one data in the database, and it was decided to be discarded in the statistical analysis and avoided unnecessary statistical interpretations over a such RCA replacement range. The sample data sets were fitted to a nonlinear regression scheme with an exponentially decaying function. Concrete systems with no RCA replacements showed a moderate-to-good data clustering around the predicted nonlinear expression depicted on the plot exhibiting a correlation of coefficient (r) of 0.5. This value was affected by a few outliers but exhibited a good data correlation. Statistically, an outlier is defined when a data lies beyond the limits greater than 1.5 times of the inter-quartile range below the first quartile and above the third quartile. When RCA replacement was increased from 1% to 60%, the r value was reduced from 0.55 to 0.3 owing to the distribution of data outliers. However, r value increased from 0.3 to 0.44 with the RCA replacement increment from 61% to 100%, regardless of those existing outliers. It showed that, regardless of the mean compressive strength value was reduced at higher RCA replacements (e.g., >60%), the data distribution had higher correlation effects experiencing a lower variability. Lower variability was attributed due to the increased material homogeneity in the concrete system, and there are few other factors that can influence the variability of the compressive strength performance. At higher RCA replacement levels, the amount of RCA contact area between adhered mortar phase and cement paste matrix is higher, such that it provides a relatively good adherence due to the rough texture of the RCA hardened portion. Therefore, depending on the morphological parameters (e.g., roughness or texture) of RCA particles can impose a substantial influence on the material performance variability in which can be difficult to account for. Further, in consideration of the high porosity of RCA particles, the low aggregate-to-cement ratio can contribute a significant variability on the compressive strength through filling the pores with finer cement and consequently, increase the strength of the RAC system or vice versa.

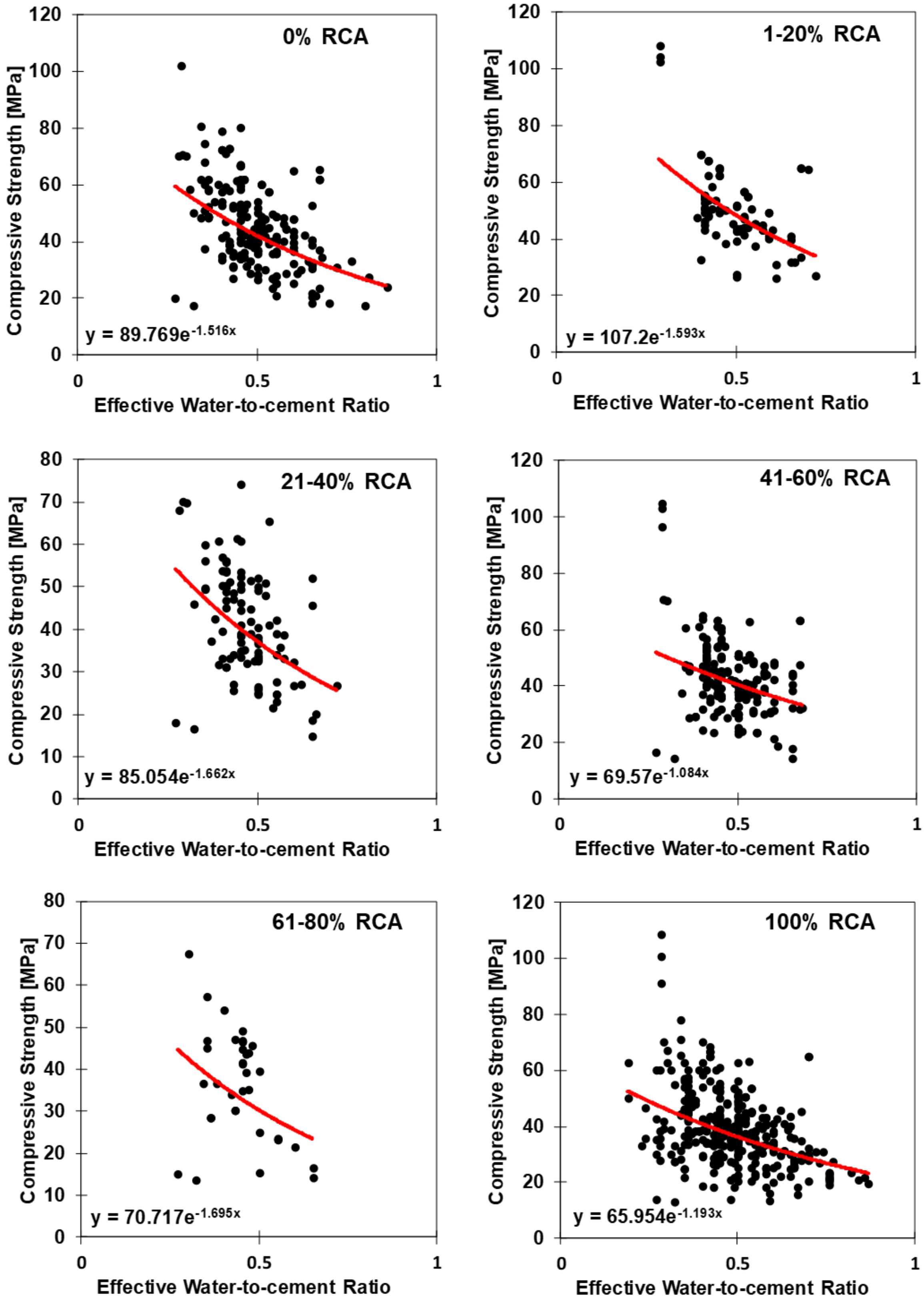


Fig. 6- Variation of RCA compressive strength with effective water-to-cement ratio

3.4.2 Variation of Elastic Modulus

The variation of the average elastic modulus is shown in Fig. 7 with corresponding replacement level class widths. Highest elastic modulus response was shown at 1-20% replacement level, where it showed a clear degradation with the increased RCA replacement level. The elastic modulus of RAC systems was reduced due to the increased adhered mortar content at high RCA replacement levels. The higher it increases the adhered mortar content, lower the aggregate stiffness will be, and consequently, the overall RCA concrete stiffness (i.e., elastic modulus) was drastically reduced at high RCA replacement levels.

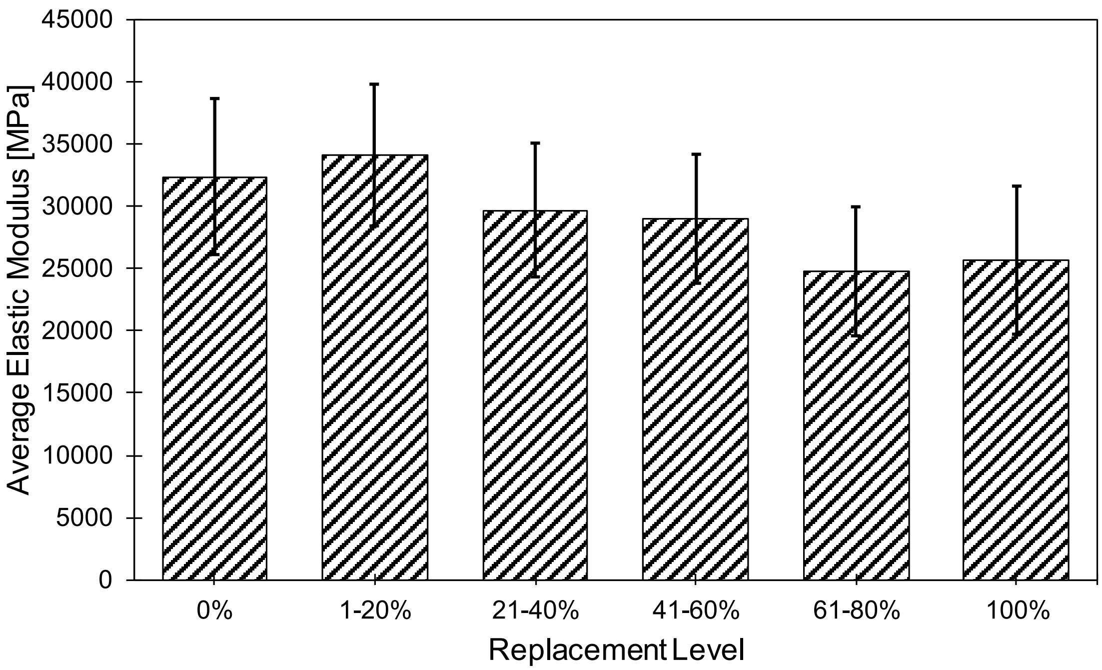


Fig. 7- Mean elastic modulus variation of RAC systems over RCA replacement levels

Variation of elastic modulus with effective water-to-cement ratio at different RCA replacement levels is shown in Fig. 8. The data sets were fitted to an exponential function and it was observed that the exponential behavior of the elastic modus data deviated to a linear trend with the increased RCA replacement. This behavior was mostly due to the material stiffness homogenization of the concrete system associated with high adhered mortar content at high RCA replacement levels.

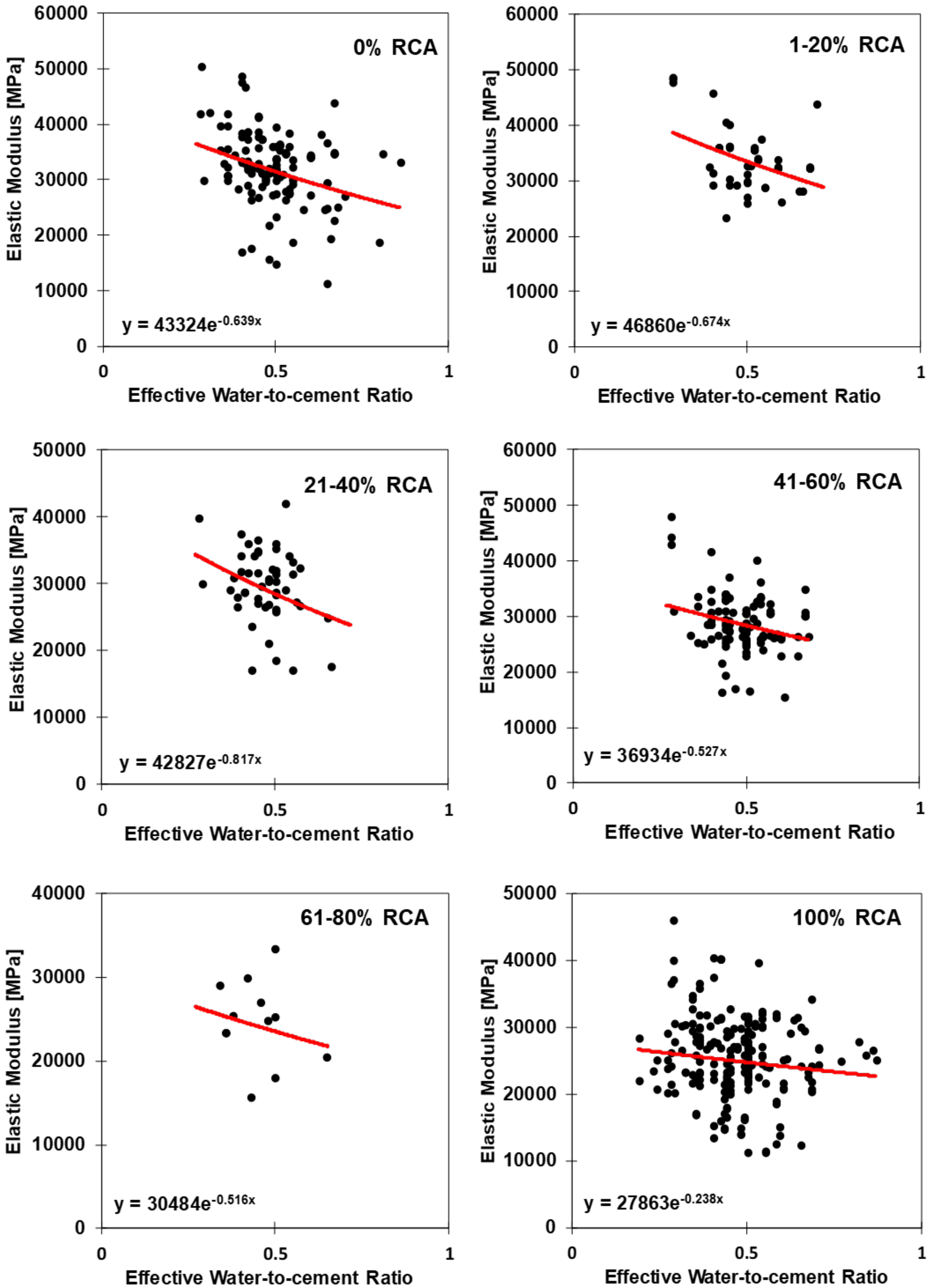


Fig. 8- Variation of RCA elastic modulus with effective water-to-cement ratio

3.4.3 Variation of Splitting Tensile Strength

Variation of the mean splitting tensile strength of RAC systems at each RCA replacement level is shown in Fig. *9*. According to the data collected, the tensile strength of RAC systems showed a continuous degradation as the RCA replacement level was increased from 1% to 80%. The main reason for the loss of strength is attributed to the weak bond between the main material phases (e.g., new and old ITZ) in the concrete system under the indirect tensile stresses applied. However, at 100% RCA replacement, the strength increased over that of at 61-80%, but it was lower than the remaining RCA replacement level class bins. At 100% RCA replacement level, the percent of adhered mortar content is much higher than at 61-80% RCA replacement level. High existence of this material phase (i.e., adhered mortar) contributed an increased overall homogeneity of the concrete system such that, the accumulation of indirect tensile stresses delayed from being reached up to its capacity[77,102]. Therefore, at 100% RCA replacement level, a potential cracking resistance was observed allowing the material to deform without failing under indirect tensile stresses to a certain extent.

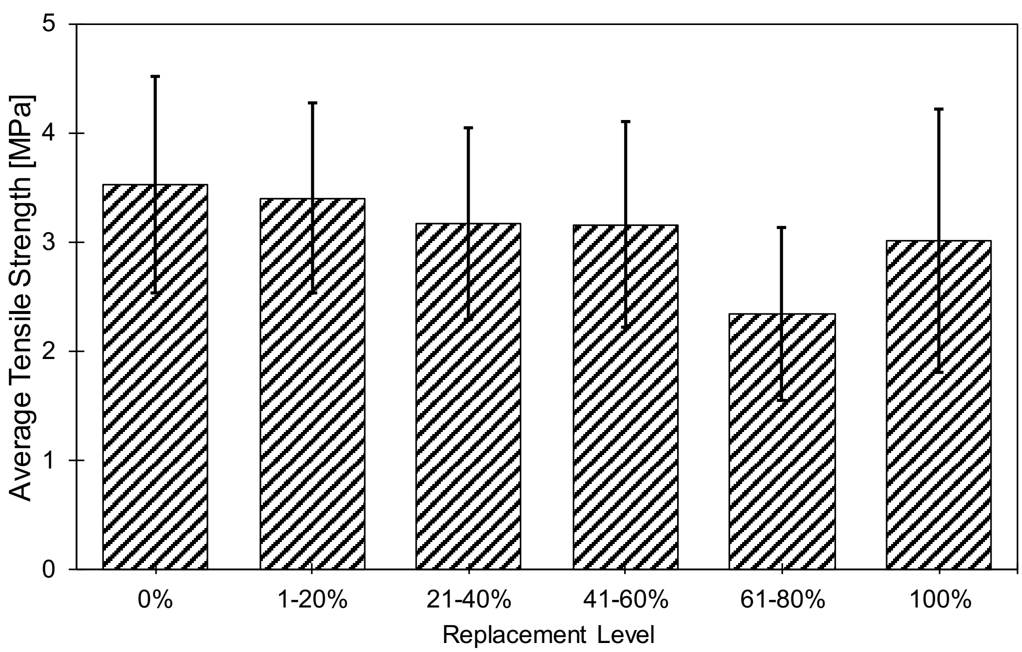


Fig. 9- *Mean splitting tensile strength variation of RAC systems over RCA replacement levels*

Fig. 10 depicts the variation of the splitting tensile strength against the effective water-to-cement ratio at different RCA replacement levels. The splitting tensile strength of RAC systems were decreased when the effective water-to-cement ratio was increased. General trends of RCA splitting tensile strengths were fitted to an exponential function that decayed depending upon the effective water-to-cement ratio. However, it can be seen that at 21-40%, 41-60%, and 61-80% RCA replacement levels, the correlation between the splitting tensile strength and the effective water-to-cement ratio was poor due to the material variability of the RAC systems. Besides, RCA replacement levels at 1-20% and 100% showed good/moderate correlations with respect to the fitted function exhibiting an r value of 0.7 and 0.4. Partly, the data clustering around the fitted model was consistent in those two RCA replacement levels may be because of the larger size of the sample space, which eventually alleviated the influences generated from multiple outliers. Therefore, based on the results shown in Fig. 10, the general trends of the splitting tensile strengths were observed with the effective water-to-cement ratio, and it was in agreement with the previous studies[17,109,110]. Furthermore, a larger set of data is required for RCA replacement levels at 21-40%, 41-60%, and 61-80% to reach out for better conclusions on the splitting tensile strength of RAC systems, and thus, the effects from outliers and material source variability can be minimized correspondingly.

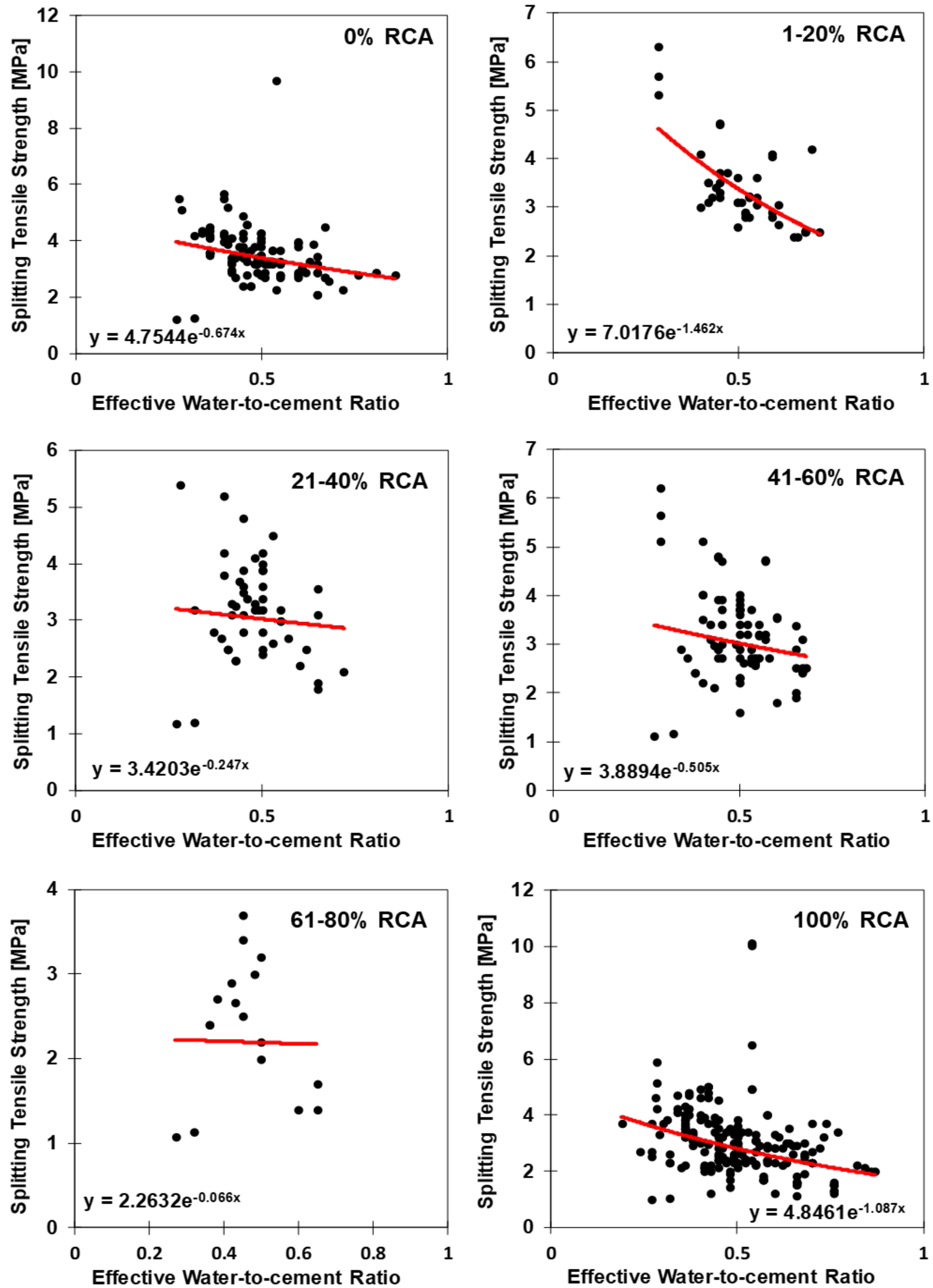


Fig. 10- Variation of RCA splitting tensile strength with effective water-to-cement ratio

3.4.4 Variation of Flexural Strength (Modulus of Rupture)

A majority of the experiments examined have used beam specimens to evaluate the flexural strength of the RCA concrete systems. As shown in Fig. 11, the mean flexural strength had a peak response when 1-20% of RCA replacement level was included. However, it was noticed that the flexural strength had peak responses locally, showing higher strength performance than the preceding level of the RCA replacement bin. The general trend of the mean flexural strength decreased with the increasing RCA replacement level.

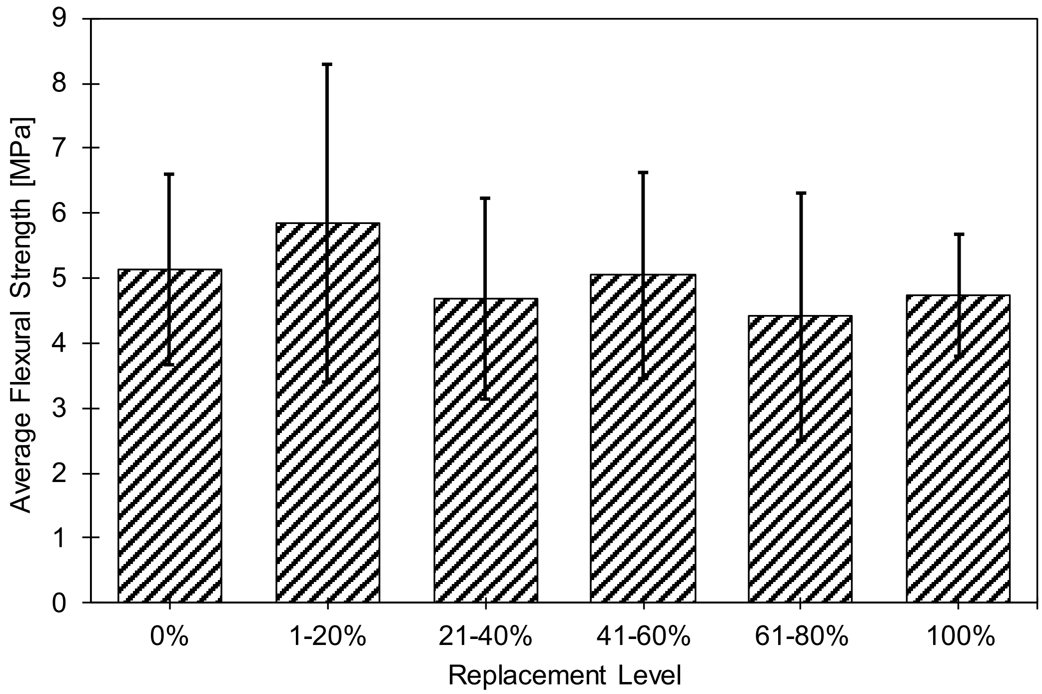


Fig. 11- Mean flexural strength variation of RAC systems over RCA replacement levels

Flexural strength of RAC systems with the effective water-to-cement ratio is depicted in Fig. 12. The data points were fitted to an exponential function and the trends were nonlinear at 0%, 1-20%, 21-40%, 41-60%, 61-80% RCA replacement levels. Concrete systems with 100% RCA replacement showed somewhat linear trend with a small exponent constant. This behavior was attributed due to the linear material behavior upon increased stiffness compatibility of 100% RAC systems. However, the data correlations were good as it showed r values of 0.5, 0.7, 0.7, 0.5, 0.7 for 0%, 1-20%, 21-40%, 41-60%, 61-80% RCA replacement levels respectively. The correlation of flexural strength data was mostly governed by the outliers and the limited amount of experimental data covered for each RCA replacement levels. It is true that the current database contains flexural strength data for different types of sample sizes, and this was one reason as to why the data had more outliers with compared to the fitted exponential curve. Therefore, it is important to have a consistency of sample sizes and testing methods when analyzing the flexural strength performance of RAC systems over a large data set. However, regardless of the outlying data points, all the RCA replacement levels showed the same general trends with a gradual decrease of flexural strength over the effective water-to-cement domain. The trends for flexural strength indicate that they match the findings of the compressive strength results. Mixtures with 1-20% replacement tend to result in an improved flexural strength. Therefore, any structural usage of RCA should be limited to lower RCA contents to ensure that appropriate flexural strength is maintained.

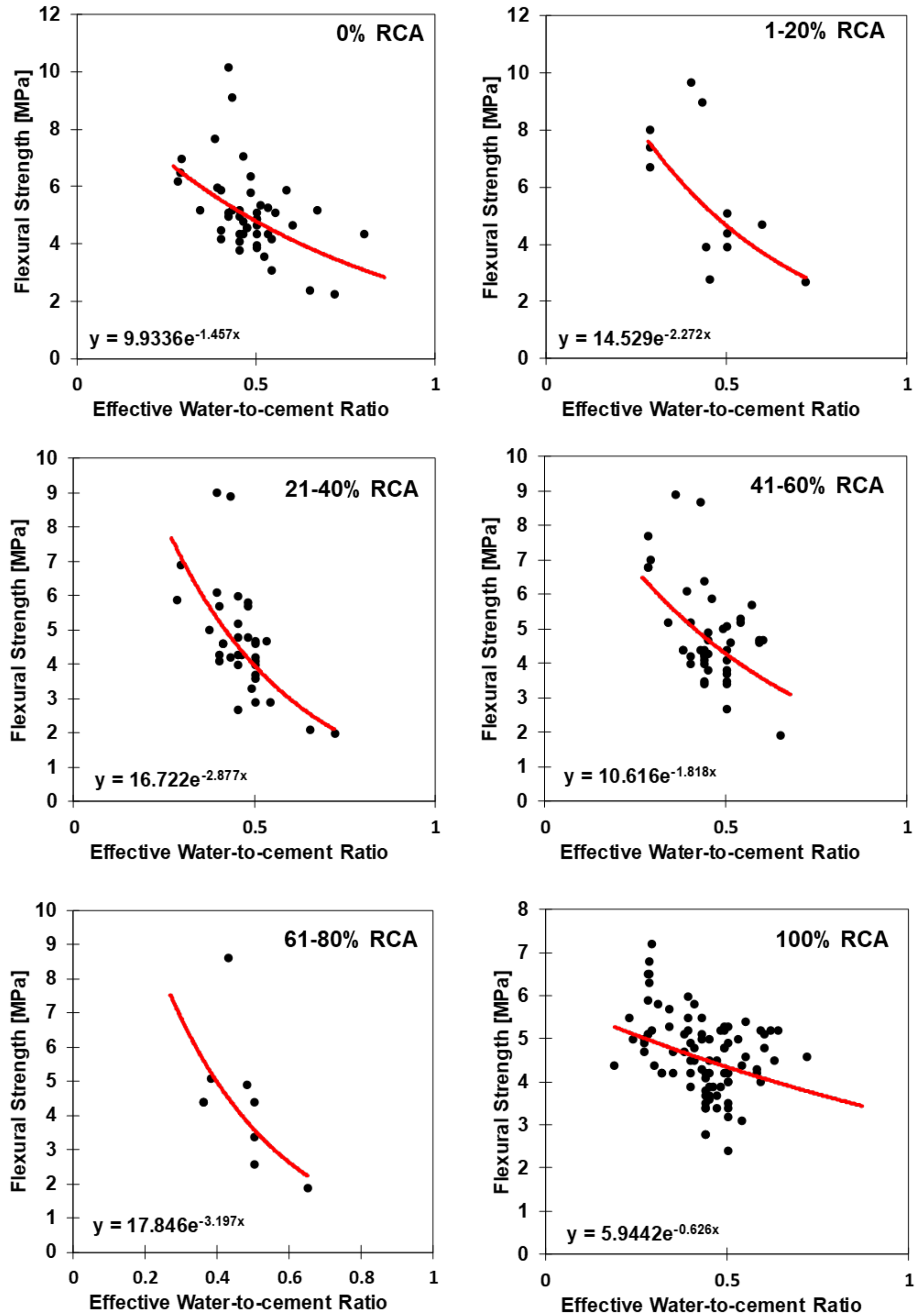


Fig. 12- Variation of RCA flexural strength with effective water-to-cement ratio

3.5 Factorial Design Procedure and Analysis Results

Material characteristics and mix design of concrete have a marked effect on the hardened properties of concrete systems, and thus, factorial design techniques have been widely used to determine the significance of factors and their interactions when the response(s) is dependent on several factors[111]. Therefore, it is an appropriate analysis tool that can be used to understand how to manipulate the materials and their properties to develop targeted responses of RAC systems. Several studies related to the application of factorial design of experiment in the area of recycled aggregates are available in existing literature[112–114]. A factorial design is a type of designed experiment that allows to study on the effects that several factors can have on a response. A full factorial design was implemented, where four factors and corresponding three individual levels for each factor were included. For the four factors; RCA replacement ratio, effective water-to-cement ratio, aggregate-to-cement ratio, and maximum aggregate size was incorporated to examine the effects on compressive strength. While conducting the full factorial design of experiment, the levels of the factors are varied as the base raised to the power by the number of factors. For example, for 3 levels of 4 factors yielded $3^4 = 81$ combinations to study the trends of the response variable due to the changes of factor levels. Table 12 shows the factorial design metrics that was incorporated to estimate the factor effects and interactions on the response variable; compressive strength.

Table 12- Factorial design metrics

Factor	Factorial Levels		
	Low	Medium	High
RCA replacement level	1-20%	21-60%	61% or higher
Effective W/C ratio	0.2-0.4	0.41-0.60	0.61 or higher
Aggregate/Cement ratio	1-2.5	2.6-3.5	3.6 or higher
Maximum aggregate size	No. 4 - ½″	½″- ¾″	¾″ or higher

The database results for each mixture design were carefully categorized according to the class bins chosen in the factorial design metrics to create 81 combinations. In this process, multiple datasets were subjected to the same combination, so that the response variables corresponding to those combinations were averaged and reported. Minitab version 17 was used to perform the statistical analysis for the current factorial design, where the results were obtained for main effects, interactions, bi-variate effects at 95% confidence intervals.

3.5.1 Main Effects

Main effect plots are used to examine the trends of the mean response with respect to the levels being changed from low-to-medium-to-high, where the trends of the responses are demarcated by a straight line connecting each level by the circular markers used in the analysis. A high gradient (i.e., steep slope) between two markers is indicative that the factor strongly influences the response, while a small gradient (i.e., gradual slope) indicates that the factor has a weak effect on the response. As shown in Fig. 13, overall trends of mean compressive strengths were decreased with the corresponding increments of RCA replacement level, effective water-to-cement ratio, and aggregate-to-cement ratio, where the mean compressive strength of the database is indicated by a horizontal segmented reference line. The results depicted on the compressive strength trends were in accordance to the experimental results obtained in the existing literature that showed an overall degradation of compressive strength when the factor levels were increased from low to high. However, RCA size level showed a different trend exhibiting a decrease of mean compressive strength from low to medium level, and eventually, it was increased somewhat at high level of RCA aggregate size. The increased RCA concrete compressive strength was believed to be due to the larger aggregate surface area associated with rough texture of aggregates (e.g., adhered mortar, natural aggregate phases) with the increased RCA size enhanced the compressive strength to a small degree. Nevertheless, it was clear that the overall trends were decreased as the selected factors were increased from low to high levels.

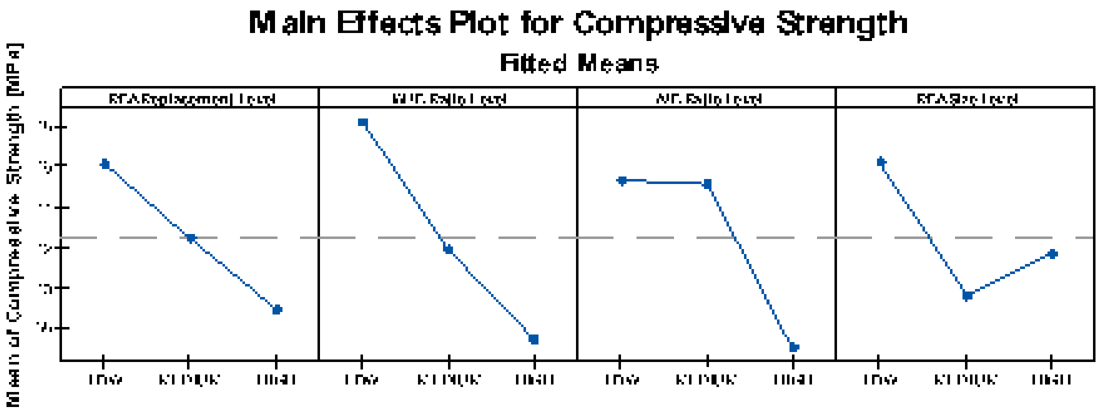


Fig. 13- Main effects plot for mean compressive strength

3.5.2 Significant Factor Effects

Pareto charts reveal the factors or factor combinations that have the largest influence on a particular mean response. These factors or factor combinations are known as *model terms* or *model term combinations*, where the pareto chart is used to quantify the statistical significance of these model terms on the RCA compressive strength at an appropriate significance level. These plots are based on the mean responses of compressive strength obtained from the database due to the variations of the factor levels between low and high levels used in the factorial design analysis. On the pareto chart, horizontal bars that cross the segmented vertical reference line are considered as statistically significant factors. The reference line is determined by pseudo standard error (PSE) evaluated at the $(1 - \alpha/2)^{th}$ quantile of a *t*-distribution with degrees of freedom equal to $n/3$, where α is the significance level and n is the number of model terms used in the statistical model. Therefore, the effect at the margin of reference line (M) is calculated as; $M = t * \times PSE$ where $t *$ is the t value obtained at upper tail significance level of the *t*-distribution. Further, the model terms that were considered for the significance analysis are shown in the *y*-axis of a pareto chart, whereas the standardized effects at the 5% significance level (i.e., at 95% confidence interval) are shown in the *x*-axis.

A pareto chart is shown in Fig. 14 and it indicated that aggregate-to-cement ratio and RCA replacement level were statistically significant on the RCA compressive strength at

95% confidence intervals respectively. The reference line was obtained from the upper tail t-distribution as explained previously, considering $n = 15$ and $\alpha = 0.05$. Despite of the effective water-to-cement ratio was not considered as a significant factor at that confidence level, the effects were substantially higher than the remaining model terms or model term combinations. It showed a little effect of RCA size on the compressive strength, but combined effects from multiple model terms were more dominating due to the factor interaction.

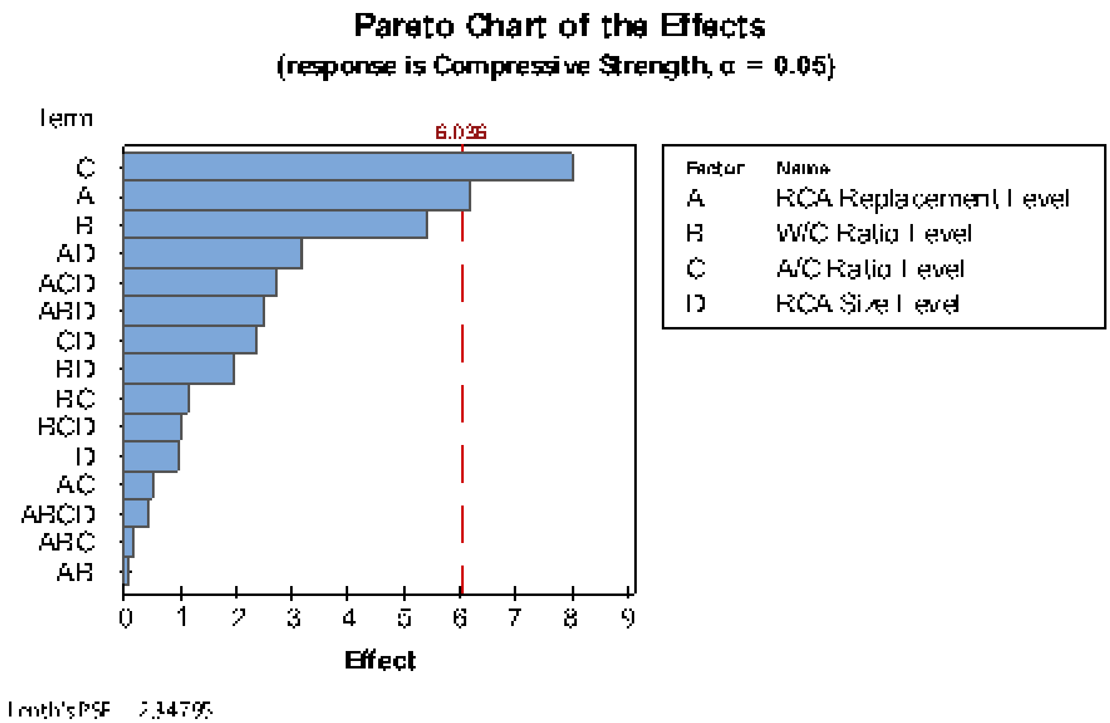


Fig. 14- Pareto chart of the standardized effects at 95% confidence interval on compressive strength

3.5.3 Factor Interactions

The interaction plot shows the mean compressive strength versus the two-way interaction between the factors included in the analysis. Given below in Fig. 15, indicates the full matrix of the interactions with different factors at their corresponding levels. The interpretation of the interaction results of the first row in the interaction plot is as follows:

- ***W/C Ratio Level * RCA Replacement***: If ***LOW*** water-to-cement ratio level is picked, ***LOW*** RCA replacement level is associated with the highest compressive strength higher than 50 MPa. If ***HIGH*** water-to-cement ratio level is picked, ***HIGH*** RCA replacement level is associated with the lowest compressive strength lower than 40 MPa.

- ***A/C Ratio Level * RCA Replacement***: If ***MEDIUM*** aggregate-to-cement ratio level is picked, ***LOW*** RCA replacement is associated with the highest compressive strength higher than 50 MPa. If ***HIGH*** aggregate-to-cement ratio level is picked, ***HIGH*** RCA replacement is associated with the lowest compressive strength less than 40 MPa.

- ***RCA Size Level * RCA Replacement***: If ***LOW*** RCA size level is picked, ***LOW*** RCA replacement is associated with the highest compressive strength higher than 50 MPa. If ***HIGH*** RCA size level is picked, ***HIGH*** RCA replacement is associated with the lowest compressive strength less than 40 MPa.

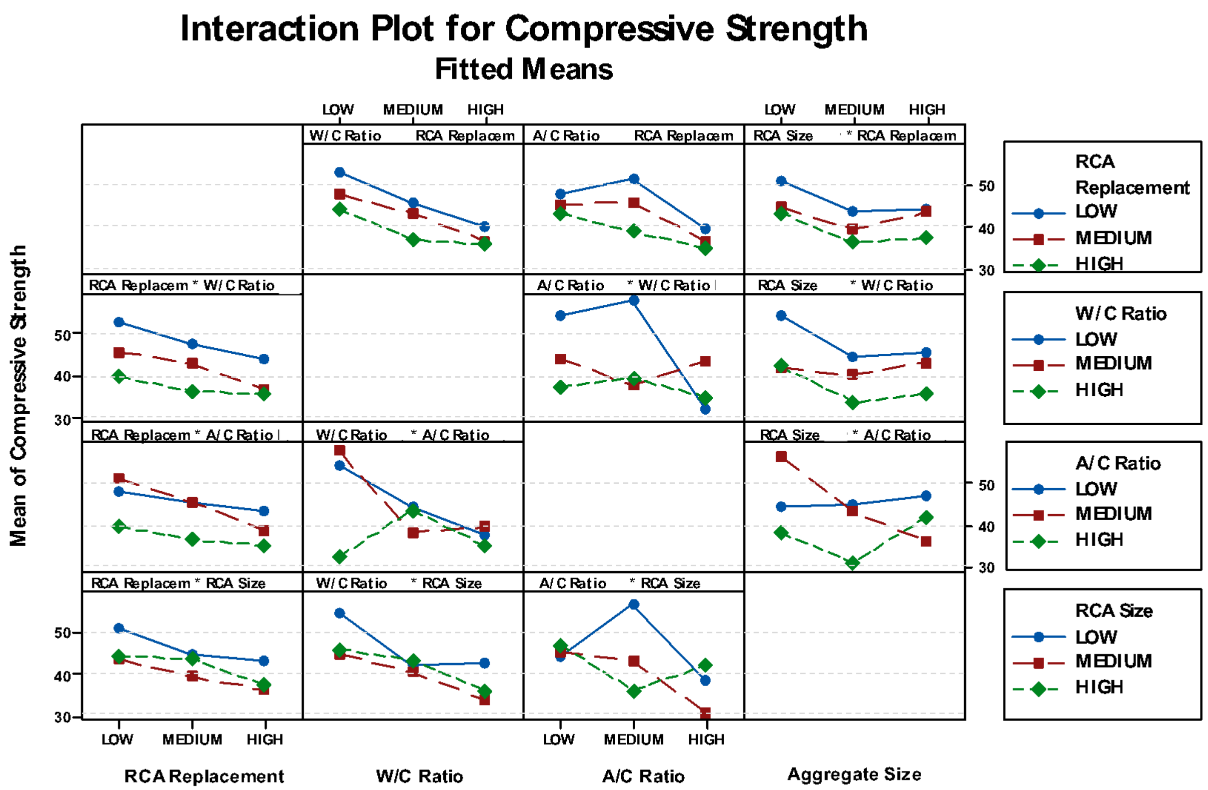


Fig. 15- Interaction plot matrix

3.5.4 Bi-variate Effects

Bi-variate effects are represented by contour plots which has the capability to study the variation of the predictions of the response variable within the provided levels. When predicting the statistical variations of a particular response, two factors can be varied while other remaining factors are being kept at average levels (i.e., medium levels). This statistical tool is very helpful to estimate and predict required factor levels for corresponding target responses. Fig. 16 shows the potential outcomes for bi-variate effects on the target compressive strength of RAC systems.

According to Fig. 16(e), the mean target strength of RAC systems were predicted to be within the range between 35 MPa and 55 MPa, where this was the largest range that was predicted throughout all the bivariate subfigures. Therefore, it showed that the target compressive strength had a higher variability when aggregate-to-cement ratio and RCA size was changed while other factors were held at their medium levels. The maximum target strength in Fig. 16(e) was predicted at 55 MPa when factor levels for aggregate-to-cement ratio, water-to-cement ratio, RCA replacement, maximum aggregate size were selected at 2.6-3.5, 0.2-0.4, 21-60%, 1/2”-3/4” respectively. Same target strength of 55 MPa was achieved in Fig. 16(c) when RCA size was reduced to No. 4-0.5” and increasing the effective water-to-cement ratio to 0.41-0.60 range while keeping the other factors at medium levels. This observation indicated that there is a potential interaction between the effective water-to-cement ratio and RCA size. The reduction of RCA size depicted in Fig. 16(d) through Fig. 16(f) has shown a substantial contribution to increase the RCA compressive strength regardless of the other levels of the factors considered due to the higher aggregate packing when less than ¾” RCA was used. When RCA replacement levels were observed in Fig. 16(a),(b), and (f), regardless of the other factors, it showed that highest RCA compressive strength (e.g., approximately 50 MPa) was recorded at 1-20% level. Based on the overall bivariate relationships studied from Fig. 16(b),(c), and (e), it was recommended to keep aggregate-to-cement ratio at medium level as it contributed for higher compressive strength performance in RAC systems.

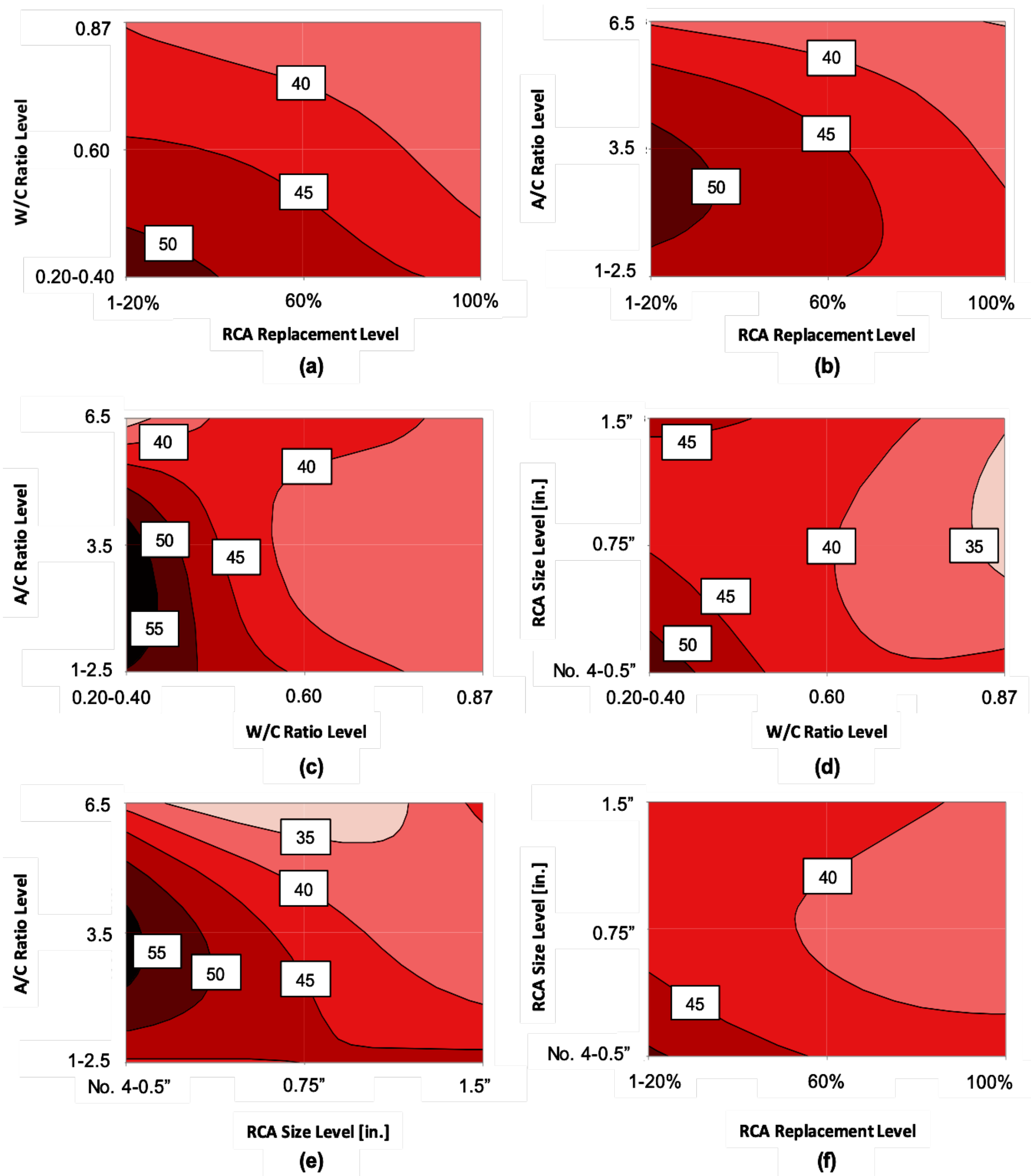


Fig. 16- Bi-variate relationships generated for RCA compressive strengths in MPa

3.6 Comparison of the Database Results with a Computational Aggregate Generation Method for RAC Systems

As a part of this database analysis project, computational work was executed to develop a methodology to generate realistic RCA generations through an algorithm, and the generated aggregate geometry was mapped on to a numerical finite element program through an image analysis procedure[108]. Eventually, the mechanical performance was simulated under applied loading conditions and the results were compared with the existing mechanical properties of RAC systems. The aggregate generation procedure is briefly explained below, and the results are discussed in the subsequent sections.

3.6.1 Aggregate Generation Procedure

The authors have developed a way to generate random aggregate generation for concrete systems containing RCA, utilizing a computational algorithm, and simulated the concrete performance under uniaxial load. The two-dimensional aggregate generation was based on a convex hull algorithm to randomize arbitrary planar shapes of RCA particles. During the generation of RAS, randomizations of the maximum aggregate size and spatial distribution of RCA particles were considered. Finite element models for RAC systems were generated based on an extensive image analysis procedure. During the generation of RAS, randomizations of the maximum aggregate size and spatial distribution of RCA particles were considered. As a part of this research project, the simulation results were compared with the existing database created, and the results showed promising trends.

The RCA generation process was controlled by the aggregate ratio; the proportion of total aggregate content relative to the total concrete area while small-, medium-, and large-size aggregates were generated adopting the Fuller curve as a representative aggregate gradation. The aggregate generation process is explained in Fig. 17, where, the created geometry of the aggregate in the concrete was mapped on to a finite element platform followed by a non-linear structural analysis under uniaxial compression. The numerical study was performed for 0% and 100% RCA replacement levels only and the concrete systems that were randomly generated are shown in Fig. 18 at varying adhered mortar contents.

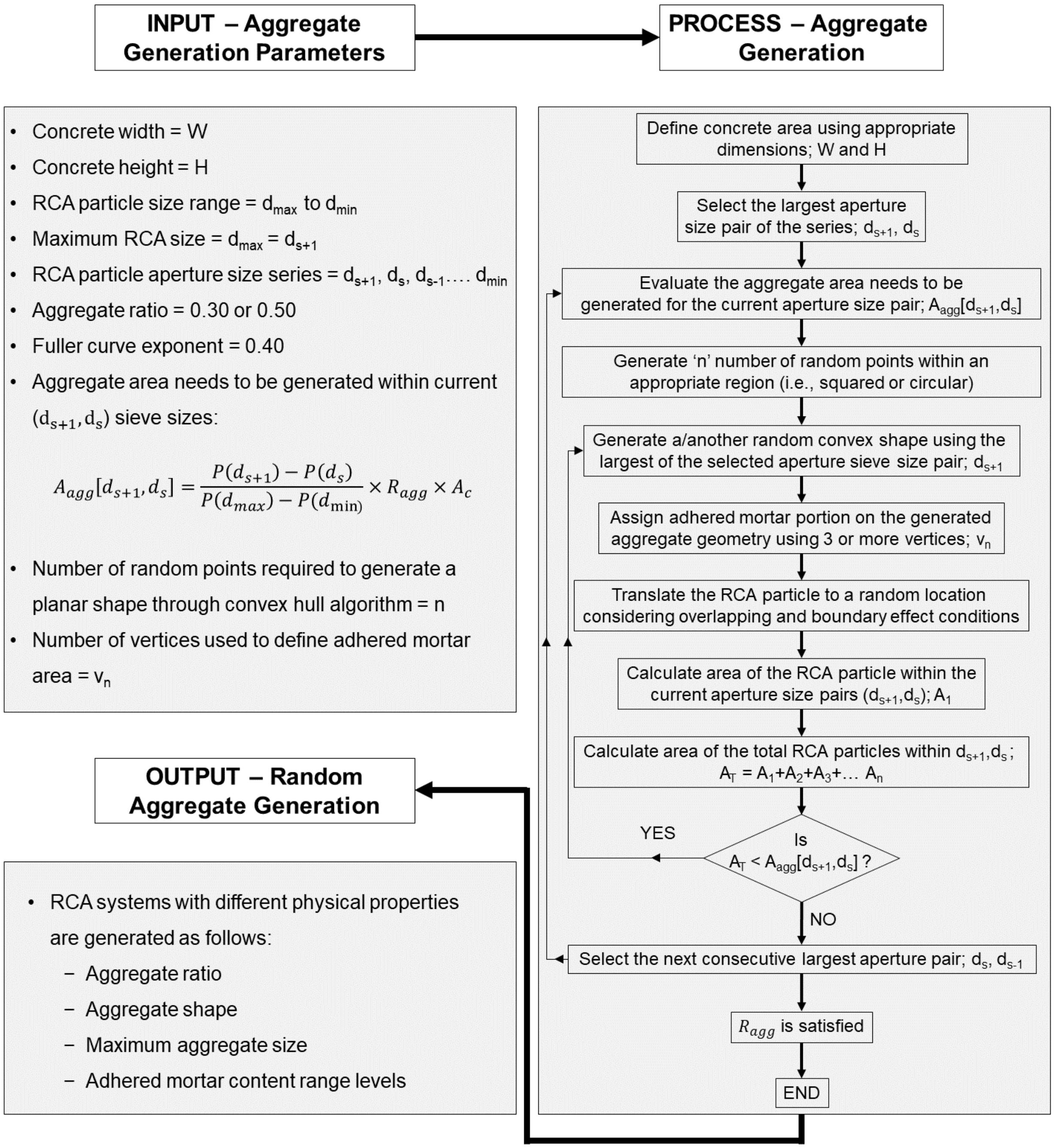
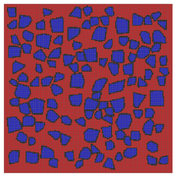
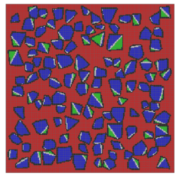
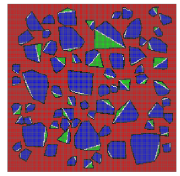
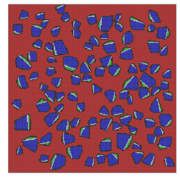
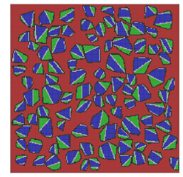
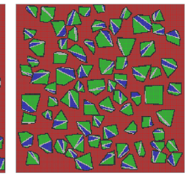
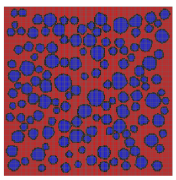
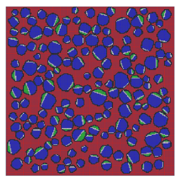
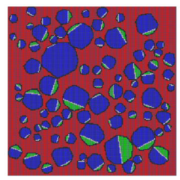
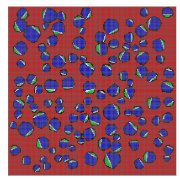
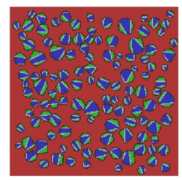
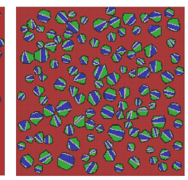


Fig. 17- Aggregate generation process flow chart

Simulation ID	C-12N0-0.50	C-12L1-0.50	C-25L1-0.50	C-12L1-0.30	C-12M2-0.50	C-12H2-0.50
RCA finite element mesh						
Adhered mortar content	0%	8.60%	9.97%	6.50%	31.02%	78.43%

(a)

Simulation ID	R-12N0-0.50	R-12L1-0.50	R-25L1-0.50	R-12L1-0.30	R-12M2-0.50	R-12H2-0.50
RCA finite element mesh						
Adhered mortar content	0%	7.44%	10.97%	9.38%	46.98%	63.03%

(b)

Fig. 18- RCA random aggregate geometries at 0% and 100% RCA replacement levels (a) angular in shape (b) round in shape

Note: Color representations: blue-natural aggregate; green-adhered mortar; red-cement paste; white-old ITZ; black-new ITZ

3.6.2 Significance of a Computational Random Aggregate Generation

It is understood from the literature review that, RCA, as coarse aggregates, exhibited a large variability in the source of interest associated with aggregates' physical, mechanical, and chemical properties that may compromise RCA concrete mechanical properties. It is somehow impossible to study the impacts due to aggregate qualities on the mechanical behavior of the concrete through experimenting actual samples considering the efforts and timespans incurred for casting, curing, and testing. However, a realistic RCA aggregate generation like this can offer a wide range of controlled environment (i.e., adopting randomness on aggregate shape, angularity, gradation, adhered mortar content level, spatial distribution etc.) to simulate similar type of testing method in a much quick time at a low computational cost. Therefore, this aggregate generation was adopted to compare the existing trends of compressive strengths and elastic moduli with the obtained results from different random RCA aggregate geometries.

3.6.3 Comparison of Numerical Analysis Results with Database Results

In total, 282 mechanical properties were utilized from the database while this work was performed, where 102 samples were found for systems with 0% replacement levels and the remaining samples were obtained from 100% replacement levels. Histogram distribution of the compressive strengths and elastic moduli for those replacement levels are depicted in Fig. 19. The histograms of mechanical properties exhibited a slight skewness to the left as the data was fitted to a Weibull distribution. It has been found out that the Weibull distribution is more applicable to fit brittle material properties and provide reliable justifications on the variability of such materials in comparison to normal distribution functions[115].

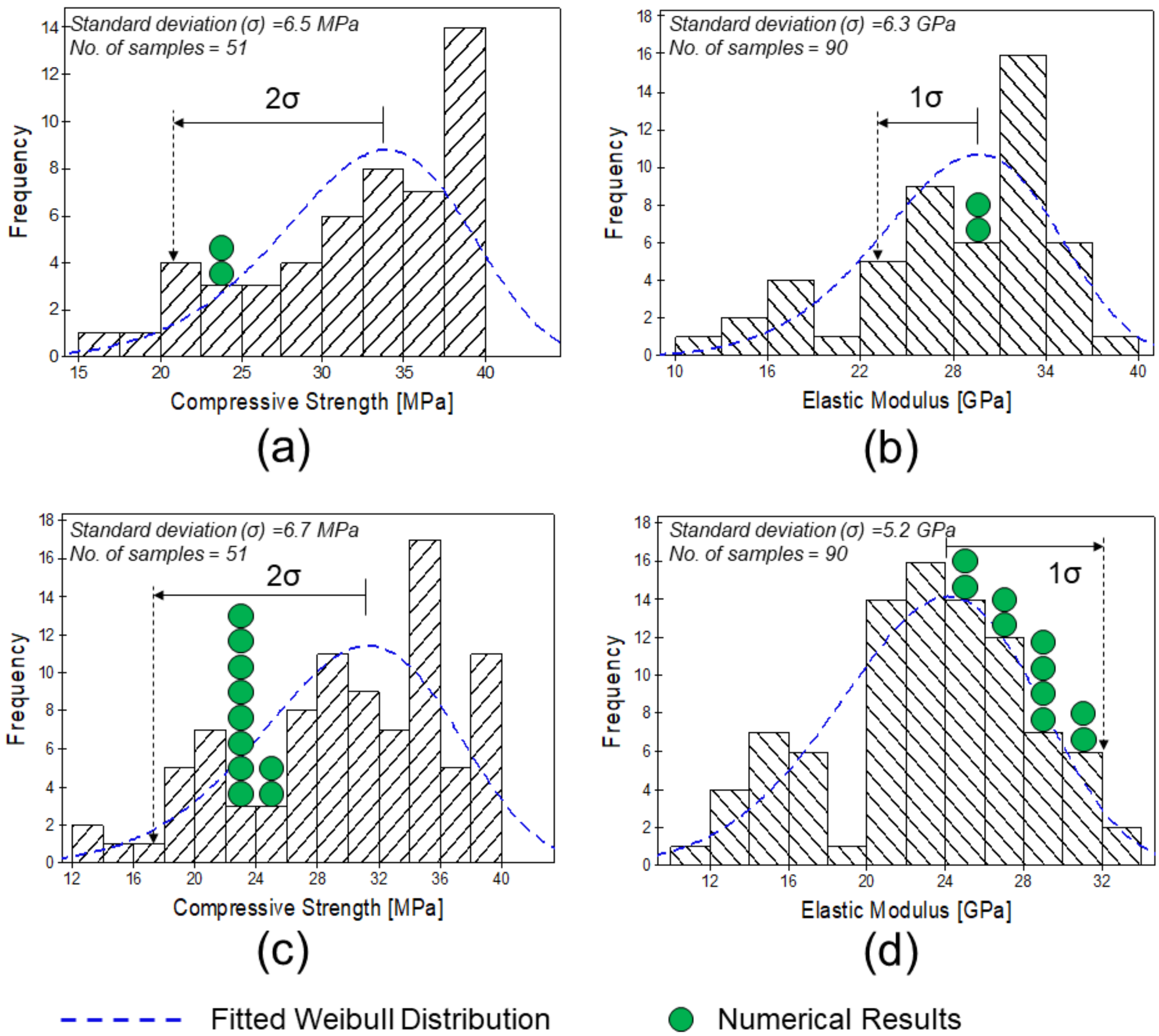


Fig. 19- Histogram of the material properties of two systems; (a) compressive strength for 0% replacement level (b) elastic modulus for 0% replacement level (c) compressive strength for 100% replacement level (d) elastic modulus for 100% replacement level

Compressive responses from the numerical simulations for 0% and 100% RCA replacement levels are displayed in green circular markers in Fig. 19(a) through Fig. 19(d), in which the numerical results were within a two-standard deviation of the overall mean distribution in the corresponding data set. The compressive strength of those concrete systems with 0% and 100% replacement levels in Fig. 19(a) and Fig. 19Fig. 19(c) deviated by 6.5 MPa and 6.7 MPa respectively, compared to the mean of the experimental data set. The deviation for the elastic modulus was 6.3 GPa and 5.2 GPa for 0% and 100% RCA replacement levels in the concrete systems respectively as shown in Fig. 19Fig. 19(b) and Fig. 19Fig. 19(d). The numerical results on elastic moduli had showed less variability compared to the data in the literature, which varied within one-standard deviation of the mean distribution. Since the compressive strength is governed by aggregate size, aggregate shape, and relative stiffness, it may show higher variability in performance in comparison to the elastic modulus which is mainly controlled by the amount of aggregate area of the concrete system, and thus, showed lower variability. Hence, the statistical results conveyed a realistic response of the computational results from randomly generated aggregates.

Since the results conveyed a realistic RCA performance compared to the existing experimental findings, the automated aggregate generation can be extremely useful to simulate and examine the concrete performance by changing the material properties and morphological properties of RCA aggregates. However, the main takeaway of this section is that the variability of RCA compressive strength is very subtle and can be easily influenced by various factors including properties of ITZ, fracture path, material heterogeneity, aggregate size, aggregate shape etc., and thus, when for new concrete mixture design are to be made, higher standard deviation is required for target RCA compressive strengths than it is recommended for normal weight concrete systems.

3.7 Guidelines for Designing RCA Mixture Proportions

3.7.1 Target Strength

The strength of RCA is influenced by many factors as discussed in the previous sections. The concrete properties (i.e., both fresh and hardened) are a function of individual material properties, mixing procedures, transportation, molding and curing methods in construction conditions, and those factors are entirely random variables which can influence the concrete strength. Therefore, from the statistical point of view, it is generally a good practice to consider a possible deviation and ensure that the strength of concrete mixed in the laboratory is higher than the design strength. According ACI 318[116] target strengths are based on three actual strengths; less than 20 MPa (3000 psi), 21-35 MPa (3000 psi-5000 psi), and larger than 35 MPa (5000 psi) with appropriate standard deviations (δ). The standard deviations for each of those strength levels are provided in Table 13 based on the database results. It is also recommended to include a constant value (*k*) to account for desired percentile to reduce uncertainties from sample deficiency. At a level of 95% confidence interval (i.e., 5% defective), a *k* value of 1.645 is used by considering the normal distribution of concrete compressive strengths, and the margin for the characteristic compressive strength can be calculated as shown in Equation 3[117]:

Table 13- Standard deviations for corresponding compressive strength ranges of the database

Specified compressive strength	Standard deviation
Less than 21 MPa	1.96 MPa
21-35 MPa	4.14 MPa
Over 35 MPa	11.60 MPa

$$Target\ Strength\ of\ concrete = Design\ strength\ (fc') + \mathrm{k}\delta \tag{3}$$

3.7.2 Evaluation of Mixture Proportions for Concrete Made with RCA

The analysis results from the bi-variate relationships were used to develop a methodology for determining the mixture proportion ranges for a desired compressive strength obtained after the target strength was established based on proper standard deviations. It is important to know that, compressive strengths were fluctuated within 35 MPa to 55 MPa in bi-variate plots. Therefore, it is recommended to choose target compressive strengths within this bound, unless the closest strength requirement should be considered for the use of the proposed methodology. The methodology is broken down into few steps as described in detail, where each step provides a determination of a material ratio that satisfies the target compressive strength requirement.

STEP 1- Determining approximate effective water-to-cement ratio: The effective water-to-cement ratio was estimated by examining the general trends of the compressive strength variation as shown in Fig. 20. In this scattered plot, the data was fitted to an exponential decaying function, and few possible outliers were eliminated considering the compressive strength data beyond 1.5 times the interquartile range (e.g., 16.6 MPa). Using the equation (or the graph) given in Fig. 20, a representative effective water-to-cement ratio is determined. This selection is statistically feasible due to the reasons that possible outliers were eliminated, and a representative exponential function was fitted that covered the entire database.

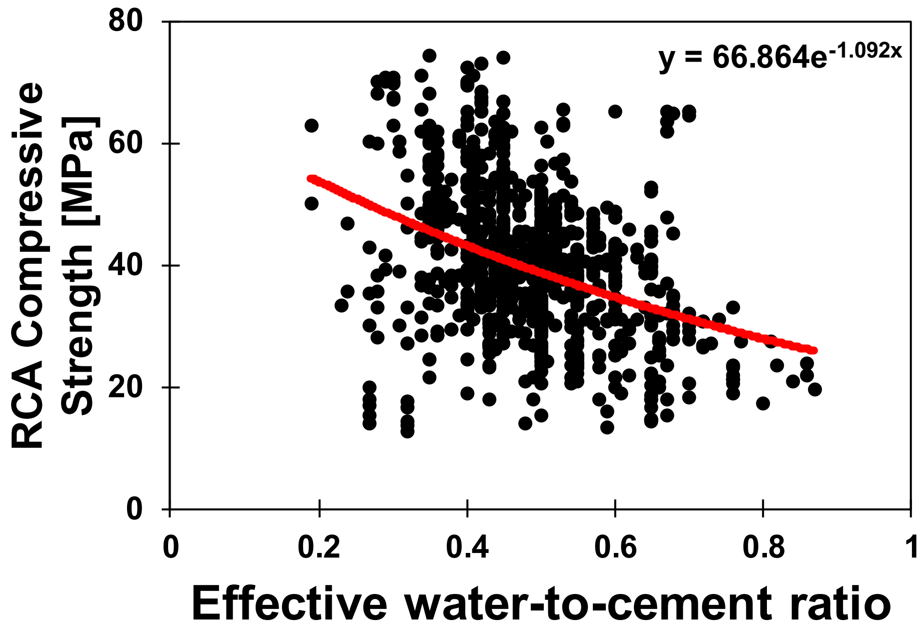


Fig. 20- Compressive strength trend over the effective water-to-cement ratio after eliminating possible outliers

STEP 2- Determining appropriate RCA replacement level: The bi-variate relationship results are used to determine the appropriate RCA replacement level in terms of a range. Based on that, the Table 14 was established to choose appropriate RCA range to meet the compressive strength criterion of the RAC system. Depending on the approximate effective water-to-cement ratio determined from Step 1, and the target strength required, an appropriate RCA replacement is selected by using Table 14. There could be multiple options that satisfy the same compressive strength requirement in selecting the RCA replacement, and it is recommended to consider all possibilities, where the correct RCA replacement level is decided in the remaining steps. If the target compressive strength is not given in the table, the RCA replacements are selected based on the rounded up nearest strength value.

Table 14- RCA replacement level selection for the target compressive strength [MPa]

Effective water-to-cement ratio	RCA Replacement		
	1-20%	21-60%	61-100%
0.20-0.40	50	45	40
0.41-0.60	45	40	35
0.61-0.87	40	35	35

Step 3- Determining aggregate-to-cement ratio: Table 15 is used to determine an appropriate aggregate-to-cement ratio level based on the values estimated for RCA replacement level(s). Depending on the rounded up nearest target strength requirement, an appropriate aggregate-to-cement ratio is selected.

Table 15- Aggregate-to-cement ratio level selection based on the RCA replacement level for the target compressive strength [MPa]

Aggregate-to-cement ratio	RCA Replacement		
	1-20%	21-60%	61-100%
1.0-2.5	45	50	35
2.6-3.5	45	45	35
3.6-6.5	40	35	30

Step 4- Finalizing material ratios: In this step, the mixture proportion ratios for three factors (i.e., effective water-to-cement ratio, RCA replacement level, and aggregate-to-cement ratio) are confirmed. Table 16Table 15 is used to determine a unique level for aggregate-to-cement ratio with compared to the estimated value of effective water-to-cement ratio level.

Table 16- Aggregate-to-cement ratio level selection based on the effective water-to-cement ratio for the target compressive strength [MPa]

Aggregate-to-cement ratio	Effective water-to-cement ratio		
	0.20-0.40	0.41-0.60	0.61-0.87
1.0-2.5	55	55	35
2.6-3.5	35	40	40
3.6-6.5	35	35	35

Step 5- Selecting aggregate size: The bi-variate relationships confirmed that when aggregate size levels between No.4 sieve size and ¾" maximum aggregate size gave compressive strengths within 35 MPa and 55 MPa. Therefore, it is recommended to keep the maximum aggregate size below ¾" for coarse aggregates (i.e., both natural aggregates and RCA).

Step 6- Selecting minimum requirements for cement contents: The minimum cement content requirements are adopted from ACI 302[118] which is recommended for flat concrete works (e.g., slab on grade, walk ways, patios etc.). According to the standard practice, the cement contents are based on the maximum aggregate size used in the mixture design proportions as followed by Table 17.

Table 17- Minimum requirements of cementing materials for concrete used in flatwork

Nominal maximum size of aggregates [in.]	Cementing materials [lb/yd^3]
$1\,{}^{1}/_{2}$	470
1	520
${}^{3}/_{4}$	540
${}^{1}/_{2}$	590
${}^{3}/_{8}$	610

Step 7- Determining mixture proportions for concrete materials: Since the cement contents for given nominal maximum aggregate size are known, representative water content and aggregate content are calculated. As there were no analysis results yielded for fine aggregate contents, it would be suitable to use a bandwidth for the ratio of fine aggregate content to the total aggregate content used in the concrete mixture. Therefore, a ratio between 0.35-0.60 is recommended to use for fine aggregate content over the total aggregate content (by weight)[119].

3.7.3 Worked Example for RCA Mixture Design

Information provided

Strength requirement	= 25 MPa
Defective percentage	= 5%
Target compressive strength	= 25 + 1.645 × 4.14 (Use Table 13)
	= 31.8 MPa

Step1:

Effective water-to-cement ratio = 0.68 (Use Fig. 20)

Step 2:

RCA replacement level = 21-60% or 61-100% (Use Table 14)

Therefore, 40% is used for RCA replacement level.

Step 3:

Aggregate-to-cement ratio = 1-2.5 or 2.6-3.5 (Use Table 15)

Note: RCA replacement level 21-60% is eliminated and 61-100% is selected based on the required target strength.

Step 4:

Final aggregate-to-cement ratio =1-2.5 (Use Table 16)

Note: Aggregate-to-cement ratio level 2.6-3.5 is eliminated and 1-2.5 ratio level is selected based on the required target strength.

Therefore, a value of 2 is used for aggregate-to-cement ratio.

Step 5:

The maximum aggregate size = ¾"

Step 6:

Prescribed cement content = 540 lb/yd^3

Step 7:

Water content required	= 0.68 × 540 (Based on effective water-to-cement ratio)
	= 367.2 lb/yd^3
Aggregate content required	= 2 × 540 (Based on aggregate-to-cement ratio)
	= 1080 lb/yd^3
RCA content	= 1080 × 40%
	= 432 lb/yd^3
Natural aggregate content	= 1080 × 60%
	= 648 lb/yd^3
Fine aggregate content	= 1080 × 45% (Based on fine aggregate ratio of 45%)
	486 lb/yd^3

Final Mixture Design Proportions

The final mixture proportions are shown in Table 18, where water adjustments required to be done for both coarse and fine aggregates. However, the coarse aggregates (i.e., both RCA and natural) and fine aggregates are recommended to pre-batch by bringing them to a state of close to surface saturated dry condition level, and on the actual mixing day, adjustments for aggregates needs to be done. This mixing procedure will enhance the mixing action by having adequate free water, as the aggregates are in SSD condition already, and no relative movement of water is possible to potentially cause shrinkage as well. In order to increase the interfacial bond strength between the aggregates and the cement paste matrix, it is also recommended to follow a two-stage mixing method developed for RCA mixing methodology developed by Tam et al.[91].

Table 18- Mixture design proportions for new concrete using RCA

Material	**Content [lb/yd^3]**
Water	367.2
Cement	540.0
Natural Aggregates (SSD)	648.0
Recycled Aggregates (SSD)	432.0
Fine Aggregates	486.0

Chapter 4
Conclusion

4.1 Summary of Project Tasks

This project report encompasses a wide range of data obtained from experimental studies carried out by researchers and provides an in-depth statistical analysis to observe the general trends of hardened strength properties at 28 days of concrete made with recycled concrete aggregates (RCA). The experimental studies were used to establish a database consisting of many factors such as; RCA replacement level, effective water-to-cement ratio, aggregate-to-cement ratio, maximum aggregate size, aggregate absorption capacity, slump etc., that may affect the strength properties of recycled aggregate concrete (RAC) systems.

Statistical analysis was performed for four different concrete strength properties such as; compressive strength, elastic modulus, splitting tensile strength, and flexural strength of RCA concrete. Due to the large variation of RCA replacement levels that had been used in the database, appropriate RCA replacement level ranges were assigned between 0% and 100%. The summary of the statistical findings and general findings through the literature survey is listed as follows:

1. Average hardened properties of RCA concrete including compressive strength, elastic modulus, and flexural strength showed superior performance at 1-20% RCA replacement level.

2. Splitting tensile strength showed a continuous decay throughout the RCA replacement level space, yet, 100% RCA replacement systems showed a markedly increase than the preceding replacement bin due to the increased homogeneity of the RAC system owing to larger adhered mortar content in the system.

3. The consistency of data was measured by the correlation coefficient (r), and it showed that consistency of compressive strength against effective water-to-cement ratio was reduced by 45% when RCA replacement was used below 60% while noticing few outlier data as well. Higher RCA replacement levels between 60% to 100% controlled the consistency of the data and increased the data correlation by 32%.

4. Elastic modulus, splitting tensile strength, flexural strength relationships with the effective water-to-cement ratio exhibited nonlinearities at lower RCA replacement levels, and the trends became more linear as the RCA replacement levels were increased.

5. Four-factor, three-level full factorial analysis showed that all the factors contributed to decrease the mean compressive strength as they were used from low to high in amounts except at high levels of RCA size, the compressive response was increased due to the aggregate interaction associated with aggregate surface texture.

6. Aggregate-to-cement ratio and RCA replacement level was found to be significant factors at 95% confidence interval that can influence the compressive strength of RAC systems. Although the effective water-to-cement ratio was not significant at the 95% confidence level, it indicated that the effects were substantial than the remaining model terms or the combination of the model terms.

7. Interaction plots indicated that compressive strength can be controlled by two-way interactions of the factors and appropriate factor levels can be foreseen to predict higher compressive strength properties in RCA concrete.

8. Comparison between the numerical findings obtained from the proposed aggregate generation and the literature review were in close agreement, where compressive strength showed higher variability (i.e., within 2-standard deviation) than the elastic modulus (i.e., within 1-standard deviation).

9. Proposed RCA mixture design procedure that was developed based on bi-variate relationships provided a helping tool to determine material proportion levels based on the target compressive strength.

10. The database is required to use more compressive strength data on RAC systems such that, the statistical analysis can be used to expand the range of compressive strengths beyond the values that was studied and minimize the effects of outlying data.

4.2 Future Studies and Recommendations

Overall, this project covers a wide range of experimental findings on the mechanical properties of RAC systems, and an extensive statistical analysis was performed using robust statistical tools and indices. Since, the mechanical properties of RAC systems are not consistent due to material variabilities, more data needs to be accounted for in the database analysis to gain more consistent statistical outcomes. Based on the current findings of the project and the state-of-the art of RAC systems available as of today, the following recommendations are provided as future research studies.

1. Extension of the current database is recommended to eliminate outliers, and the mechanical properties can be subjected to a thorough statistical framework.

2. Study the influence of supplementary cementitious materials on the mechanical properties of RAC systems through a database analysis similar to this project.

3. Investigate the significance and the degree of applicability of current standardized tests (i.e., ACI and ASTM standards) for RCA (e.g., soundness testing, LA abrasion test, aggregate crushing value test etc.), by establishing a statistical framework employing the existing data from literature.

4. Use the computational algorithm developed for RCA aggregate generation to evaluate the mechanical performance trends based on the variabilities of adhered

mortar properties and its contents through a rigorous statistical model such as Monte Carlo simulation.

4.3 Database Access

Existing database of mechanical properties of RAC systems is available as a Google Sheet document, and it can be only viewed by visiting the link in the footnote[1]. The numerical data listed in the database are in SI units unless specified otherwise (i.e., force scale in Newton [N], linear length scale in millimeter [mm]), and therefore, the mechanical properties are displayed in N/mm^2 or in MPa.

If there are any third-party individuals who are interested in willing to help gather more data into this database on RCA mechanical properties are appreciatively invited to take part of a Google Form which can be accessed from the link in a footnote[2]. This form consists of two sections; the first section contains basic information about the user who is adding data into the database, and the second section contains the attachment of the data in a spreadsheet format (i.e., Excel file). In order to control the consistency of the original database, and the integrity of the data included in it, the users are not allowed to edit or modify the original database. However, as a research team, we will carefully read the data filled by the users and later, the data will be published on the original database after a proper review period. Since the original database spans out for several column descriptions (e.g., 19 columns), it would be much faster to copy the table descriptions and paste onto a separate excel file that the user intends to fill in the additional data on RCA mechanical properties. Therefore, it is highly recommended that the users require to use the same database template as the original database that has been already created.

[1] https://docs.google.com/spreadsheets/d/1dWJeHuL2uWvpyXN_8-xHCkEYTNlTycsBxiI3Z0Tmcfc/edit?usp=sharing
[2] https://docs.google.com/forms/d/e/1FAIpQLSf82P5ZnJLozrY0gXARW-WEjEHuv1hmPDw3MmeiyYaeAyM9DQ/viewform

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