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Designing Concrete Mixtures with RCA

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16. Abstract

The use of recycled concrete aggregates (RCA) as a replacement in new concrete has gained popularity worldwide as a method of reducing natural aggregate consumption. Many individual studies have been completed but little work has been done to analyze that work to make broad conclusions on RCA concrete mechanical properties. This report presents the development and analysis of a database of mechanical properties of concrete containing coarse RCA and provides an investigation the applicability of numerically generated recycled concrete aggregate (RCA) systems by varying the material properties. A sensitivity study of RCA systems was conducted through a full-factorial analysis to explore how the mixture design proportions influence the RCA concrete hardened properties. The modeling methodology was adopted by using a computational algorithm that can generate concrete systems with different RCA replacement levels to numerically simulate RAC systems under mechanical loading. Numerically simulated results are compared with an experimental database that has been established, including a substantial data set on RAC mixture design proportions. RAC geometries and material properties were stochastically generated using Monte Carlo simulation methods, resulting in 200 representative numerical models that were subjected to simulated mechanical loading.

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Table of Contents

List of Figures

List of Tables

1. Introduction and Background

During World War II massive amounts of structural debris accumulated and this spurred initial research into using construction and demolition (C&D) waste as recycled concrete aggregates (RCA) in new concrete (RCA concrete systems) [1]. As sustainable construction practices have become more common, using RCA concrete has been the focus of significant amounts of research in the past few decades [2–13]. Waste concrete generation has increased significantly in the past 20 years due to replacement of old infrastructure, growing populations requiring newer construction, and through structural failures caused by natural disasters [14–16]. Consequently, the massive amount of concrete waste disposal activities can initiate environmental issues as the availability of landfills has reduced [13, 17]. Particularly in urban regions, access to quality aggregates for use in concrete has decreased resulting in a need to travel farther to access natural aggregates, further impacting the sustainability of urban construction [18]. Thus, it implies that there is a significant market and need to increase the utilization of RCA, but a lack of general understanding of how to do so has acted as a blockade [9, 19, 20].

Worldwide, the utilization and the importance of reusing waste concrete as RCA have been extensively discussed within the concrete and sustainability communities but the discussions have been mainly concentrated on three major fields; 1) techniques of producing RCA from waste concrete, 2) methods and guideline for evaluating the quality and material classification of RCA, and 3) implementing regulations and standardizations to encourage RCA application as a construction material [21]. The International Union of Laboratories and Experts in Construction Materials Systems, and Structures (RILEM) formed the first committee (37–DRC) in 1978 to study waste concrete processing and recycling techniques and presented a state-of-the-art report covering the years 1945–1977 [1]. Subsequent versions of the report were then implemented and introduced by RILEM on the reuse of concrete waste as a construction material covering the years 1978–1985 and 1985–1989 [22, 23]. In the 1990s, the American Concrete Institute (ACI) committee 555 developed a guideline for use of RCA that was updated in 2002 [24]. Existing consensus documentations such as, ACI 555 [24], ASTM C33 [25], European RILEM Standards [26], Japanese Industrial Standards [27–29], and German Standards [30] place certain limitations on the properties of RCA for when they can be used in concrete, but do not provide information on reliability of achieving concrete strengths or durability with traditional mixture design techniques when replacing natural aggregates with RCA nor do they provide new mixture design information. Therefore, this research is more focused on understanding and implementing proper guidelines to use RCA in new concrete that has predictable strength properties and long-term serviceability characteristics.

Research has shown that there can be large variability in the mechanical properties and qualitative characteristics of RCA and RCA concrete systems [31–33]. This is caused by the variability of RCA as a material that is produced from multiple waste concrete sources and through various RCA production measures. RCA is produced by crushing waste concrete with mechanically operated equipment into aggregate size particles. Due to the crushing mechanism, an RCA particle consists of two main material phases composed of adhered mortar and natural aggregate as shown in Figure 1, where those phases are separated by an extremely thin material layer known as the old interfacial transition zone (OITZ). When used as an aggregate in new concrete, the new interfacial transition zone (NITZ) is the interface between the RCA particle and the new cement paste matrix. As a result of large crushing forces applied through mechanical devices when RCA are produced, micro-cracks can be initiated and weaken the adhered mortar phases as well as the OITZ regions [34, 35]. Therefore, the amount of such mechanically induced micro-cracks due to crushing operations can increase the porosity of the adhered mortar in RCA, and it can yield inferior concrete strength which is associated with lower toughness, lower density, and higher absorption [36]. Some work has been done to repair and improve the aggregate quality of RCA materials adopting heat treatment [37, 38], acid treatment [39, 40], polyvinyl alcohol (PVA) treatment [41], and pozzolanic material treatment [42–44]. However, best practices have not been developed due to the need of special mechanical equipment, longer processing times required to carry out tests, and the increase of energy which devalues the purpose of RCA utilization. Overall, the current research understanding on the post-processing techniques of the crushed waste concrete still requires further investigations on how to produce high quality RCA materials for concrete applications.

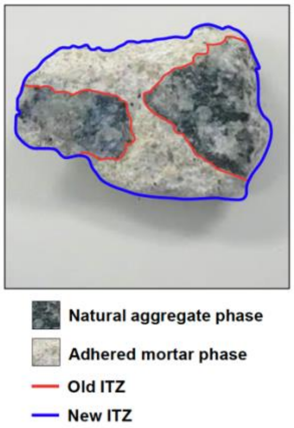


Figure 1: Meso-structure of material phases in an RCA particle

At a mesoscopic level, the adhered mortar attached to the RCA particle is considered as a porous material due to the cementitious hydrated phase which makes up a portion of the aggregate. On average, an RCA particle is made up of 25–60% of adhered mortar by volume [45–

47] (20–70% by mass [48, 49]), though others have reported significantly less contents [50]. Therefore, when RCA materials are derived from unidentified parent concrete structures, the composite behavior of concrete systems exhibit higher variabilities in strength characteristics given that the adhered mortar has significant material property variations. The key strength characteristics of RCA concrete systems, such as compressive strength, elastic modulus, splitting tensile strength, and flexural strength can show diverse performances due to the material heterogeneity (i.e., stiffness compatibility), impurity content (e.g., brick, asphalt, plastic, wood) [51, 52], and morphological parameters (e.g., angularity and surface texture/roughness) [53]. Therefore, the predicted RCA concrete material behavior is more complex compared to the natural aggregate concrete systems. This also means that the existing concrete design guidelines and formulations derived for conventional concrete cannot be utilized on RCA systems. Therefore, new guidelines need to be developed, and this requires the formation of large datasets which then need to be analyzed to understand the trends and variability in RCA concrete.

Despite higher material variabilities, computer-aided modeling procedures such as linear/non-linear regression analyses [54–56], artificial neural networks [55, 57, 58], and genetic programming [14, 56] have been used to predict targeted responses of RCA concrete strength properties. Furthermore, sophisticated database analyses were also developed by Gholampour et al. [14] and Tósíc et al. [59] to compare the mechanical properties of both natural aggregate concrete systems and RCA concrete systems, and examined the influence of RCA replacement levels on the hardened properties of RCA concrete systems. Additionally, the proposed formulations derived in those studies were correlated against the existing concrete design codes, and the differences have been reported [14, 59]. For example, Gholampour et al. [14] carried out a database analysis to formulate the target strengths of RCA concrete systems and investigated the correlation between the compressive strength and other RCA concrete hardened properties, such as elastic modulus, flexural strength, and splitting tensile strength. Despite observed variabilities, their study showed that RCA concrete strength trends with respect to compressive strength had compatible relationships (i.e., correlation curves) compared to the global code specifications that are prescribed for natural aggregate concrete systems. Their work presented the tools for determining the strength of concrete based off the RCA replacement level and the W/C; however, they did not provide information on the impact of aggregate content or aggregate size on mixture properties. The strength characteristics of shear and flexural strength in reinforced RCA concrete were studied by Tósíc et al. [59] through another database analysis approach. The database was composed of 16 experimental datasets, covering 217 strength property results, and the experimental data were compared with the Eurocode 2 specifications [60]. The study concluded that the experimental results correlated with the code specified predictions within close agreements except for a few outliers. Database analysis is a useful tool to understand and predict the variabilities of the mechanical responses of RCA concrete systems.

Similarly, other database analyses such as those by Duan et al. [55], Deshpande et al. [61], Behnood et al. [58] and González-Taboada et al. [56] focused on either examining or predicting compressive strength rather than developing tools for creating full concrete mixture designs.

This report presents the development and statistical analysis of a large database on carefully selected experimental data on RCA concrete strength properties that are available in the literature. From this work, reliable and accurate predictions can be made, such that it effectively captures the RCA material variability. This study serves as a supportive tool to develop, analyze, and interpret statistical data on RCA concrete mechanical properties. Future use of this database and the provided results will be able to be used to develop design methodologies for making RCA concrete and improve risk assessments for agencies interested in using RCA. This work is a key step in moving research on RCA concrete into practice. The original proposal for this work stated that this database and mixture design technique would be used to develop and test laboratory mixtures. Unfortunately, due to the COVID-19 pandemic, access to our laboratory was severely limited and procurement of materials was impacted by long delays. As such, the project was pivoted away from laboratory testing to focus on computational modeling. Therefore, a systematic study of stochastic effects of material phase variabilities on RCA concrete strength parameters was performed through an extensive set of Monte Carlo numerical simulations using finite element modeling. The Monte Carlo simulations help to better understand how variations in the cementitious phases in RCA systems, such as adhered mortar and cement mortar matrix, influence the hardened RCA concrete mechanical properties in uniaxial compression and tension loading conditions. Monte Carlo simulation outputs are analyzed, and statistical results of simulations are compared with the responses from the experimental database.

This work will help support engineers and architects as they work to utilize waste concrete as a substitution for natural aggregate in concrete. Particularly the mixture design tools and understanding the variability of different mixture design choices on concrete properties is important for ensuring high quality concrete that meets structural requirements and durability requirements. Increasing the use of RCA in concrete will support overall sustainability goals for communities by preventing the landfilling of waste material, reducing the need to quarry additional aggregates, and reduce costs.

2. Methodology

2.1. Data collection process for database development

One of the goals of this work was to create a large database that contained mechanical properties from a variety of RCA concrete systems. The creation of this database was completed through systematic review of experimental studies published in peer-reviewed journal articles. Only articles published in English were considered for this work. The selected peer reviewed articles were then read, cataloged, and summarized into the database while confirming that there were no replications of the same data over multiple articles. Experimental parameters used for each study were carefully reviewed according to a data collection procedure, and the hardened strength properties of RCA concrete systems used in the experiments (e.g., compressive strength, tensile strength, elastic modulus, and flexural strength), the mixture design parameters, and the RCA properties were extracted and recorded in the database. Figure 2 illustrates the selection criteria that was adopted for the data collection process in the database. A thorough cross section of articles has been searched and studied to ensure that it encompassed a substantial representation of the international research community.

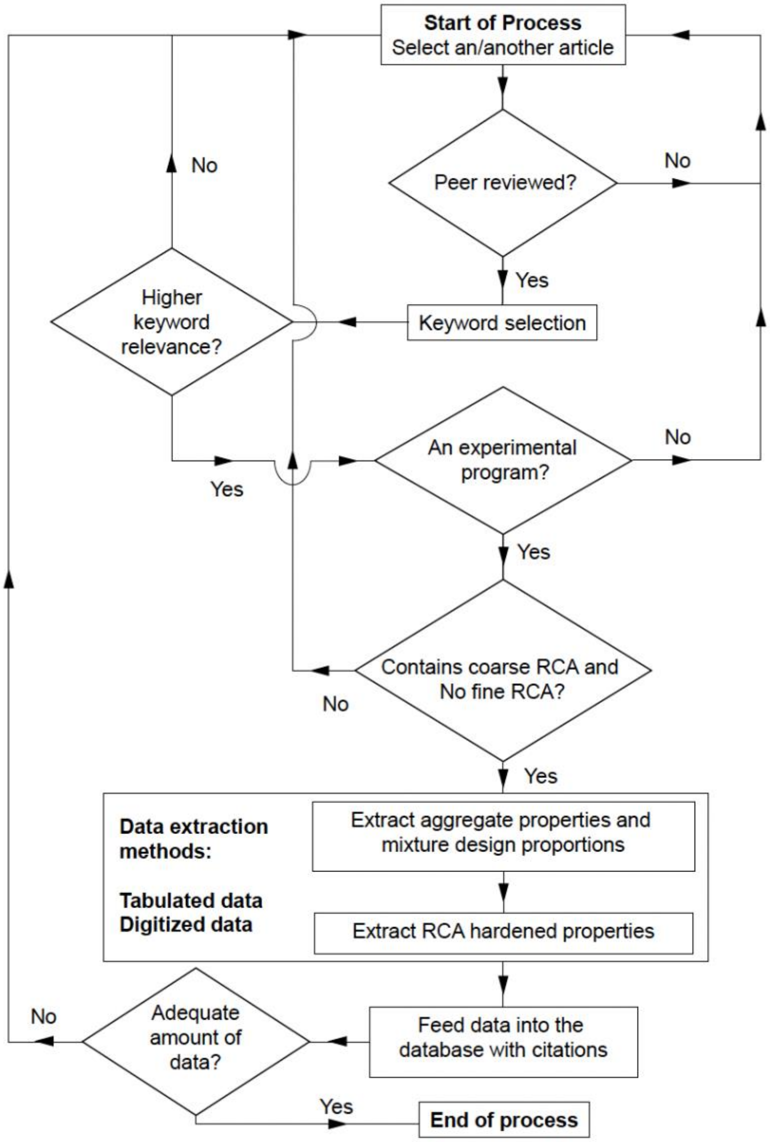


Figure 2: Flow chart used for the database creation

During the construction of the database, keywords related to the current topic were used to find relevant peer reviewed articles. The relevance of the keywords was considered through a screening process before an article was determined whether to include in the database or not. In the primary screening process, all of the keywords that were mentioned in the peer reviewed articles were collected and stored in a separate spreadsheet for further screening stages. Then, the keywords and the corresponding articles were compared against the topics relevant to RCA materials and RCA concrete mechanical properties. Subsequent screening processes were employed to distinguish between experimental work and disregard the non-experimental works (e.g., computational or analytical studies, which were not considered) from the database system. The research team did not consider concrete mixtures that included fine RCA particles (i.e., RCA smaller than 4.75 mm); nor were the use of cementitious materials other than Portland cement (even at small replacements) considered. While the inclusion of fine RCA is of interest for future versions of the database, the current available data is limited in scope. Therefore, any consideration of special concrete types, chemical admixtures beyond superplasticizers, or treated RCA materials were not incorporated in the experimental database for the current statistical analyses. Systems using non-Portland cements or supplementary cementitious materials are also of interest for future iterations of the database, but the introduction of the additional set of variables was out of the scope of work for this research.

Data extraction into the database from selected peer reviewed journal articles was done using one of two methods depending on how that data was included in each experimental work. If the experimental results related to the database (based on the keyword selection) were presented in a tabular form, the data extraction was done directly from the listed tables and entered into the database system. There were occasions during the data extraction where the mechanical properties were presented as a graphical interpretation, and as such, the research team utilized a digital data processor to transpose the approximate values from the graphs. For this purpose, the Plot Digitizer [62] program was used to digitize the graphs as an image, and the data points were extrapolated based on the graphical scale. Since the selection criterion of the peer reviewed journal articles is regulated by the keyword relevance to the database topics, the existing research scope on RCA and RCA concrete systems is limited by the conditional statements indicated in the flowchart in Figure 2. Therefore, the number of selected journal articles that were required for the current database was based on the keywords that were determined to be relevant to the statistical study. As a result, the authors were able to obtain adequate amount of literature information without any replication of the same data over multiple articles reported in the database. After the database was created, an in-depth statistical analysis was performed based on the collected data, and the strength trends were observed through non-linear regression analysis and conclusions were made using selected statistical indicators.

2.2. Database components

Following the flowchart provided in Figure 2, the database was created with more than 2200 mechanical property data on RCA concrete compressive strength (970 sample data) [3, 5, 17, 18, 46, 63–92, 92–136], elastic modulus (571 sample data) [3, 5, 46, 69, 71, 75, 76, 78–81, 83–85, 87, 88, 91–94, 96, 97, 99, 100, 103, 104, 106–108, 111, 112, 114, 115, 117–120, 128–132, 134, 135, 137–144], flexural strength (240 sample data) [69, 76, 79, 84, 85, 88, 92, 97, 99, 103, 104, 107, 115, 119, 127–129, 132, 136–138, 141, 144, 145], and splitting tensile strength (511 sample data) [3, 5, 18, 46, 49, 70, 71, 76, 78, 79, 81, 84, 85, 88–90, 92–94, 96, 97, 103, 104, 106, 108, 112, 114, 116–119, 127–130, 132, 135–137, 139, 141, 145–147]. The database is available for viewing and can be seen online at Jayasuriya and Adams [148].

Laboratory testing for concrete compressive strength is generally determined by using either cylinder or cubic shaped specimens with different sizes according to the prescribed codes and standards [149, 150]. In general, cube specimens exhibit higher strengths due to the lower aspect ratio (i.e., length-to-diameter ratio) and uncapped end conditions when tested under uniaxial compression [151, 152]. Therefore, to explore distinct variations, the experimental results in the database for the compressive strength were categorized into two subsets depending on the specimen shape on which the compression test was done. The compressive strength testing specimen sizes varied between these two types of specimens. All recorded experimental tests for splitting tensile strength and modulus of elasticity on RCA concrete systems were done using cylinder specimens. The recorded flexural strength tests were measured for prism specimens. This study considered a large scope of experimental studies that were completed using a variety of experimental procedures following different standards, and as such, the specimen sizes varied from one experiment to the other. However, the specimen size-effects on the cylinder compressive strength can be treated as a minor influence as the aspect ratio of the cylinder specimens included in the overall database was limited to 1:1 or 1:2, and moreover, such size differences in cylinder specimens can account approximately 2-13% of strength difference [153, 154]. This type of strength difference is negligible when addressing the common trends of the RCA concrete strength properties while different factors are varied over a large-scale database system.

The mechanical properties of RCA concrete systems can be influenced by many factors including the mixture design proportions and the aggregate physical properties. Ten factors that influence concrete compressive strength with varying levels of intensity were chosen for inclusion in the database; these include:

- RCA replacement level (i.e., based on the mass replacement of natural coarse aggregates),

- Effective water-to-cement (W/C) ratio (i.e., either as reported, or calculated based on mixture design proportions in the document. If effective/not-effective was not provided, the reported W/C ratio was assumed to be the effective W/C ratio),
- Total aggregate-to-cement (A/C) ratio (calculated from the mixture design proportions provided),
- Cement-to-sand (C/S) ratio (calculated from the mixture design proportions provided),
- Maximum aggregate size,
- Cement content,
- RCA water absorption capacity,
- Natural aggregate water absorption capacity,
- Slump, and
- Specimen shape tested for the concrete hardened properties (cylinder or cube).

Concrete mixtures are designed to meet specific strength, durability, and workability requirements [53]. Mixture design is done using several parameters that include aggregate grading, cement to sand content, aggregate to cement content, water to cement ratio, total cement content, and total water content. Therefore, understanding mixture design parameters is very important for producing concrete with predictable performances. As indicated above, four RCA mixture design parameters were identified for RCA replacement level, effective W/C ratio, total A/C ratio, and C/S ratio where each factor has unique effects towards the RCA concrete strengths. From the collected information in the database, the histogram distributions of these mixture design parameters are shown in Figure 3. Among those distributions depicted, Figure 3(a) showed higher variability for RCA replacement level due to the larger range (e.g., 0–100%) that researchers have utilized in the RCA concrete experiments while Figures 3(b)-(d) exhibited approximate resemblance to normally distributed data clusters for effective W/C, A/C, and C/S ratios respectively. Therefore, the RCA concrete strength patterns would exhibit higher fluctuations due to the variabilities induced by the mixture design proportion factors. Hence, a statistical database analysis needs to be implemented to understand the relationship between the mixture design factors and measured RCA concrete strengths. The detailed statistical analysis and results are discussed in the following section based on the data processed through the database.

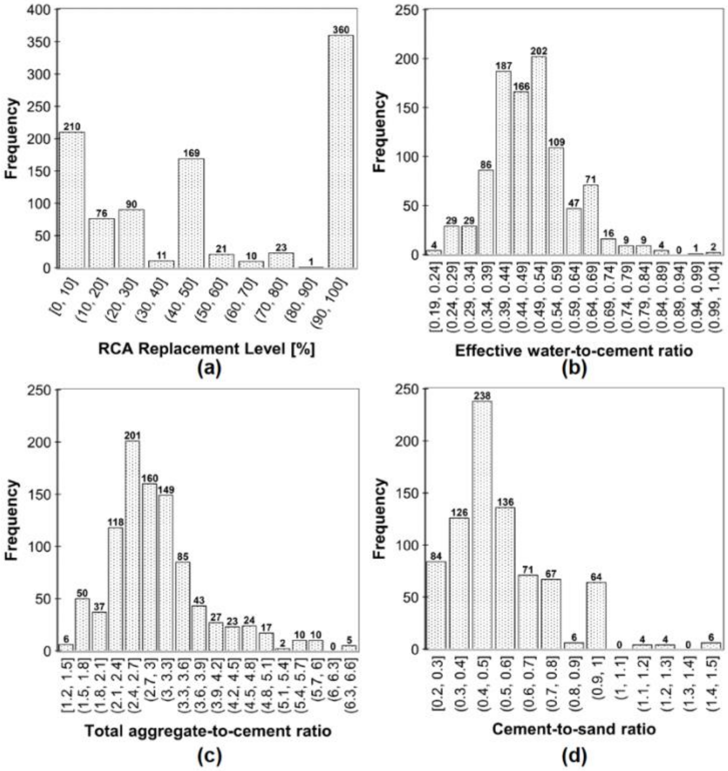


Figure 3: Histogram distribution of the RCA concrete mixture proportion factors in the database; (a) RCA replacement level (b) effective W=C ratio (c) total A=C ratio (d) C=S ratio

3 Results

3.1. Database analysis

3.1.1 Variability of mechanical properties of RCA concrete systems

Four RCA strength properties including compressive strength, elastic modulus, tensile strength and splitting tensile strength trends were observed. The database entries were composed of 28–day strength results as reported in the literature. The strength trends were observed in relation to the effective W/C ratio for each RCA replacement level bandwidth. This method was chosen because the effective W/C ratio is the key parameter that influences concrete mechanical properties and the RCA replacement levels showed higher variability due to the scattered frequency distribution (see Figure 3(a)). Table 1 shows the strength ranges (e.g., minimum, maximum, and average strengths) that researchers have obtained through experiments. At 5% replacement increments there was not enough data to provide reliable statistical analyses, and for some replacement ranges (e.g., 5%, 85%, and 95%) no data was available. There was only one data point available for 90%, and thus, that data point was not included in the statistical analysis to avoid false interpretations due to the scarcity of data on a wide range of RCA replacement of such. Therefore, it was decided that the replacement levels need to be grouped into wider bandwidths which can capture adequate amounts of data to analyze and interpret statistical results. The strength types for compressive strength, elastic modulus, splitting tensile strength, and flexural strength trends were observed at 0%, 1–20%, 21–40%, 41–60%, 61–80%, and 100% RCA replacement level bandwidths against the effective W/C ratio. While these larger bandwidths may introduce some additional variability due to the range of RCA replacements considered in each one, it will provide better analysis. The ranges can be decreased in the future as more data becomes available. Therefore, a reasonable RCA replacement bandwidth of 20% increments were utilized in the analyses including 0% and 100% RCA replacements bounded by the lower and upper limits correspondingly.

Table 1: Strength ranges observed in the database at each RCA replacement levels

Replacement	Compressive Strength [MPa]				Elastic Modulus [MPa]				Flexural Strength [MPa]				Splitting Tensile [MPa]			
Level [%]	Count	Min.	Avg.	Maximum	Count	Min.	Avg.	Maximum	Count	Min.	Avg.	Maximum	Count	Min.	Avg.	Maximum
0	200	17.3	44.0	80.8	131	11400	32264	50410	46	2.3	5.1	10.2	114	1.3	3.5	9.7
5	-	-	-	-		-	-	-		-	-	-		-	-	-
10	10	26.0	46.2	64.6	4	23300	35375	43900	2	3.9	6.5	9.0	6	2.6	3.2	4.2
15	12	32.7	48.4	55.3	2	29100	29150	29200	1	9.7	9.7	9.7	2	3.0	3.4	3.7
20	64	26.4	48.6	69.9	44	23000	33229	48540	9	2.7	5.1	8.0	39	2.4	3.4	6.3
25	34	14.7	37.7	60.7	18	23570	32190	37415	15	2.1	4.2	6.0	24	1.2	3.1	5.2
30	56	20.0	43.6	74.0	23	17000	27751	41900	11	3.6	5.7	9.0	20	2.3	3.1	4.5
35	5	34.1	44.7	68.0	4	26900	31713	39850	4	4.3	5.2	5.9	4	3.3	4.1	5.4
40	6	25.9	33.5	48.0	3	25782	26201	26600	4	2.0	2.9	4.1	4	2.1	2.6	2.8
45	10	44.6	50.9	56.9	0	-	-	-	0	-	-	-	0	-	-	-
50	159	14.4	41.9	70.8	105	15500	28933	47930	41	1.9	4.9	8.9	81	1.1	3.2	6.2
55	4	29.6	37.6	41.4	0	-	-	-	0	-	-	-	0	-	-	-
60	17	23.5	42.7	54.7	7	24533	27239	33333	5	2.7	4.7	6.4	5	2.3	3.1	3.9
65	3	39.5	40.8	41.6	1	33500	33500	33500	1	4.4	4.4	4.4	2	3.2	3.3	3.4
70	7	28.4	35.6	46.8	5	15700	22978	27000	3	4.4	4.6	5.1	3	2.4	2.5	2.7
75	13	13.8	29.2	47.1	2	20500	25250	30000	2	1.9	5.3	8.6	8	1.1	1.8	2.9
80	7	15.4	43.6	67.5	2	18048	21649	25250	2	2.6	3.0	3.4	2	2.0	2.1	2.2
85	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
95	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
100	360	12.8	38.4	78.2	216	11300	25600	46100	89	2.4	4.6	7.2	194	1.0	3.0	10.1

3.1.2 Variability of average RCA concrete compressive strength

Figure 4 depicts the average cube and cylinder compressive strengths that were recorded and analyzed from the database at each RCA replacement level bandwidth. It was observed that the cube compressive strength was higher than that of the cylinder strength due to larger frictional resistance and the shorter distance between the top-bottom platen restrains for cubic specimens [155]. The individual compressive strength averages for each RCA replacement in the database indicated that regardless of the specimen shape and RCA content, the average compressive strengths were able to produce adequate compressive strengths for normal strength concrete in many applications. For example, the minimum strength requirement for concrete used in sidewalk concrete in the Standard Highway Specifications for New York City Department of Transportation [156] is 3200 psi (22 MPa), and all the average results of the database strengths satisfy this requirement. This indicates that, in general, concrete of adequate strength can be made with RCA at all replacement levels. However, the large variability within each bandwidth shows that it is necessary to complete testing to confirm strength when using a particular RCA source. In Figure 4, it was observed that the average concrete compressive strength showed an increase when RCA replacement levels were increased up to 20% in quantity, whereas it resulted in a 13.3% strength increase compared to the natural aggregate concrete systems (i.e., 0% RCA replacement level). The individual strength change between a natural aggregate concrete system and a 20% RCA concrete system for a particular mixture was also examined from the experimental findings in the literature. It was found that the compressive strength of concrete systems that had up to 20% RCA replacement levels showed 12.0%, 11.7%, 8.5%, 6.0%, and 4.5% higher average strengths compared to the corresponding natural aggregate concrete mixtures reported by Domingo-Cabo et al. [87], Poon et al. [74], Taffese [18] (used 10% RCA replacement), Andreu and Miren [157], and Thomas et al. [130] respectively. However, the reason for such variability of these strength differences was caused by the RCA source and the curing conditions. The 11–20% RCA replacement level bandwidth produced the highest average compressive strength performance considering the overall average strengths of RCA concrete system as shown in Figure 4. The increase of concrete compressive strength was attributed to the aggregate interaction between the RCA (i.e., adhered mortar phase) and the cement paste matrix that wraps around the aggregate. When the RCA replacement level is increased, the adhered mortar is increased, and the amount of surface friction due to the aggregate roughness is also increased. Additionally, increased adhered mortar improves the elastic compatibility in the concrete system under experimental loading [158]. Therefore, higher adhered mortar contents in the RCA concrete systems contributed higher average compressive strength performances. Based on the data, results showed that 11–20% was the optimum RCA replacement range that can produce the highest average compressive strength. Although higher adhered mortar contributed higher RCA concrete strengths, further increments of RCA replacements beyond 11–20% caused the strengths to decay gradually and restricted the average compressive strength improvements. The reduction of RCA concrete compressive strengths at more than 20% was due to the existence of widespread ITZ phases (e.g., both OITZ and NITZ). ITZ phases in the concrete system increase the stress concentration effects upon applied strain (i.e., load during the compression tests) due to the weak link between the major material phases in RCA concrete meso-structure [158, 159]. Therefore, the performance of the RCA concrete compressive strength has a strong dependency on the ITZ phases and their distribution inside the concrete meso-structure for predictable strength properties. It has been observed that, regardless of the ITZ distribution in the RCA concrete systems, the compressive strengths can be slightly improved due to the aggregate interlocking behavior associated with the RCA angularity and higher shearing resistance during the test [160, 161]. Therefore, it can be seen as a reason for the localized peak compressive strengths above the decreasing trend displayed at 41–50% and 100% RCA replacement levels. In essence, it was found that the average compressive strength trends showed an improved performance through 0–20% RCA replacement levels, after which it depreciated with the increase of RCA content in the concrete mixture.

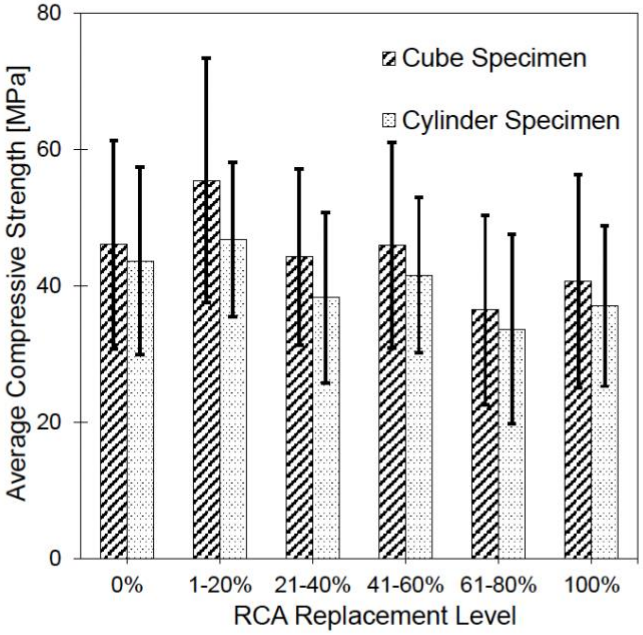


Figure 4: Average compressive strength trends at various bandwidths of RCA replacements

Further analyses were completed to investigate the influence of the RCA replacement level on the compressive strength by assessing the change in strength caused by the incorporation of RCA. Figure 5 shows the average relative strength reductions observed at each RCA replacement level bandwidth. It was observed that when RCA replacement level bandwidth was increased, the average relative strength decreased. As a result of this analysis, it was observed that on average, the strength of RCA concrete systems was decreased by 9.9% when RCAs were used as a full replacement for natural coarse aggregates.

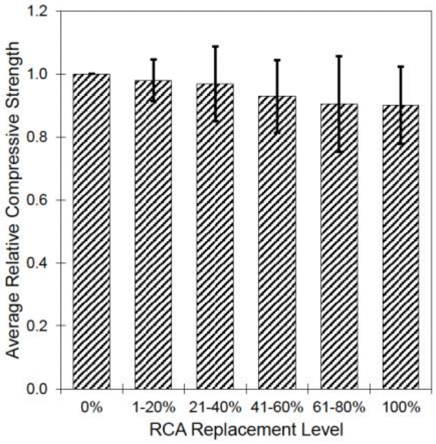


Figure 5: Average relative compressive strength of RAC systems compared to natural aggregate concrete systems

In addition to the RCA replacement level, the remaining mixture design proportion factors, such as effective W/C ratio, A/C ratio, and C/S ratio can be highly significant when predicting the RCA compressive strength. Thus, it is necessary to observe the RCA compressive strength trends with the combined effects, and statistically fit the data using non-linear regression schemes. The influence of effective W/C ratio on the RCA compressive strength is shown in Figures 6(a)- (f) representing RCA replacement levels and corresponding average A/C, C/S ratios indicating the corresponding standard deviations in each bandwidth. Overall, the compressive strengths for all RCA replacement levels were decreased exponentially with the increasing effective W/C ratio. By its general definition, the concrete systems with no RCA replacement showed moderate data clustering around the predicted nonlinear expression depicted on the scattered plot with a correlation of coefficient I of 0.5. However, it was clear that the amount of outlying data changed the data correlation and thus, the variability of RCA compressive strength was affected. As such, when RCA replacement levels were increased from 1% through 60%, the r value was reduced from 0.55 to 0.30 with identified outliers. Regardless of a few outliers, further RCA increments beyond 60% increased the r value from 0.30 to 0.44 as most of the sample data was located around the fitted curve, and thus, the effects from outlying data were minimized. Higher data correlation (i.e., lower variability) at higher RCA replacement levels was attributed to the increased material homogeneity in the RCA concrete system and the number of samples included in the dataset. As a result, at higher RCA replacement levels, when the stiffness compatibilities between the cement mortar matrix and the adhered mortar increase, the concrete systems tend to show consistent material behavior (e.g., under compression) with lower variability.

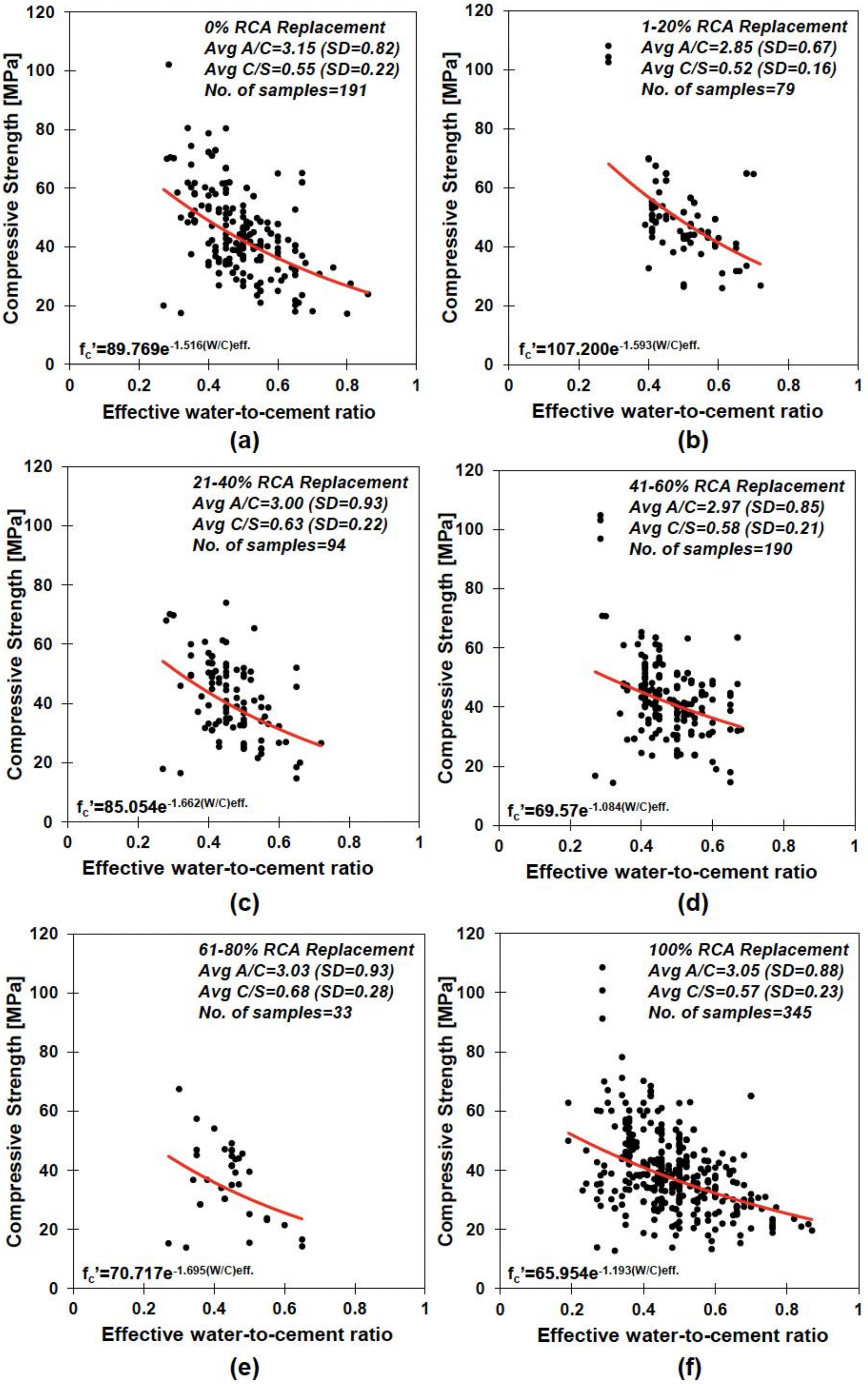


Figure 6: RCA concrete compressive strength distribution for each replacement level; (a) 0% (b) 1-20% (c) 21-40% (d) 41-60% (e) 61-80% (f) 81-100%

3.1.3. Variability of average relative RCA concrete elastic modulus

The distribution of the average relative elastic modulus is shown in Figure 7. Based on the distribution, it was observed that the average relative elastic modulus of RCA concrete systems decreased with the increasing amount of RCA replacement levels. Higher adhered mortar contents can be present when higher RCA replacement levels are used in concrete mixture proportions which will decrease the overall concrete stiffness due to the higher porosity in adhered mortar [75, 161, 162]. Therefore, for the concrete systems that contained RCA as replacement, the elastic modulus properties were weaker than that of natural aggregate concrete systems. On average, the analysis results showed that compared to a natural aggregate concrete system, the elastic modulus was decreased by 4.5% when RCAs were used up to a 20% for natural aggregates. An average reduction of 19.6% was noted when mixtures included a full replacement of natural coarse aggregates with RCA. The average reduction in modulus of elasticity was 21.5% for the 61-80% replacement level bandwidth, lower than for the 100% replacement. When 100% RCA replacement is used, the effects of large material heterogeneity due to the presence of natural aggregates reduce, and thus, the areas that would have been subjected to higher stiffness discontinuities are low (i.e., relatively low stress concentration). Therefore, such systems may have the ability to perform better, and exhibit lower average relative elastic modulus reductions (e.g., less than 20%) [83, 144]. It is important to note, however, that the variation within the datasets for the 61-80% bandwidth and 100% bandwidth are high compared to the difference in average relative elastic modulus, indicating that the difference between the two values may not be significant.

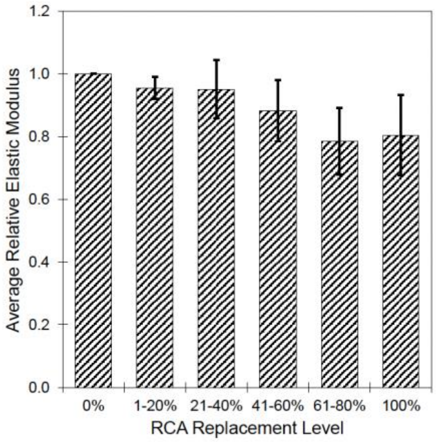


Figure 7: Average relative elastic modulus of RAC systems compared to natural aggregate concrete systems

Variation of elastic modulus with effective W/C ratio at different RCA replacement levels is shown in Figures 8(a)-(f). Although the data points were fitted to a nonlinear exponential function, the nonlinearity was further decreased as the RCA replacement levels were increased due to the stiffness homogenization of RCA concrete systems associated with the higher adhered mortar contents. Since the elastic modulus is governed by the individual material stiffness components in the concrete, its variability exhibits a larger disparity across all RCA replacement levels. For example, Figures 8(b)- (f) indicated that the r value was changed from 0.41 to 0.12 (i.e., nearly 70% reduction) and indicated higher variabilities of the fitted trend line. In this context, the impact of impurities due to foreign materials (e.g., brick, asphalt, wood chips, etc.) can exacerbate the variability effects of the RCA elastic modulus. The strength trends at each RCA replacement level were inversely proportional to the effective W/C ratio, and it was noted that the RCA concrete elastic modulus was affected by the combined effects of both replacement ratio and the effective W/C ratio.

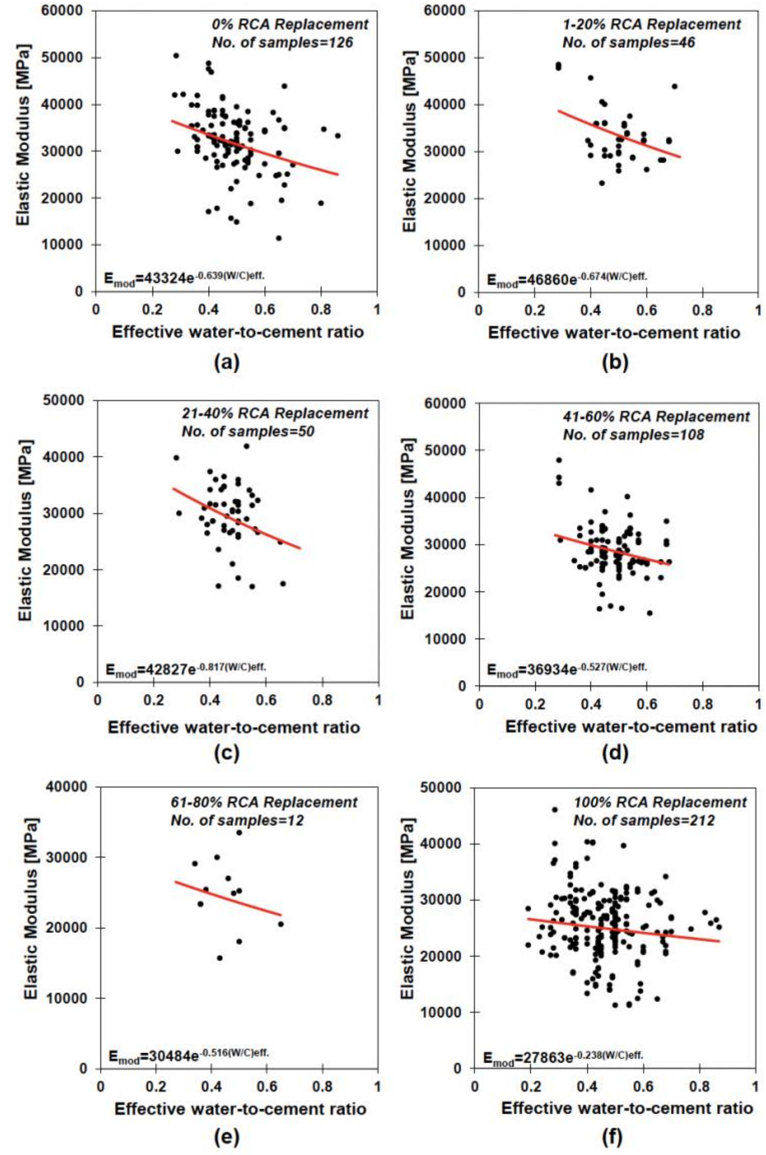


Figure 8: RCA concrete elastic modulus distribution for each replacement level; (a) 0% (b) 1-20% (c) 21-40% (d) 41-60% (e) 61-80% (f) 81-100%

3.1.4. Variability of average relative splitting tensile strength

The average relative tensile strength of RCA concrete systems at each RCA replacement level bandwidth is shown in Figure 9. Based on the data collected, the RCA concrete tensile strength exhibited a continuous strength loss over the RCA replacement levels through 1–80%. The tensile strength data logged into the database was obtained through experiments that were tested under indirect tension, and thus, the failure mechanism was due to interfacial failure [158]. The distribution of the ITZ regions cumulatively increases with higher contents of RCA replacement levels and increases the cracking propensity under the applied indirect tensile strains. Frequently, when the concrete material is subjected to tensile loads, larger tensile strains are localized at the major material boundaries (e.g., NITZ) in the RCA concrete system, and the macroscopic failure is accelerated by tensile fracture [158, 163, 164]. Therefore, the average RCA concrete tensile strength depicted in Figure 9 decreased with increasing amount of RCA replacement level. Like the modulus of elasticity, the average reduction in splitting tensile strength was lower in the 61-80% bandwidth than for the 100% replacement bandwidth. As with the elastic modulus findings, this may be due to the reduction in stiffness discontinuities from a lack of natural aggregates; or it may not actually be a significant difference given the high variation of results. Further research into these issues is required to understand why 100% RCA replacement systems perform better, on average, than 61-80% RCA replacement systems.

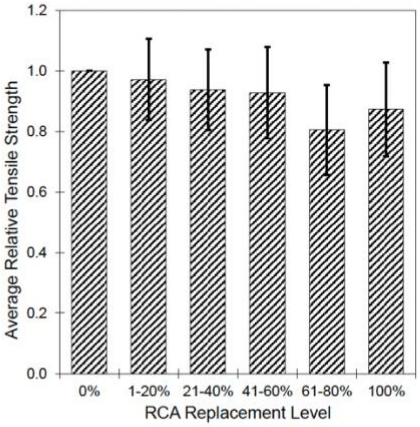


Figure 9: Average relative tensile strength of RAC systems compared to natural aggregate concrete systems

The scattered distribution of the RCA concrete splitting tensile strength data with the effective W/C ratio is shown in Figures 10(a)-(f) representing each RCA replacement level bandwidth. The data clusters in each distribution were fitted to a nonlinear exponential function, where it showed that the RCA concrete splitting tensile strength is inversely proportional to the effective W/C ratio. However, it can be seen from the Figures 10(c)-(e), that the RCA replacement levels did not show good correlation between the effective W/C and the corresponding tensile strengths due to the material variability of RCA concrete systems associated with the widespread

ITZ regions. Furthermore, it has been found that under uniaxial tension, concrete-like materials (e.g., both regular concrete and RCA concrete systems) exhibit unpredictable fracturing processes through interfacial failure promoted by the irregular distribution of ITZ phases [160, 164]. Therefore, with less ITZ dispersion in the concrete system, it was seen that the correlation of the data obtained at RCA replacement levels 0%, 1-20%, and 100% were comparatively better than the remaining RCA replacement levels. Consequently, the data clustering around the fitted model was consistent in Figures 10(a), (b), and (f) due to the larger size of the sample space, which eventually alleviated the effects generated from multiple outliers. Based on the results shown in Figure 10, the general trends of the RCA concrete splitting tensile strengths were observed, and the results were in good agreements with the previous studies conducted [165, 166].

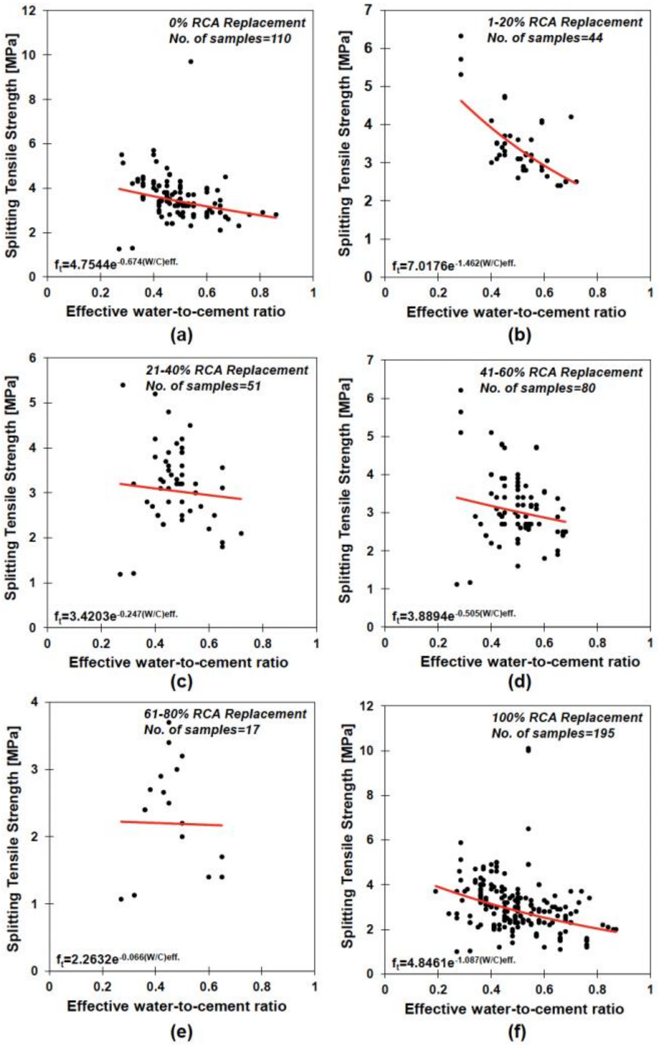


Figure 10: RCA concrete splitting tensile strength distribution for each replacement level; (a) 0% (b) 1-20% (c) 21-40% (d) 41-60% (e) 61-80% (f) 81-100%

3.1.5. Variability of average relative flexural strength

Since RCA materials are often used in pavement construction, the flexural strength is considered as a required strength parameter to quantify the unreinforced RCA concrete beam's or slab's ability to withstand failure in bending. The data collected into the database for RCA concrete flexural strength were from two types of beam sizes; 100 mm×100 mm×500 mm and 150 mm×150 mm×750 mm. The distribution of the average relative flexural strength of RCA concrete systems is shown in Figure 11. The average flexural strength patterns shown in Figure 11 can be moderately analogous to the splitting tensile strength patterns since the loading in both tests induces indirect tensile stresses. However, the average magnitudes can be a bit higher in flexural strength as compared to the splitting tensile strength because the concrete material can further deform under flexure. The results indicated in Figure 11 showed that systems which contained 1-20% RCA replacements had the least strength reduction that affected by only 0.5%, and further, the strength loss increased with the addition of RCA replacement levels. As it was discussed earlier that when the test specimens are subjected to indirect tensile stresses, the ITZ regions in the RCA concrete system promote immediate failure and resulted in a drastic slump of flexural strength over the RCA replacement level bandwidths. Like the observations made in both modulus of elasticity and splitting tensile strength, the average reduction in flexural strength was lower in the 61-80% bandwidth than for the 100% replacement bandwidth. This may be due to the reduction in stiffness discontinuities from a lack of natural aggregates; or it may not actually be a significant difference given the high variation of results. Further research into these issues is required to understand why 100% RCA replacement systems perform better, on average, than 61-80% RCA replacement systems.

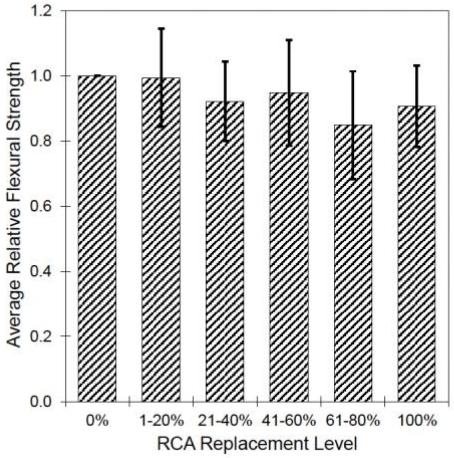


Figure 11: Average relative flexural strength of RAC systems compared to natural aggregate concrete systems

Flexural strengths of RCA concrete systems in the database are depicted against the effective W/C ratio in Figures 12(a)-(f) at each RCA replacement level bandwidth. Due to the combined effects of the RCA material variability and the sizing of the specimens, the RCA concrete flexural strength properties exhibited sparse distributions off the fitted nonlinear scheme. Although the flexural strength trends showed nonlinear distributions at 0%, 1–20%, 21–40%, 41–60%, and 61–80% RCA replacement levels with varying effective W/C ratio, 100% RCA replacement showed a linear strength decay with a lower exponential constant (see Figure 12(f)). This behavior was attributed to the material homogeneity due to the high elastic stiffness compatibility in 100% RCA replacement level. Flexural strengths of RCA concrete systems showed good data correlation in terms of the fitted nonlinear scheme. For example, the r values for RCA replacement levels at 0%, 1–20%, 21–40% 41–60%, and 61–80% were 0.50, 0.70, 0.70, 0.50, and 0.70 respectively (see Figures 12(a)-(e)). The r value showed a prominent influence on the number of outlying data located far off the fitted trend line because of RCA material variability, specimen size, number of data included in the sample space, and the failure criteria that is generally governed by the ITZ distribution. Despite the existence of potential outliers shown in Figures 12(a)-(f), common trends were observed that the strengths were decreased with increasing effective W/C ratio at any given RCA replacement level bandwidth.

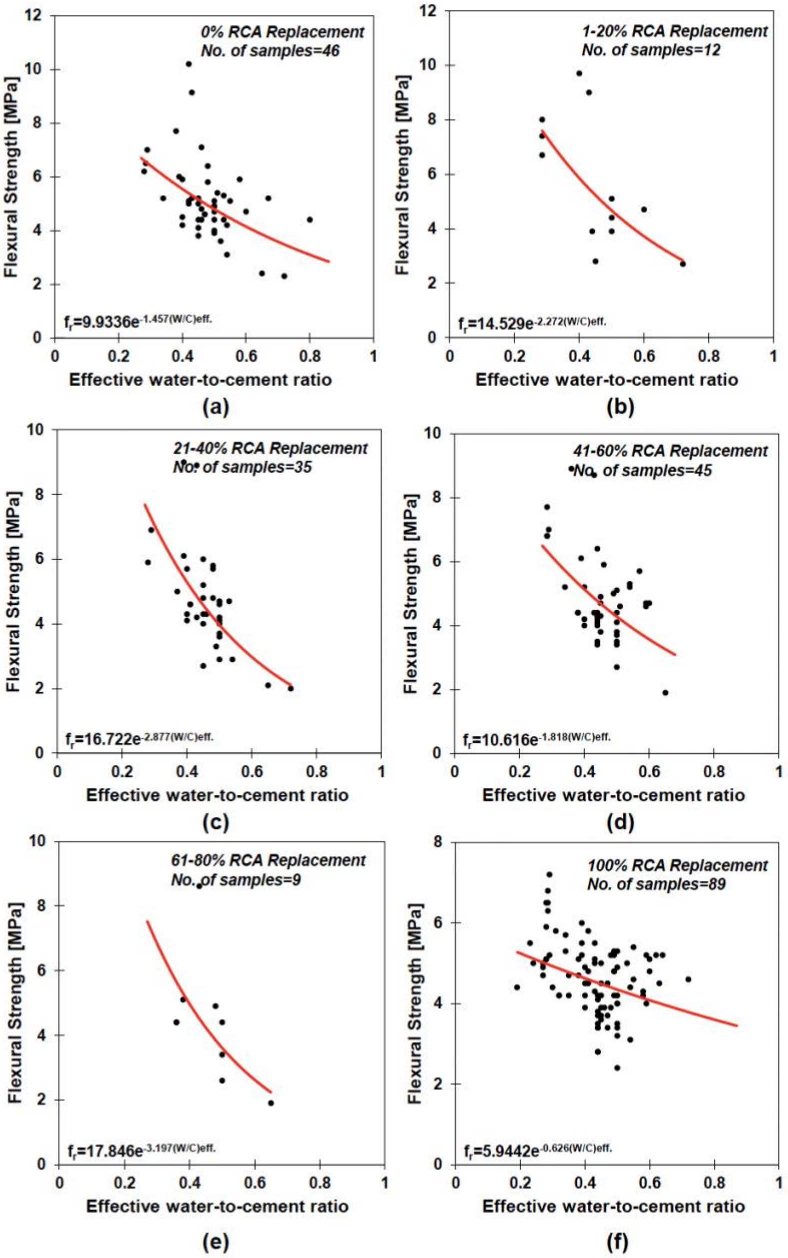


Figure 12: RCA concrete flexural strength distribution for each replacement level; (a) 0% (b) 1-20% (c) 21-40% (d) 41-60% (e) 61-80% (f) 81-100%

The major findings of the analysis of compressive strength, modulus of elasticity, splitting tensile strength, and flexural strength are summarized in Table 2 where it shows the relative strength distribution for each RCA replacement level bandwidth. Based on the results obtained, it was found that for all mechanical properties investigated, average relative strength decreased as the RCA replacement level increased through 80% replacement. Systems with 100% replacement saw slightly higher relative strengths than systems in the 60%-80% bandwidth due to reasons discussed above. The average relative compressive strength loss was less than 10% at all levels which shows RCA replacements can be used effectively without losing a substantial amount of concrete strength.

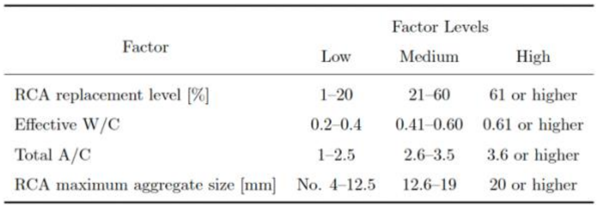
Table 2: Analysis summary on average relative strengths of RCA concrete systems

Strength Type	RCA Replacement or Bandwidth	Average Relative Strength	Average Strength Loss Relative to 0% RCA system [%]
Compressive Strength	0%	1.000	-
	1-20%	0.980	2.0
	21-40%	0.968	3.2
	41-60%	0.929	7.1
	61-80%	0.905	9.5
	100%	0.901	9.9
Elastic Modulus	0%	1.000	-
	1-20%	0.955	4.5
	21-40%	0.951	4.9
	41-60%	0.883	11.7
	61-80%	0.785	21.5
	100%	0.804	19.6
Splitting Tensile Strength	0%	1.000	-
	1-20%	0.972	2.8
	21-40%	0.938	6.2
	41-60%	0.929	7.1
	61-80%	0.805	19.5
	100%	0.873	12.7
Flexural Strength	0%	1.000	-
	1-20%	0.995	0.5
	21-40%	0.922	7.8
	41-60%	0.948	5.2
	61-80%	0.849	15.1
	100%	0.907	9.3

3.2. Factorial design procedure

The variability in material properties and mixture design proportions has a marked effect on concrete hardened properties, and therefore, factorial design techniques have been widely used to quantify the significance of each factor and the influence of factor interactions on a particular response(s) (i.e., RCA concrete hardened property) [167–169]. Adopting such a statistical tool can be used to interpret the effect of the material properties and the mixture design proportions on concrete strengths, in which it allows the user to manipulate those factors to develop predictable strength requirements for RCA concrete systems [168, 170, 171]. In this study, a full factorial analysis was implemented for the RCA compressive strength response by adopting the fundamentals of design of experiments [172]. Four factors and three individual levels for each factor were selected by considering the overall distribution of the data in the database such that, it satisfied a substantial data coverage included in each factorial level during the analysis. Therefore, the number of factors influenced the compressive strength was limited to four, and to comply with the computational analysis time, the number of levels were limited to three. The factors were included for RCA replacement level, effective W/C ratio, total A/C ratio, and maximum aggregate size where each factor was varied across low, medium, and high levels of magnitude ranges. While conducting the full factorial analysis on the RCA compressive strength response, the levels of the factors were varied as the base raised to the power by the number of factors (e.g., 34 = 81), and thus, in total, 81 factorial combinations were carefully generated. The factorial design metrics are shown in Table 3, whereas the limits are indicated for each level in correspondence to the factors considered. The complete analysis was performed through a statistical software [173], and the full factorial design analysis outputs were obtained for main effects, significant factors, and bivariate relationships.

Table 3: Factorial design metrics used in the statistical analysis



Factor	Factor Levels		
	Low	Medium	High
RCA replacement level [%]	1–20	21–60	61 or higher
Effective W/C	0.2–0.4	0.41–0.60	0.61 or higher
Total A/C	1–2.5	2.6–3.5	3.6 or higher
RCA maximum aggregate size [mm]	No. 4–12.5	12.6–19	20 or higher

3.2.1. Main effects on RCA concrete compressive strength

The main effect plots are used to interpret the individual factor effects on a particular average response at different levels of magnitude. As shown in Figure 13, the effects from each factor on the average RCA concrete compressive strength is depicted by a straight line connecting each factorial level with a circular marker, in which the trends were observed for each factor as they were changed from low-to-medium-to-high levels. A higher gradient (i.e., steep slope) between two markers is indicative that the response is strongly affected by the average compressive strength, while a gradual slope has a comparatively weaker effect on the compressive strength response. The average RCA concrete compressive strength of the data included in those 81 factorial combinations was 42.51 MPa, and it is demarcated by a segmented line across all the main effect plots. Regardless of the intermediate level in each factor, the main effect plots depicted in Figure 13 showed decreasing trends for RCA concrete compressive strengths between the low and high levels. When RCA replacement level is increased, the amount of adhered mortar is also increased, and the compressive strengths are further limited due to the higher relative stiffness difference and the ITZ distributions in the RCA concrete system. According to the main effect plots, the average strength reduction due to the increase of RCA replacement was about 16%. Since it is a common understanding that the compressive strength of concrete is inversely proportional to the amount of W/C ratio, a strength reduction of 23% was observed due to the increased effective W/C ratios from low-to-high levels. At higher A/C ratios, the cement content is generally lower in the concrete mixture designs and thus, it resulted in lower average compressive strengths (e.g., about 19% reduction) showing an abrupt strength decrease when A/C ratios were used from medium to high levels. However, at low and medium levels of A/C ratios, the average compressive strengths showed significant increase due to the adequate amounts of cementing materials present in the concrete system. With the increasing RCA maximum aggregate size from low-to-medium level, the average concrete compressive strength is reduced by nearly 14% due to the smaller surface-to-volume ratio, and often leads to a weakened coarse aggregate-cement paste bond when the aggregate size is increased [53]. Nevertheless, a slight compressive strength gain (e.g., about 5% increase) was observed at high levels of RCA aggregate sizes, and it was believed to be due to aggregate roughness associated with the adhered mortar phases and the aggregate interlocking behavior that contributed an additional material resistance in compression [160].

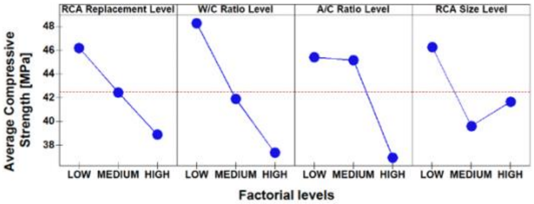


Figure 13: Main effects plot for RCA concrete compressive strength

3.2.2. Significant factors influencing the RCA concrete compressive strength

The significant factors or factor combinations on the RCA concrete compressive strength is determined based on the Pareto charts under a given significance level (e.g., significance level of 5% or confidence interval of 95%). A Pareto chart that represents the factor or factor combinations is shown in Figure 14 at 5% significance level. On the Pareto chart, the horizontal bars that cross the dashed vertical reference line (denoted as 5.764) are considered as statistically significant factors that strongly influence the RCA concrete compressive strength. The location of the reference line is quantified based on the pseudo standard error (PSE) evaluated at the (1 − α/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 factors or factor combinations used in the statistical model. Based on the calculation, the statistical program evaluated the PSE value of 2.24, and this is indicated as the Lenth's PSE in the Pareto chart. Eventually, the effect at the margin (M) of the reference line is calculated as M = t∗ × PSE where the t∗ is the t value obtained at upper tail significance level corresponding to a degree of freedom at n/3.

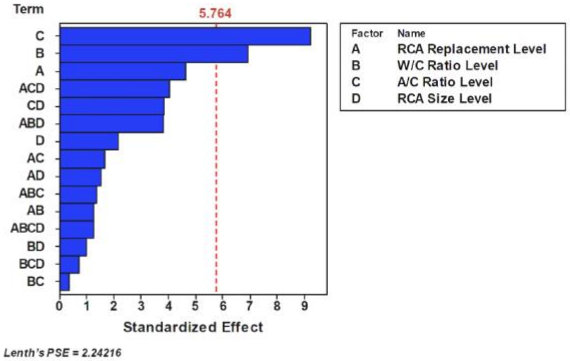


Figure 14: Pareto chart of the standardized effects at 5% significance level (i.e., 95% confidence interval) for RCA concrete compressive strength

According to the Pareto chart shown in Figure 14, the A/C ratio and the effective W/C ratio were considered as statistically significant factors on RCA concrete compressive strength under 95% confidence interval. This result and the output obtained by main effect plots (see Figure 13) provide a clear indication that at lower A/C ratios and effective W/C ratios, the RCA concrete compressive strength can yield higher prediction values within a confidence level of 95%. Although the RCA replacement level was not detected as a significant factor during the statistical analysis, the standardized effects showed that its significance on RCA concrete compressive strength was substantially higher than any of the remaining factor or factor combinations. It is also observed from the Pareto chart that some of the combined effects had higher standardized effects than that of the sole consideration of the RCA size. However, if a lower RCA size is combined with a lower RCA replacement level and a lower A/C ratio in a concrete mixture, a stronger RCA concrete compressive strength may be achieved, but, further combined effects with RCA size will not improve the strength in the RCA concrete system. Observing the combined effects associated with RCA-related factors (e.g., A, C, and D in Pareto chart), it showed that factor combinations between A and other factors, C and other factors, or D and other factors were not significant on the compressive strength under the given confidence interval. Hence, it can be concluded that there are no significant interactions between A, C, or D and other factors that can influence the concrete compressive strength in RCA systems.

3.2.3. Bivariate relationships

Bivariate relationships were studied to understand the variations of the predicted RCA concrete compressive strengths within the levels of two factors using a two-dimensional contour plot. When predicting the statistical responses (i.e., RCA concrete compressive strength), two factors can be varied simultaneously while other factors are being kept at their medium levels. Based on the four factors considered in the statistical analysis, six different bivariate relationships were established as shown in Figures 15(a)-(f) for RCA concrete compressive strength predictions.

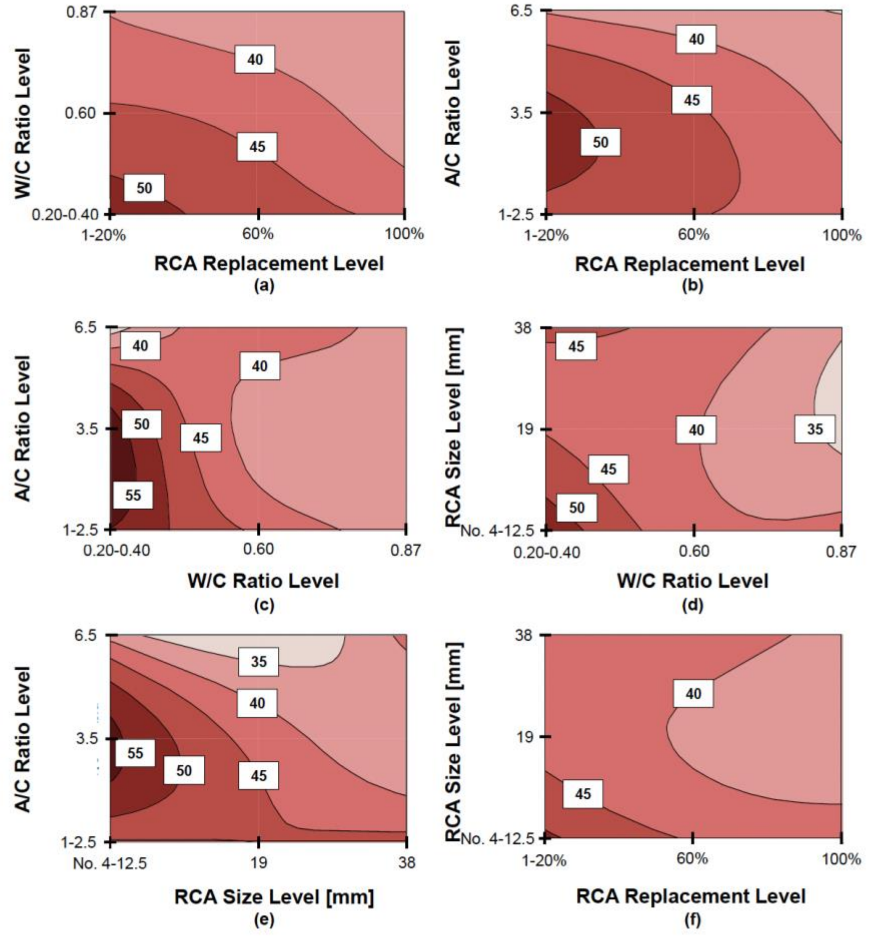


Figure 15: Bivariate relationships generated for RCA concrete compressive strength in MPa

The largest range of the RCA compressive strength predictions was observed in Figure 15(e) fluctuated between 35 MPa and 55 MPa. Although the significance of RCA size on the concrete compressive strength was found to be minimal according to the Pareto chart in Figure 14, the combination with the A/C ratio increased the predicted strength variability as shown in Figure 15(e) as opposed to the Figures 15(d) and (f). The highest RCA concrete compressive strength was achieved in Figures 15(c) and (e) by means of adjusting the A/C ratio, W/C ratio, and RCA size at minimum levels. Figures 15(d)-(f) confirmed that with low levels of RCA size can yield a substantially higher compressive strength which was attributed to the higher surface area bounded by the cement paste with a good adherence and the improved aggregate packing. Regardless of the factor varied with the RCA replacement level, Figures 15(a), (b), and (f) indicated that approximately 50 MPa can be predicted with the use of RCA replacement under 20%. Furthermore, it is clearly seen through Figures 15(b), (c), and (e), the compressive strength can yield higher predictable values at lower-to-medium levels of A/C ratios by increasing the amount of cementing materials in the concrete mixture. Overall, the results shown in the bivariate relationships not only provide a graphical interpretation of how the strength changes across two factors, but also, it indicates the significance on how to select material proportions for predicted RCA strength performances guided by the experimental data analyzed in the database.

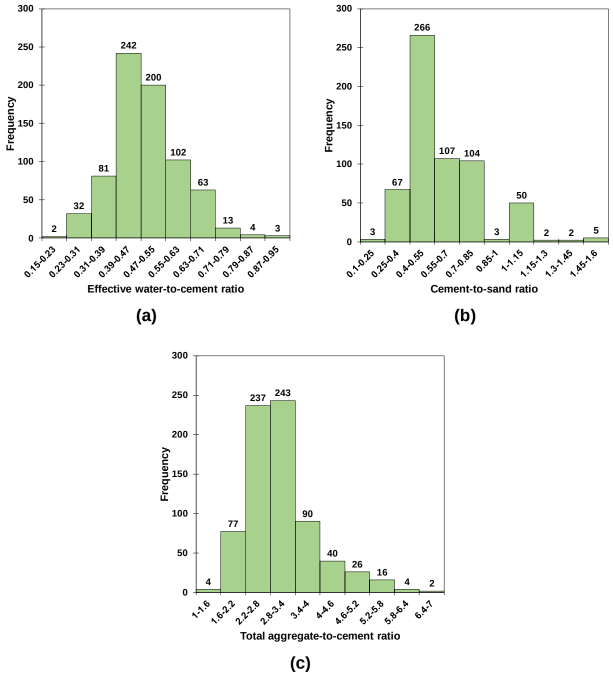
Since the current statistical tool developed through bivariate relationships is extremely useful to estimate the material requirements for a predicted compressive strength, such material characterization has a feasibility to develop a novel mixture design guideline for RCA concrete systems through the data analyzed in the database. Among those currently available mixture design procedures, ACI 211 [174] provides a productive design guideline for normal weight concrete mixtures to achieve predicted strength and durability properties of concrete, and thus, the main design philosophy can be adopted to adjust the process and the material limitations based on the findings in this section. Although the long-term durability-based properties were not included in the statistical database analysis, the strength performance of RCA concrete systems can be considered while the concrete materials should not be applied on severe environment conditions until further reliable statistical conclusions are drawn for RCA concrete durability. However, since the statistical analysis was performed through actual experimental data which most likely was designed to a standard mixing procedure, the data may include durability properties to a certain extent. Nevertheless, it is recommended that the RCA concrete systems should not be subjected to extreme environmental conditions.

The statistical database analysis results provide an important level of understanding about the general trends of RCA strengths based on various factor effects in RCA concrete systems. On average, RCA concrete compressive strength, elastic modulus, tensile strength, and flexural strength at 28 days recorded in the database were decreased by 16%, 14%, 12%, and 7%, respectively, with the effects of RCA replacement levels through 1–100% compared to average strengths of the natural aggregate concrete systems. As reported in the literature, the presence of RCA materials in concrete resulted in a strength reduction, and the existing experimental findings [75, 78, 135, 137, 144, 175–177] validated the current statistical trends on RCA strengths obtained through the database analysis. However, it was noted that the higher variability of the strength trends was strongly affected by the amounts of materials and their physical properties introduced into the mixture design when RCA concretes are made. Specifically, adhered mortar and its contents play a significant role in predicting the strength of RCA concrete [162]. Cementitious properties in adhered mortar, such as high absorption due to higher porosity levels can increase the W/C ratio demand in the concrete mixture, and directly influence the compressive strength. Using lower RCA aggregate size, the predicted RCA concrete compressive strength can be increased because small-sized RCA can increase the particle packing, as well as having higher adhered mortar contents associated with higher stiffness compatibility [48, 178, 179]. It also decreases potential stress localization effects in the aggregate system inside the concrete such that higher strengths can be achieved [158, 162]. This statistical finding signifies that the current RCA production methods needs to be adjusted, such that the RCA undergoes several crushing stages where it can break off the adhered mortar phases in high quantities. As such, if the adhered mortar is derived from a high-strength parent concrete, the predicted RCA compressive strength would be high [144, 160] due to the higher stiffness compatibility of the concrete system [158, 162]. Henceforth, appropriate RCA classification guidance can be implemented as well. However, increased adhered mortar can affect the RCA concrete elastic modulus as the aggregate stiffness is hindered due to the increased adhered mortar contents, and thereby, a limit for the amount of adhered mortar in an RCA concrete system is suggested. According to the strength trends depicted in Figures 4, 7, 9, and 11, the optimum RCA replacement level at 11-20% resulted the highest strength performance based on the statistical observations, and thus, RCA replacement levels are recommended to limit below of 20% for predictable RCA strength performances. Statistical implications from the bivariate relationships derived through the database analysis for RCA compressive strength provide guidance in selecting various material proportions based on the target strengths. As far as the bivariate results are concerned, mixture design proportions can be predicted, such that the design compressive strengths fall between 35 MPa to 55 MPa. Although appropriate standard deviations need to be stipulated for considerate target strength ranges for this purpose, the current statistical database study can fully accommodate the potential values for such design methodologies. Since the bivariate relationships for target strengths were created based on material proportion ratios, additional code specified guidelines would require to approximately quantify the individual material proportions for appropriate concrete applications. For example, if RCA is used for flat concrete works, ACI 302 [180] standard can be adopted to estimate the cement content required based on the RCA maximum aggregate size. This enables the concrete community to provide stronger guidance for proportionating materials for RCA concrete using the bivariate relationships.

4 Stochastic mesoscopic modeling of concrete systems containing recycled concrete Aggregates using Monte Carlo methods

4.1 Statistical distributions of mixture proportions in the database

The primary material constituents for normal weight concrete mixtures made with RCA recorded in the database are water, cement, coarse aggregate (RCA and natural aggregates), and fine aggregate (i.e., sand), where no other solid materials are used such as pozzolanic materials. Due to the existence of large variability of the individual material quantities that have been used in the mixture designs, three mixture design proportion ratios [210] were calculated using the collected database of information to further simplify the analysis process: effective water-to-cement ratio, cement-to-sand ratio, and total aggregate-to-cement ratio. Corresponding histogram distributions of each material proportion ratio are shown in Figure 16, in which the variability of each distribution of the database exhibited Gaussian characteristics that was tested and ensured through a graphical tool using quantile-quantile plots (i.e., QQ plot) of the standardized data and the standard normal distributions. However, a slight positive skewness was observed in each distribution owing to the higher mean and median values of the distributions than the mode. The mean distributions for the entire data set of effective water-to-cement ratio, cement-to-sand ratio, and total aggregate-to-cement ratio were 0.48, 0.57, and 3.00 respectively with corresponding standard deviations of 0.11, 0.22, and 0.86.



(a)

(b)

(c)

Figure 16: Histogram distribution of mixture design proportion ratios; (a) effective water-to-cement ratio (b) cement-to-sand ratio (c) total aggregate-to-cement ratio.

A reliability analysis conducted by Jayasuriya et.al.[218] on the compressive strength of RCA concrete material phases showed that the properties of the cement mortar matrix were the second most statistically significant factor that influenced the compressive strength in the RCA concrete meso-structure subsequent to natural aggregate stiffness. However, due to the effective water-to-cement ratio, the variability of the cement mortar matrix properties is higher than the variations that were seen in mineralogical properties of the natural aggregates in the experimental database. Therefore, the effective water-to-cement ratio was considered to be the governing factor that constituted the selection of other mixture design proportion ratios in the experimental database.

4.1.1 Stochastic generation of mixture design proportion ratios

The stochastic generation process utilized in this work is focused on initiating probabilistic mixture design proportion ratios that represent the mixture design data reflected in the experimental database. The stochastically generated mixtures are then used to simulate corresponding RCA concrete systems through finite element analysis. Hence, the current study provides an understanding on how numerically simulated recycled aggregate concrete is able to predict mechanical properties of RCA concrete through comparisons with the data available in the experimental database. The inputs to the numerical simulation accounts are provided through Monte Carlo simulations wherein the effects of various phases of RCA concrete systems are considered (e.g., cement mortar matrix, adhered mortar matrix, RCA replacement ratio). Monte Carlo simulations are a method of probability analysis completed by running a number of variables through a model in order to determine the range of possible outcomes. Generation of stochastic mixture design proportions from the database were obtained for effective water-to-cement ratio, cement-to-sand ratio, and aggregate-to-cement ratio.

The distribution of effective water-to-cement ratio shown in Figure 16(a) followed the statistical empirical rule (i.e., 68-95-99.7 rule), where it can be assumed that the data cluster resembled a normal distribution. This empirical rule can be applied and observed in approximately normal distributions such that the values within one standard deviation of the mean account for approximately 68% of the set; within two standard deviations account for approximately 95%; and within three standard deviations account for approximately 99.7% [219]. The range of the distribution varied from 0.19 to 0.87, and according to the empirical rule, the distribution was divided into three subregions (i.e., bandwidths) such that, it covered 70% of the data within the first standard deviation (i.e., $1\sigma_{w/c}$) of the mean, and the remaining 30% of the data was below (i.e., 15% of data) and above (i.e., 15% of data) the first standard deviation with equal proportions. Based on this data distribution criteria, the first 15% of the data, second 70% of the data, and the last 15% of the data were distributed between effective water-to-cement ratios of 0.19–0.39, 0.40–0.59, and 0.60–0.87 respectively. The purpose of dividing the population into three bandwidths was to reduce the number of random variables in later portions of RCA concrete.

After determining the three bandwidths for effective water-to-cement ratio, corresponding material proportion ratios were then stochastically selected for cement-to-sand ratio and aggregate-to-sand ratio by adopting conditional distribution criteria. The conditional distribution is primarily evaluated based on the probability density of a sub-population of a given set of data. Therefore, three independent conditional distributions were established for cement-to-sand ratio and aggregate-to-cement ratio given that, an effective water-to-cement ratio was randomly picked based on its stochastic distribution from the experimental database. Further, the cement contents that were used in the experimental database were included in the process to stochastically determine the aggregate content based on the conditional probability that an effective water-to-cement ratio was stochastically picked. A detailed flowchart is shown in Figure 17 to illustrate the selection criteria of conditional distributions and the corresponding conditional probabilities for cement-to-sand ratio, aggregate-to-cement ratio, and cement contents based on the selected effective water-to-cement ratio.

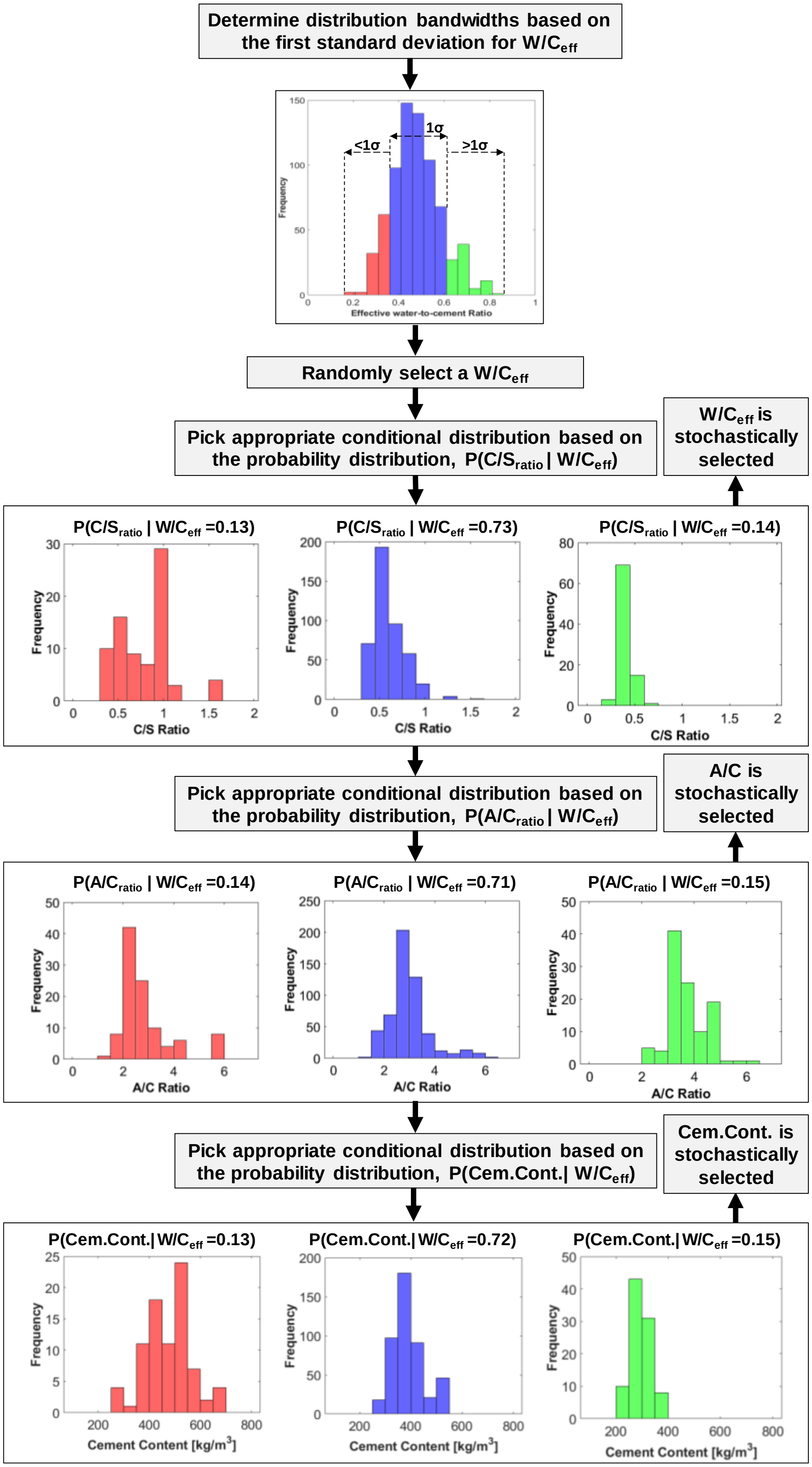


Figure 17: Schematic flowchart used for the stochastic generation of mixture design proportions.

The number of stochastically generated material proportion ratios that were needed for Monte Carlo simulations was estimated according to the principles of population proportion technique. The population proportion is fundamentally influenced by many factors such as the margin of error of the original population, confidence interval that specifies the amount of uncertainty associated with the estimate (i.e., the chance that the margin of error will contain the true proportion), size of the population, and the likelihood of the sample proportion (i.e., the proportion selected based on previous data proportioning) [220]. Therefore, the representative sample size of the numerical simulations that was studied under Monte Carlo simulation was determined based on the following sample size calculations provided in Equation 1 and Equation 2,

$$n = \frac{N\beta}{N+\beta-1} \tag{1}$$

$$\beta = \frac{(Z_{\alpha/2})^2 \times p(1-p)}{MOE^2} \tag{2}$$

where *n* is the minimum sample size required, *N* is the population size, *β* is the assumed sample size, $Z_{\alpha/2}$ is the critical value of the normal distribution at *α/2* (i.e., for confidence interval of 90%, α/2 is 0.05, and the critical value is 1.645), *p* is the sample proportion, and *MOE* is the margin of error. For the current study, 5% margin of error, 90% confidence interval, 50% sample proportion for the cumulative population of 742 RCA concrete properties in the database were chosen. Based on the selected values, a total of 200 samples were stochastically generated for RCA concrete systems, and numerically simulated under uniaxial compression and tension.

4.2 Selection of representative material properties for the numerical analyses

RCA concrete is a heterogeneous composite material comprised of five material phases as shown in Figure 1, and has unique individual mechanical properties [221-223]. These five material phases include the cement mortar matrix, the adhered mortar, the natural aggregate, the old ITZ between the natural aggregate, and the new ITZ between the adhered mortar and the cement mortar matrix. Although the hydrated phases of the interface adjoining the cement mortar matrix to the natural aggregate and adhered mortar phases have minor differences in mechanical properties at a microstructural level [224], the complete interface contacting the cement mortar matrix to the overall RCA particle is considered as one ITZ region in this study to further simplify the complexity caused by the higher material heterogeneity of the concrete system. However, since the emphasis of this study is focused on studying the variability of the hardened material phases in RCA concrete systems (e.g., cement mortar matrix, adhered mortar, and old/new ITZ phases) influencing the concrete strength properties, the natural aggregate material properties were kept constant. Given that 200 samples of randomly generated aggregate structures for RCA concrete systems were required, the material properties of those five material phases were calculated based on the mixture design proportion ratios determined through the stochastic generations (see Figure 17) for effective water-to-cement ratio, cement-to-sand ratio, and aggregate-to-cement ratio. The effects of water-to-cement ratio and the cement-to-sand ratio on the cement mortar mechanical properties were studied by Singh et al. [225], and the results showed that the strength properties of cement mortar specimens under uniaxial compression and split tension had excellent correlation when water-to-cement ratio was changed from 0.50 to 1.20 and the cement-to-sand ratio was incrementally changed from 1:3 through 1:7. Corresponding strength properties for compressive strength and splitting tensile strength are shown in Figure 18, where similar relationships were adopted in this study to define the cementitious material properties of RCA concrete systems. The compressive and tensile strength properties were estimated based on the stochastically generated mixture design proportion ratios obtained from the experimental database. Consequently, the tensile and compressive properties were established for cement mortar matrix and adhered mortar phases for each RCA concrete system over the sample size of 200 different systems.

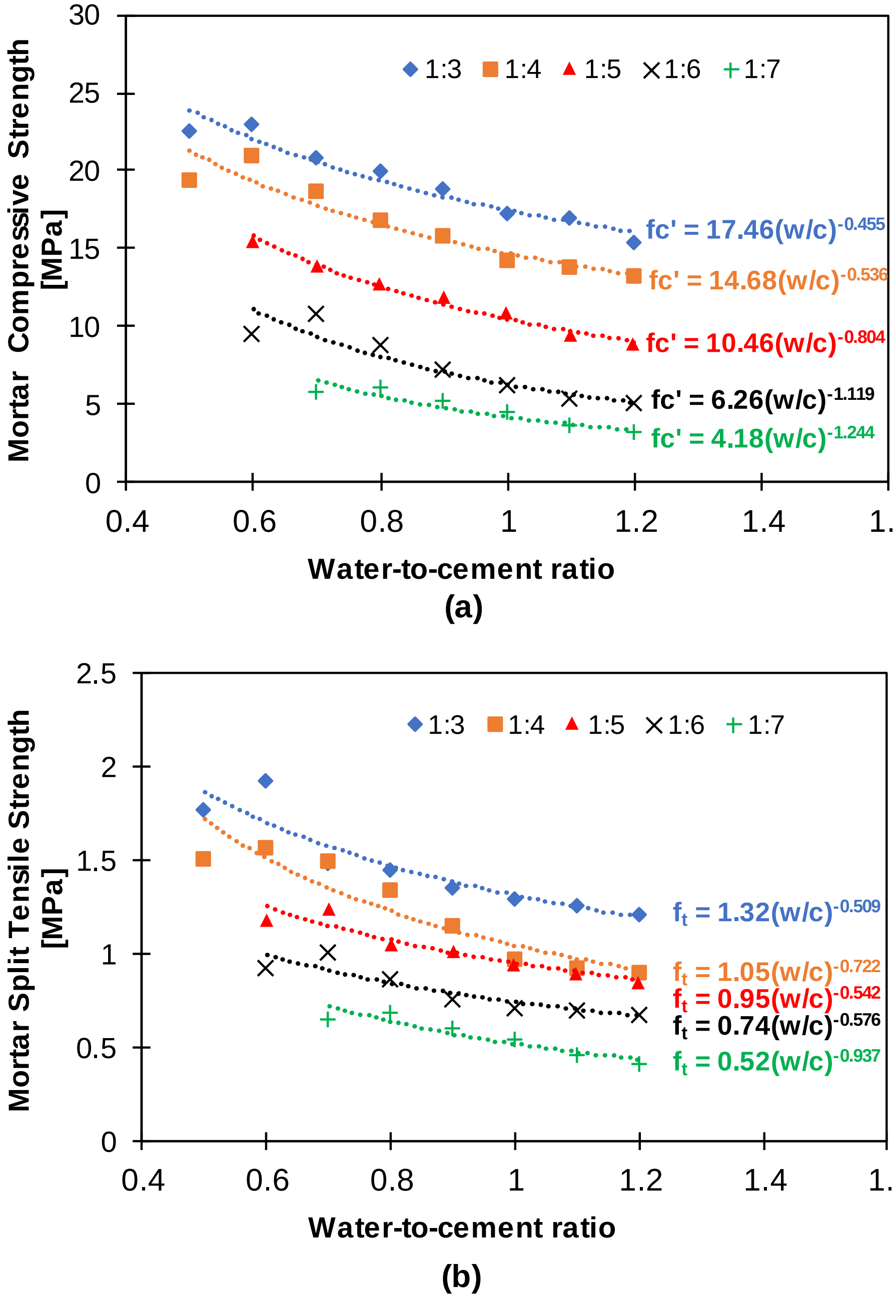


Figure 18: Cementitious material properties based on water-to-cement ratio and cement-to-sand ratio adopted by Singh et al.[45]; (a) compressive strength (b) split tensile strength.

The number of total aggregates generated in the numerical simulations was based on the stochastic selection of aggregate-to-cement ratio and the cement content as illustrated in Figure 17. First, the aggregate weight per unit volume was computed by multiplying the aggregate-to-cement ratio by the cement content (i.e., in kg/m^3) for each experimental mixture in the database. Then, a representative volume was computed by adopting the corresponding aggregate bulk densities obtained from aggregate properties provided in the experimental database. Once the total volume of the aggregates in the RCA concrete was known, the aggregate volume ratio of the modeling geometry for numerical simulations was evaluated, and it was assumed as the aggregate ratio that was needed as an input to populate the aggregate geometry in the simulation. Since the numerical simulations are generated based on the database results, the probabilistic nature of the RCA replacement levels was distributed over the 200 samples by considering the proportional probability of each RCA replacement that had been used in the experimental database. The elastic properties of each of those material phases were coupled with the compressive strength, such that the modulus of elasticity for the cement mortar matrix and adhered mortar was obtained through an extensive parametric analysis performed by Xiao et al. [226].

The lack of systematic and accurate experimental data to determine the ITZ properties has been a concern to understand the link between the main material phases in concrete. However, it has been observed that the ITZ regions increase the cracking propensity of the RCA concrete due to the weaker interface characteristics, regardless of whether it is the old ITZ region (i.e., between the adhered mortar and natural aggregate) or new ITZ region (i.e., between the cement mortar matrix and the RCA particle) [224, 227, 228]. Therefore, the material properties for both ITZ phases have lower strength characteristics than the other material phases in the RCA concrete system. Based on test data obtained through nanoindentation work [226], the mechanical strength reduction of ITZ phases were assumed as 70% of the main cementitious material phase (i.e., cement mortar matrix or adhered mortar) corresponding to the appropriate ITZ phase (i.e., new or old). Poisson's ratio for all five material phases were considered as constants where the values for natural aggregate [214], cement mortar matrix[214, 226], adhered mortar matrix [226], new ITZ [229], and old ITZ [229] were used at 0.16, 0.22, 0.22, 0.20, and 0.20 respectively.

In order to capture a smooth concrete softening behavior near the peak response, appropriate fracture properties need to be estimated. The ratio between the tensile fracture energy and the compressive fracture energy was set at 0.10, such that the RCA concrete material satisfied an exponential and parabolic softening behavior for tensile and compressive responses respectively. Furthermore, the numerical convergence was successfully captured for both the softening period and the post-peak response, until the final material failure had occurred. Based on the studies performed under meso-scale numerical analyses by Kim and Al-Rub[230] and Li et al. [231], the ratio between the fracture energies of cementitious materials and their corresponding ITZ phase was set to 0.80, and thus, similar ratios were used herein the study. A summary of mechanical properties of the material phases in RCA concrete systems that were adopted for the numerical Monte Carlo simulations is provided in Table 4. The histogram distributions for stochastically generated random input variables are depicted in Figure 19, where the compressive and tensile material properties of cementitious materials (i.e., adhered mortar and cement mortar matrix) are provided with the RCA replacement levels used in the numerical models.

Table 4: Mechanical properties of material phases in RCA concrete system

Material phase	Linear elastic properties		Mechanical properties		Tensile fracture energy [N/mm]
	Elastic modulus [GPa]	Poisson's ratio	Compressive strength [MPa]	Tensile strength [MPa]	
Natural aggregate	70	0.16	144	9.6	0.455
Cement mortar matrix	19.8-24.8	0.22	17.5-27.4	1.4-2.9	0.04-0.08
Adhered mortar	19.8-24.8	0.22	17.5-27.4	1.4-2.9	0.04-0.08
New ITZ	13.9-17.3	0.20	12.2-19.2	1.0-2.0	0.03-0.06
Old ITZ	13.9-17.3	0.20	12.2-19.2	1.0-2.0	0.03-0.06

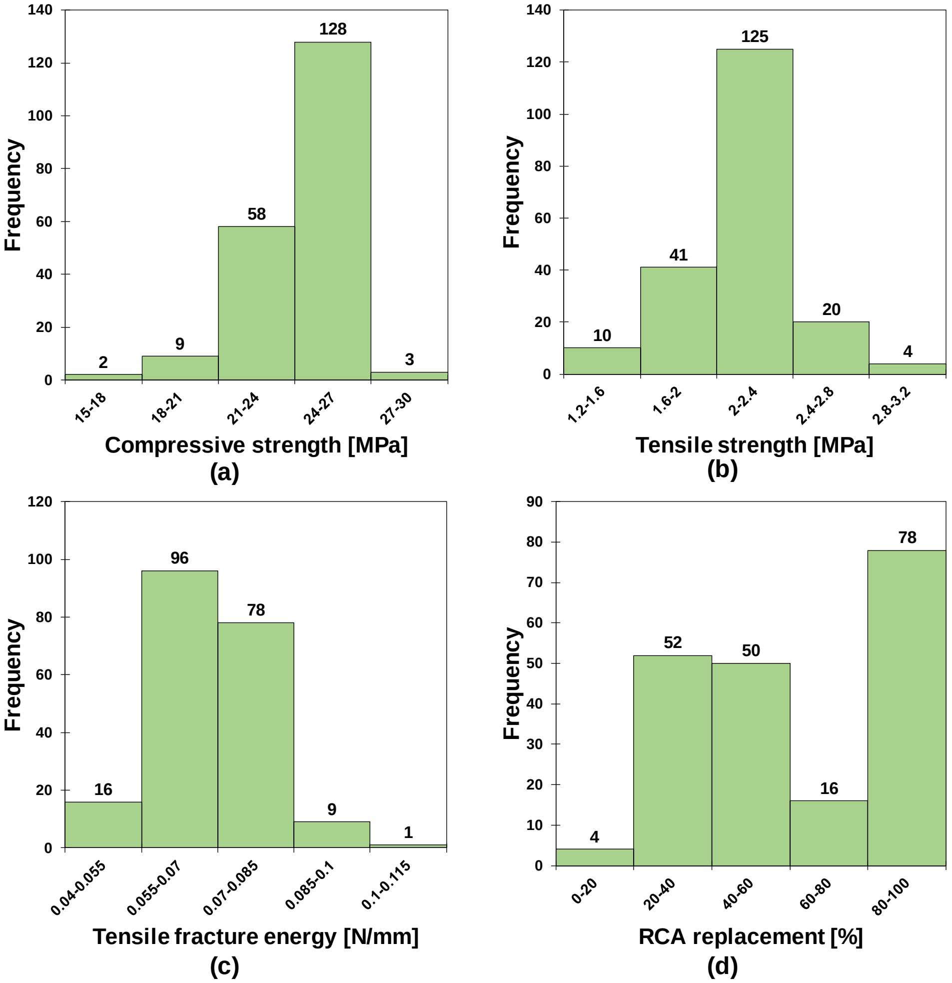


Figure 19: Histogram distributions of stochastic input parameters; (a) compressive strength of adhered mortar and cement mortar matrix (b) tensile strength of adhered mortar and cement mortar matrix (c) tensile fracture energy of adhered mortar and cement mortar matrix (d) RCA replacement levels.

4.3 Numerical simulation setup

4.3.1 Meso-scale geometry of RCA concrete systems

A methodology to generate random aggregate structure at a meso-scale level utilizing a comprehensive computational algorithm for RCA concrete systems was recently developed by the authors [213]. The current study used an identical framework in developing the aggregate structure for RCA in terms of particle size distribution, spatial distribution of aggregates, defining of randomly located adhered mortar portions attached to the natural aggregate, aggregate boundary effects near the concrete edge, etc. Although it is a reasonable justification to consider random pores in the concrete system at a mesoscopic level, the porosity of the cement mortar matrix has been considered in the mechanical properties of the matrix as they were obtained from the experimental database. Therefore, the pores were not introduced in the RCA concrete geometry, given that the RCA concrete systems may further inhibit their strength performance which would underestimate the numerical results.

While previous research has claimed that the strength properties of RCA concrete systems exhibit strong dependency on the RCA replacement level, residual mortar content, and the particle shape[183, 213, 232, 233], this study mainly focuses on examining the influence of the RCA replacement for angular aggregates with random attachments of residual mortar contents to the natural aggregates. A substantial proportion (i.e., more than 50%) of experimental mixture designs that were studied in the database have adopted 20 mm maximum size crushed RCA, and thus, the same maximum aggregate size was chosen in the numerical model geometry.

The numerical simulations were proportionally assigned to effective water-to-cement ratio bandwidths discussed in the previous subsections based on the experimental database distributions. Out of 200 numerical models, proportions of 15%, 70%, and 15% were allocated to effective water-to-cement ratio bandwidths between 0.19–0.39 (i.e., 30 simulations), 0.40–0.59 (i.e., 140 simulations), and 0.60–0.87 (i.e., 30 simulations), respectively. The random geometries that were generated for each numerical simulation had RCA replacement levels between 10–100%, and the corresponding total aggregate content covered 50-56% of the overall concrete geometry area which was identical to the subset of the experimental database used for comparison as the aggregate properties (i.e., aggregate bulk density and total aggregate content) provided in the database information were considered during the generation of numerical models. However, since the adhered mortar was not quantified in the experimental database (due to a lack of available information in the original studies), the adhered mortar was randomly distributed through the adopted algorithm where adhered mortar content varied as a function of RCA replacement level. The distributions of geometric properties of the numerical models represented by the three bandwidths of effective water-to-cement ratio are provided in Table 5.

Table 5: Quantitative estimates of RCA particles used in the numerical models

Effective water-to-cement ratio bandwidth	Number of simulations	RCA replacement level [%]	Adhered mortar content [%]	Aggregate ratio [%]
0.19 – 0.39	30	20 – 100	1.24 – 35.50	50 – 54
0.40 – 0.59	140	10 – 100	3.86 – 37.80	52 – 56
0.60 – 1.00	30	10 – 100	1.37 – 33.33	51 – 54

4.3.2 Finite element modeling of RCA concrete systems

Adopting the image analysis criteria in random aggregate generation previously developed by the authors [213], 200 numerical simulations were produced for varying RCA replacement levels, aggregate distributions, and representative material properties that were stochastically generated through the experimental database. The RCA concrete geometries were implemented on a commercial finite element program; DIANA Release 10.2 [214]. Given the significant computational time incurred during the generation of the 200 numerical models, the geometry of the concrete systems in the simulations was chosen as 100 mm × 100 mm with plane stress elements. The plane stress elements were comprised of 4-noded quadrilateral shape functions, where the nodal loads and nodal point boundary conditions were assigned at the top and bottom boundaries of each numerical model simulated as shown in Figure 20. Static equilibrium along the horizontal direction of the model geometry due to the load applied vertically at the top was maintained by assigning a pinned support at the left-most corner, whereas vertical equilibrium was maintained through roller supports at the remaining nodal points of the RCA concrete geometry. The reason for the roller support assignment at the bottom boundary conditions was to prevent strain localizations that would have been induced due to the lateral deformation from the Poisson's effects of the RCA concrete system.

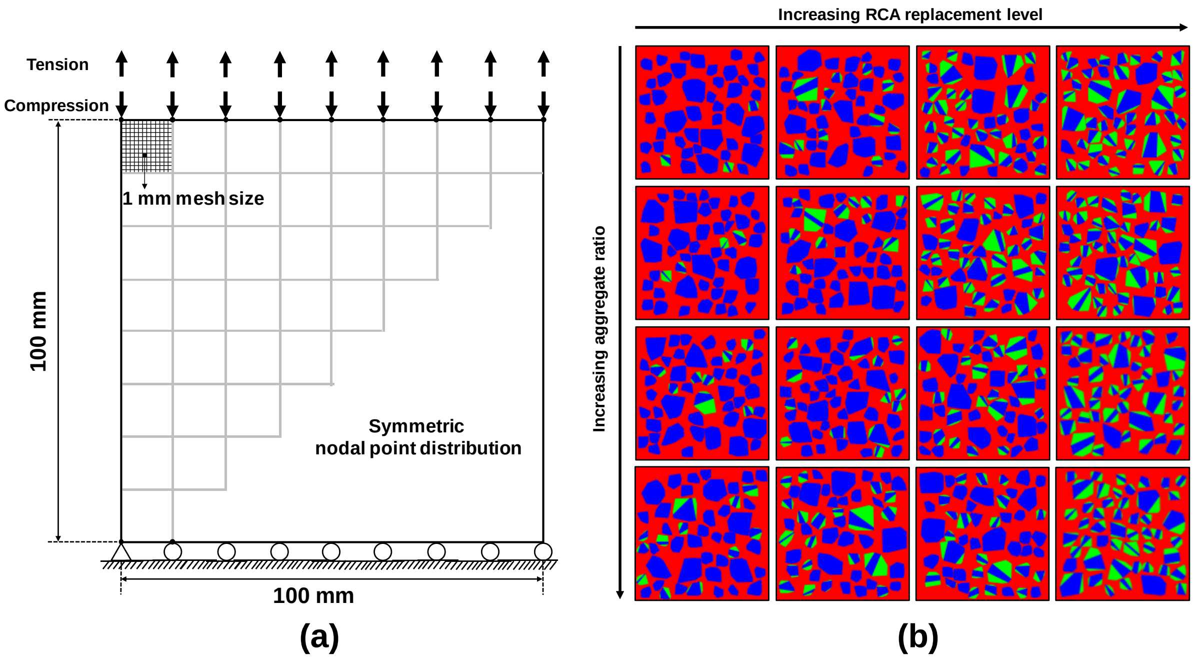


Figure 20: Schematic of compressive and tensile loading geometries for numerical simulations; (a) loading geometry and mesh distribution (b) representative RCA concrete geometries.

4.3.3 Material models and input parameters for nonlinear analysis procedure

The damage constitutive relationship of each material phase in RCA concrete system was captured by implementing a total strain-based fixed crack model developed by Feenstra [235]. According to the constitutive relationship, the compressive and tensile material behavior of the post-peak response was captured through a parabolic and exponential softening phase as shown in Figure 21.

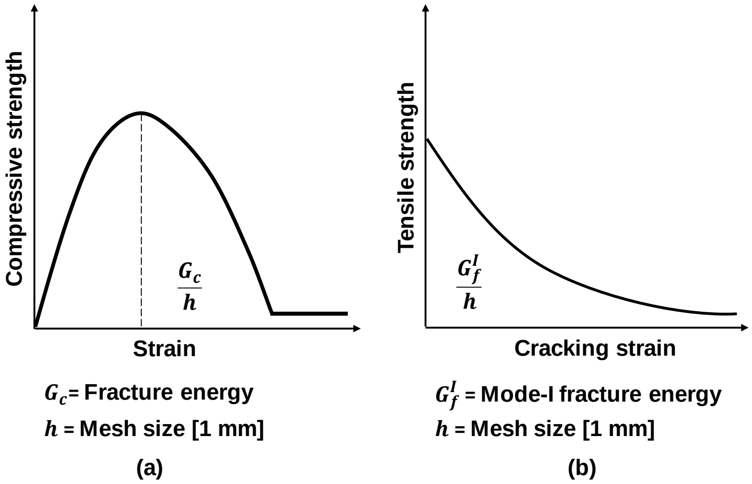


Figure 21: Softening behaviour of the material phases in RCA concrete system under applied deformation conditions; (a) compressive response (b) tensile response.

Input parameters for the nonlinear analysis were determined based on three selective criteria; load incrementation criteria, iterative solution method criteria, and convergence criteria. Since the load was applied on the nodal points on each RCA concrete geometry as a prescribed deformation, a displacement control was adopted. The prescribed deformation was 0.001 mm (i.e., strain increment of 10 με), and it was applied in the loading direction (i.e., for compression, vertically down, and for tension, vertically up) until the equilibrium of the concrete system was no longer satisfied. The solution of nonlinear system equilibrium equations was achieved by adopting an incremental-iterative solution method. Therefore, this study followed a Quasi-Newton secant method with Broyden–Fletcher–Goldfarb–Shanno (BFGS) [236] iteration method. The accuracy of the solution in a nonlinear analysis is associated with how close the solution to the equilibrium path measured by convergence criteria. The convergence criteria for each numerical analysis were considered under three norm tolerances; force, displacement, and energy. In this paper, the analyses were based on the tolerances estimated at 1%, 0.1%, and 0.01% for force, displacement, and energy respectively, such that the complete material behavior was captured throughout the loading period.

4.4 Monte carlo simulation results

Uniaxial compression and tension tests were numerically simulated on representative RCA concrete systems based on the experimental database. The motivation of adopting a Monte Carlo simulation was to better understand the variability of the influence of RCA replacement level, adhered mortar content, and the mechanical properties of cementitious phases on the strength characteristics of RCA concrete systems. The statistical responses of RCA concrete strength characteristics through Monte Carlo simulations were studied for compressive strength, elastic modulus, and tensile strength, where the experimental database strength results were compared with the numerical outputs.

4.4.1 Variability of compressive strength

Numerically simulated compressive strengths (i.e., peak stresses) were determined based on the stress-strain relationships developed for each geometry developed from Monte Carlo simulations. As shown in Figure 22, the stress-strain relationships were obtained by dividing the cumulative reaction forces at the nodal support boundary conditions by the cross-sectional area (i.e., 100 mm × 100 mm) of the concrete geometry at each deformation step, where the corresponding strain level was calculated based on the length ratio between the applied deformation and the initial length of the concrete model along the loading direction. Figure 22 depicts all 200 simulated responses as well as four characteristic stress-strain curves: three average responses for the corresponding water-to-cement bandwidth (i.e., 0.19–0.39, 0.40–0.59, and 0.60–0.87) and one overall mean response. The characteristic curves shown in Figure 22 indicated that the average responses of the simulated RCA systems showed a substantial reduction in the compressive strength performance when the corresponding effective water-to-cement ratio bandwidths were increased from 0.19 to 0.87. For example, the average compressive strength trends in RCA concrete systems were 42 MPa, 40 MPa, and 32 MPa for w/cm ratios of 0.19–0.39, 0.40–0.59, and 0.60–0.87, respectively. The standard deviations in these respective bandwidths of water to cement ratios were 1.5 MPa, 0.75 MPa, and 2.2 MPa, respectively.

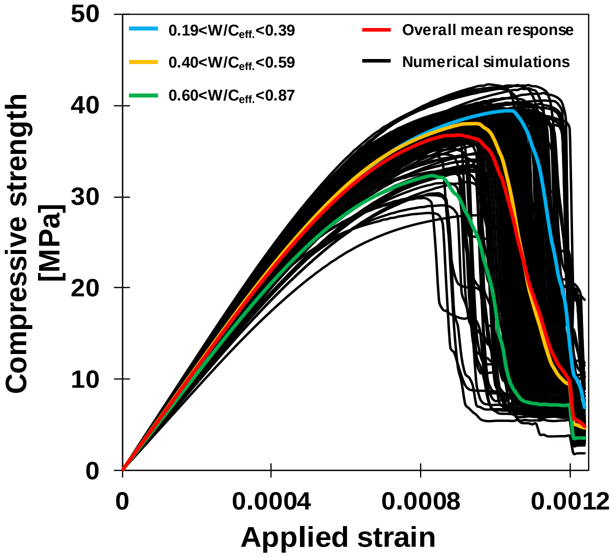
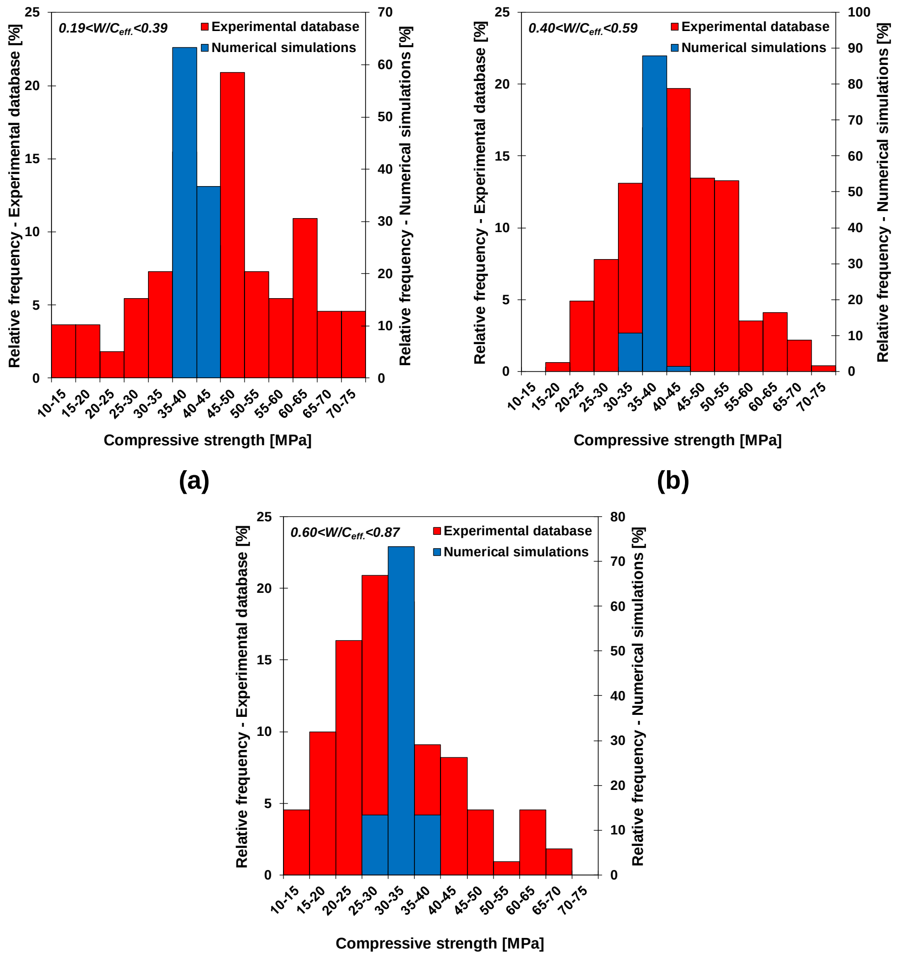


Figure 22: Stress-strain curves under uniaxial compression for 200 Monte Carlo simulations.

A distribution comparison of the compressive strength results obtained through the experimental database analysis and the numerical analysis is shown in Figure 23 at each effective water-to-cement ratio bandwidth. Based on the database analysis results within 0.19–0.39 effective water-to-cement ratio, the distribution of the experimental database exhibited an average compressive strength of 45 MPa with a standard deviation of 14.5 MPa. Corresponding numerical results predicted that the average compressive strength was 40 MPa with standard deviation of 1.5 MPa. For 0.39–0.59 and 0.60–0.87, the database showed average compressive strengths of 42 MPa and 31 MPa with respective standard deviation of 10.7 MPa and 12 MPa. Further, the corresponding numerical simulations showed average compressive strengths of 39 MPa and 33 MPa with respective standard deviations of 0.75 MPa, and 2.2 MPa. Therefore, it was seen that the predicted average compressive strengths of numerically simulated RCA concrete systems were in close agreements; however, the variability in predicted strength observed in the experimental database was not comprehensively captured in the simulations.



(a)

(b)

(c)

Figure 23: Comparison of compressive strength histogram distributions for effective water-to-cement ratio bandwidth; (a) $0.19<W/C_{eff.}<0.39$ (b) $0.40<W/C_{eff.}<0.59$ (c) $0.60<W/C_{eff.}<0.87$

Several possible reasons and limitations were identified in this study that may have caused for the lack of variability exhibited in the numerical simulations, and they are outlined as follows:

1.) *Aggregate morphology* – In consideration of aggregate morphological characteristics, such as maximum aggregate size, aggregate shape effects, angularity, elongation, and surface texture can influence the concrete properties [213, 215, 232], and collectively, these characteristics could cause higher order effects on the strength properties of RCA concrete systems. Such morphological characteristics were not varied in combination in the numerical models due to added computational time that would have been required. As such, a substantial source of variability of RCA concrete strength properties was not captured through the current numerical analysis.

2.) *Adhered mortar content* – During the generation of random aggregate structures, the adhered mortar content was randomly attached to the natural aggregate phase using a similar generation algorithm for all the RCA concrete geometries. Therefore, the amount of adhered mortar area and the location that it would attach to the natural aggregate was not influenced by the experimental database inputs. Furthermore, due to the lack of information that quantifies the adhered mortar in the available literature review, the variability of concrete strength properties is more susceptible to change at a greater extent. Therefore, the variability of the database for RCA concrete compressive strength could not be captured through the current aggregate generation procedure in the numerical simulations.

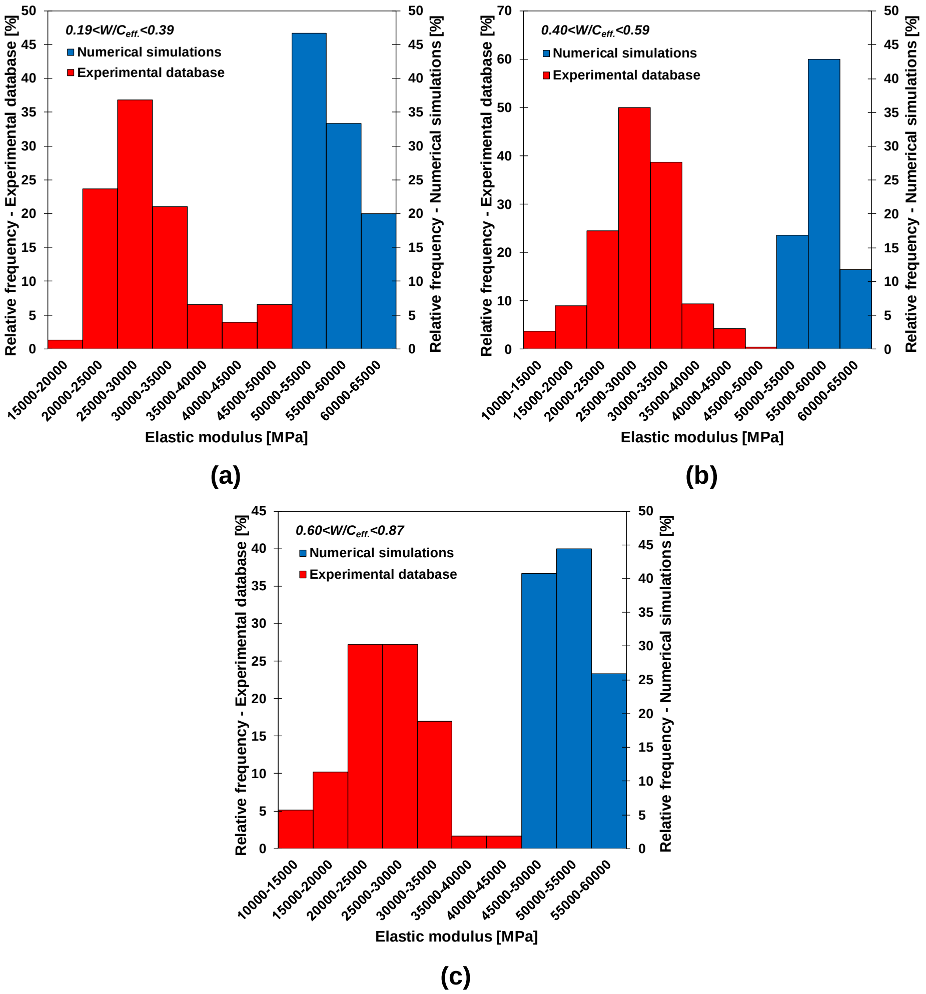
3.) *ITZ mechanical properties* – Although the input parameters for the ITZ material phases were incorporated in the meso-scale modeling of RCA concrete systems based on a limited number of research findings [214, 226, 237], the actual variability in in the ITZ properties (i.e., old ITZ and new ITZ) were not included as there were no detailed descriptions available in the database. As such, the true variability of these material phases is likely higher than what was used in the numerical simulations, resulting in lower variability in the simulation results compared to the database.

4.) *Selection of appropriate cementitious material properties* – The Monte Carlo simulations adopted in this study were used to examine the general trends of RCA concrete strengths due to the variability in the cement mortar matrix and the adhered mortar phase. The mechanical properties of cementitious phases were considered according to the selection of effective water-to-cement ratio and the cement-to-sand ratio, where the properties were estimated based on a study performed for cement mortar in which the mechanical property trends were interpolated with discrete experimental data points fitted through a nonlinear regression analysis [225] (see Figure 18).

4.4.2 Variability of elastic modulus

Elastic modulus for each simulated RCA concrete system was obtained through the linear material behavior of stress-strain relationship under compression. According to the standard procedures guided by ASTM C469 [238] and Eurocode II [239], the elastic range of the compressive stress-strain curve was determined based on the gradient between zero stress and strain, and the point at 40% peak compressive strength. The elastic modulus of the numerical models in this study was evaluated based on the same criteria, where those elastic properties of RCA concrete systems were compared with the experimental database results.

The distributions of the elastic moduli of RCA concrete systems for the numerical models and the experimental database are shown in Figure 24 at each effective water-to-cement bandwidth. The average elastic modulus of the database results for the three effective water-to-cement bandwidths 0.19–0.39, 0.40–0.59, and 0.60–0.87 were 29.6 GPa, 28 GPa, and 25 GPa respectively, where the numerical simulation results for those corresponding bandwidths were 56 GPa, 57 GPa and 53 GPa. The standard deviations for the database results were approximately 7 GPa, 6 GPa, and 6 GPa, while for the numerical results, it was 3.3 GPa, 3 GPa, and 3.8 GPa respectively, considering the same effective water-to-cement ratio bandwidths 0.19–0.39, 0.40–0.59, and 0.60–0.87. According to the distributions shown in Figure 24, the mean response of the numerical simulation results exceeded the experimental database results. It is hypothesized that two main sources of error caused this divergence. First, a study performed by Jayasuriya et.al.[33] concluded that the elastic modulus was primarily governed by the amount of adhered mortar content in the RCA concrete system. Since the experimental database did not have adhered mortar contents quantified, correlative numerical results could not be obtained.



(a)

(b)

(c)

Figure 24: Comparison of elastic modulus histogram distributions for effective water-to-cement ratio bandwidth; (a) $0.19<W/C_{eff.}<0.39$ (b) $0.40<W/C_{eff.}<0.59$ (c) $0.60<W/C_{eff.}<0.87$.

Another aspect that leads to noncomplementary numerical results is due to the higher stiffness that often exhibited by the numerical simulations compared to physical experiments [240]. Although the material properties for RCA concrete systems are assigned into the numerical models precisely, the realistic structural properties of concrete such as the effects of the concrete pore geometry, boundary conditions, and localized strain rates cannot be directly related to a larger dataset of experimental results. Therefore, the numerical results tend to result in systems that behave with higher stiffness compared to real experiments.

4.4.3 Variability of tensile strength

The evaluation of tensile strength response was completed by subjecting the numerical simulations to a direct tensile load applied at the top-most nodal points of each finite element model geometry. Identical RCA concrete geometries, support boundary conditions, strain increments, material properties, constitutive relationships, iterative solution method, and convergence criteria were assigned for each Monte Carlo simulation sample. The only difference between the compressive and tensile simulations was that the prescribed loading direction was applied upwards in the tensile numerical simulations.

Numerical simulation results were obtained for 200 RCA concrete systems under uniaxial tension where corresponding stress-strain curves were established as shown in Figure 25. Since the RCA concrete systems were loaded in tension, the expected softening phase was captured with an exponentially decaying function. In addition to the stress-strain curves for the 200 responses shown in Figure 25, four other characteristic average curves are reported, representing the mean response for each bandwidth of water-to-cement ratio, and the overall mean response. The overall average tensile strength was recorded as 3.50 MPa with a standard deviation of 0.45 MPa. The average tensile strength response of the RCA concrete systems that were within the first standard deviation of the effective water-to-cement ratio coincided with the overall average response of the 200 numerical simulations. Furthermore, the average responses of RCA concrete systems that were below and above the first standard deviation of effective water-to-cement ratio resulted in average tensile strengths of 4.10 MPa and 2.70 MPa respectively, with corresponding standard deviations of 0.32 MPa and 0.20 MPa.

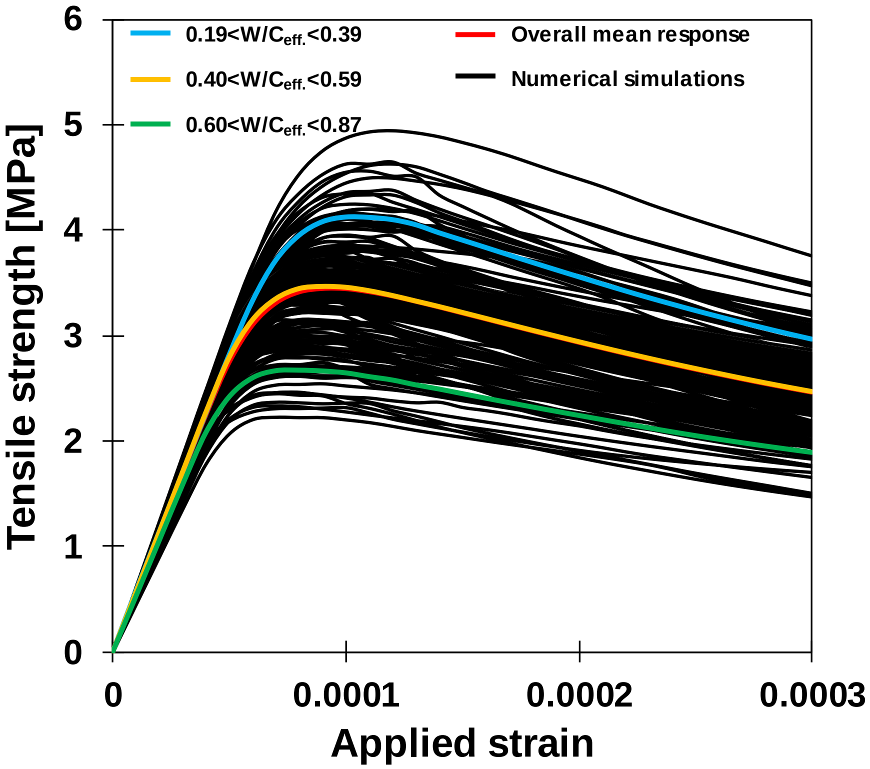
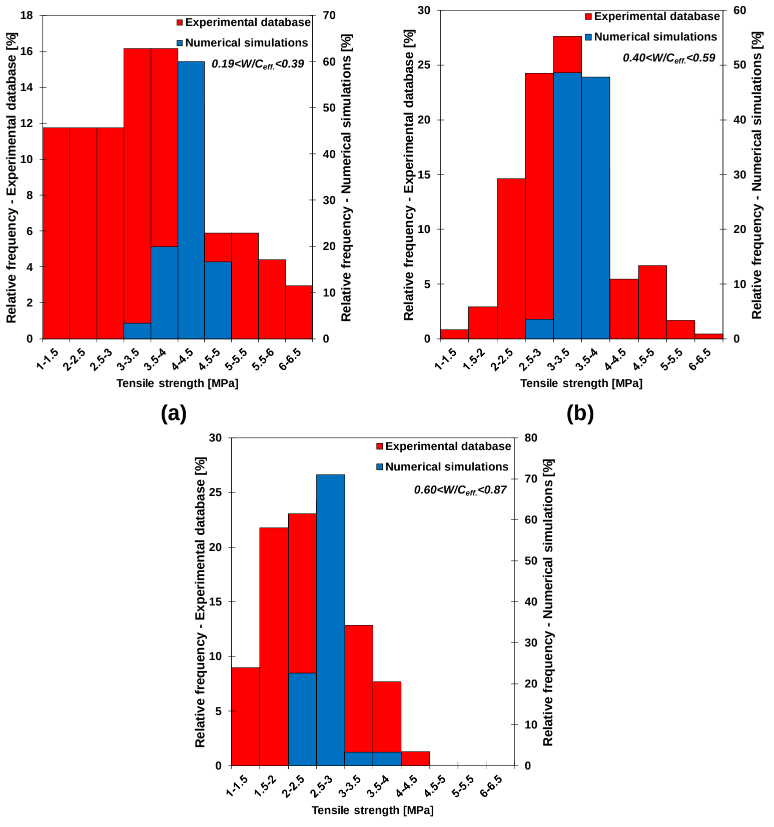


Figure 25: Stress-strain curves under uniaxial tension for 200 Monte Carlo simulations.

Figure 26 depicts the histogram distribution of the tensile response of RCA concrete systems obtained through experimental database and numerical simulation results at each effective water-to-cement ratio bandwidth. The distribution of the two approaches shown in Figure 26 shows a good representation in terms of the average tensile response comparisons. Within the effective water-to-cement ratios 0.19-0.39, 0.40-0.59, and 0.60-0.87, the average tensile strengths for database results and numerical results were 3.4 MPa, 3.2 MPa, 2.4 MPa, and 4.1 MPa, 3.5 MPa, 2.7 MPa respectively. Also, the standard deviations for the obtained for the database and the numerical simulations were 1.3 MPa, 1 MPa, 0.7 MPa, and the 0.3 MPa, 0.2 MPa, 0.2 MPa respectively, under the consideration of the corresponding effective water-to-cement ratio bandwidths. Based on these distributions studied here, it showed that the variability of tensile strength in the experimental database is higher than that of the numerically simulated RCA concrete systems. However, when comparing the RCA concrete material behavior in compression and tension, the variability of the numerical simulations of RCA systems under tension contained a substantial area of the distribution than observed in the compressive response (refer Figure 23 and Figure 26).



(a) (b) (c)

Figure 26: Comparison of tensile strength histogram distributions for effective water-to-cement ratio bandwidth (a) $0.19<W/C_{eff.}<0.39$ (b) $0.40<W/C_{eff.}<0.59$ (c) $0.60<W/C_{eff.}<0.87$

Variability in observed tensile strength was indicative of how the fracture process for RCA systems loaded under pure tension can be highly complex and variable due to the existence of ITZ phases, promoting different fracture paths unlike the concrete systems that were loaded in compression [226, 237, 241]. In order to visualize and compare the damage occurrence due to higher strain deformations, three representative RCA concrete systems were selected from three effective water-to-cement ratio bandwidths that contained approximately 20% RCA content. Figure 27 depicts the principal strain variation at each of the peak responses related to tension and compression, and it is clear that, under tension, the concrete material is subjected to a higher principal tensile strains, localized near the ITZ phases (i.e., both old/new ITZ). In contrast, the compressive behavior of RCA concrete had limited strain localization only at the new ITZ, where the peak response was achieved at higher strain deformation (e.g., 10 times more than that of tensile peak strain). Therefore, it can conclude that strain localization at multiple areas (i.e., old and new ITZ) is a source of variability in the tensile strength of RCA concrete systems.

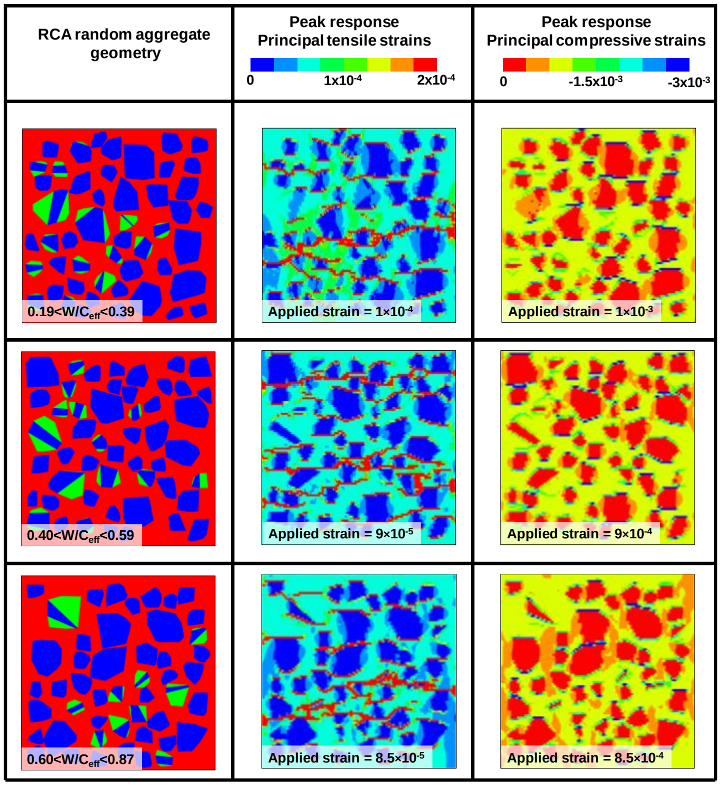


Figure 27: Principal strain variation under tension and compression of representative RCA concrete geometries

5. Conclusions and future research needs

A robust statistical analysis was performed on the RCA concrete strength properties by adopting a large database analysis composed of experimental data that included a substantial representation of the international research community. The major topics were covered in this report to observe general trends of RCA concrete hardened properties including compressive strength, elastic modulus, splitting tensile strength, and flexural strength. Among those factors that were considered in the database, RCA replacement level, A/C ratio, W/C ratio, and RCA size were chosen as they represent the mixture proportion used in producing the concrete, and their influence was statistically quantified through statistical indices. In the process, the overall histogram distributions of the factors, strength dependency on RCA replacement level and the W/C ratio, and the factors influencing the RCA concrete compressive strength, such as main effects of factors, significance of factors, and bivariate relationships were subjected to an in-depth statistical analysis. In comparison to the other existing database studies carried out in the literature, the analyses in this report uses a larger dataset and provides a set of statistical tools that can be transitioned to a mixture design methodology. The full factorial study carried out in this study is highly distinguished from other analysis procedures published in the literature due to the ability to predict the mixture design proportions, beyond RCA replacement level or W/C, for target RCA concrete compressive strength requirements, including aggregate to cement ratio and maximum aggregate size. A summary of the statistical findings and important implications based on the database analysis is shown as follows:

- The optimum RCA replacement level that produced the highest RCA concrete strength properties (e.g., compressive strength, elastic modulus, splitting tensile strength, and flexural strength) is below 20%. However, adequate average strengths for a wide variety of concrete applications were observed at all coarse RCA replacement level bandwidths.
- Although the RCA concrete strength properties exhibited decaying trends with the addition of RCA replacement level, 100% RCA concrete systems indicated a noticeable increase compared to the preceding replacement level due to the increased material homogeneity attributed by the stiffness compatibility.
- Due to the material variability captured in the database, the data correlation coefficient of the compressive strength between the RCA replacement level and the effective W/C ratio decreased by 45% for the distributions that had RCA replacements less than 60%. Further increments of RCA replacement levels have shown that the data correlation increased by 32% due to the induced material compatibility.
- The RCA strength properties analyzed in this study showed decreasing trends to the amounts of effective W/C ratio increased.
- The main effect plots established based on the full factorial analysis showed that the general trends of each factor had decreasing effects on the RCA compressive strength when used from low-to-high. However, the compressive strength increased when RCA size was increased from medium to high levels due to the aggregate interaction associated with the surface texture and the interlocking behavior.
- A/C ratio and effective W/C ratio showed significant factor effects on the RCA compressive strength. Regardless of being non-significant, RCA replacement level showed higher standardized effects compared to the remaining factors or factor combination effects.
- While the bivariate relationships confirmed the common trends observed in main effect plots of each factor induced upon the RCA compressive strength, it also created an excellent insight on developing guidelines on selecting materials for predicted strength requirements.

The work presented here was focused on creating a database structure for RAC systems and developing essential statistical tools to predict target compressive strengths across when a variety of mixture design inputs are used. For example, from this work, bivariate relationships are a tool that can be adopted to approximately determine mixture design proportions for target strengths considering RCA replacement level, W/C, aggregate to cement ratio, and maximum aggregate size.

The statistical database presented in this report covers a substantial representation of the mechanical properties of RCA concrete based on previous experimental data. However, the variability may still be a considerable factor, especially for strength properties, such as RCA concrete elastic modulus, flexural, and tensile strengths due to the unpredictable fracture behavior with large stiffness heterogeneity in the concrete system. Therefore, more data needs to be collected on top of the existing database entries, and similar analysis program can be implemented to capture the material variability in RCA strength characteristics. Also, strength improvements of RCA-based concrete need more research emphasis on using supplementary cementitious materials or admixtures that can be used in addition to the raw materials in concrete mixture designs. Therefore, this database can also be expanded towards various study areas including RCA processing and classification methods, RCA quality, material characterization, mixture design guidelines, durability design, and eventually utilize RCA in structural concrete applications.

Monte Carlo methods were used to generate random inputs to numerical finite element models to investigate how variability of the cementitious phases in RCA concrete systems influence simulated mechanical properties. In total, 200 simulations were statistically studied under uniaxial compression and tension loading conditions, and results were compared with an experimental database for compressive strength, elastic modulus, and tensile strength. Based on the analysis results, the following conclusions were drawn:

- The average compressive strength of stochastically developed numerical models showed excellent predictions compared to that of the results displayed in the experimental database, where the difference between the predicted and the experimental average compressive strengths was 6%.
- The variability in predicted compressive strength was not well captured in the numerical simulations due to limitations such as aggregate morphology, presence of adhered mortar in the form of RCA, reliability of the sources that the material properties were stochastically estimated from, and the lack of information of ITZ material phase properties. Therefore, further information needs to be developed understanding the ITZ strength properties to better develop computational models.
- Although the average predicted elastic modulus of RCA systems did not match the experimental database, the simulations were able to capture similar levels of variability as observed experimentally.
- Tensile behavior in RCA is an extremely complex mechanism due to the existence of randomly dispersed ITZ zones (i.e., old/new ITZ), which consequently, increased the variability of tensile strengths of RCA concrete models.

- With an increase in effective water-to-cement ratio, the variability of RCA concrete compressive strength and tensile strength decreased due to the weak cement mortar matrix properties, and damage was concentrated at the ITZ phases.

6. Recommendations

This report shows that concrete made with RCA can be made that will meet the strength requirements of a wide range of construction projects, both structural and non-structural. The design tools presented provide tools for concrete engineers to develop new concrete mixtures using RCA. The variability study provides information on what properties of RCA are most impactful on the strength of concrete systems utilizing RCA. As such we recommend the following for communities, engineers, and owners looking to utilize more RCA in their systems:

1. Engineers and concrete providers should take the time to understand the properties of the RCA they are looking to utilize in new concrete. This includes the absorption capacity, specific gravity, and even the amount of adhered mortar.
2. New concrete mixture designs can be utilized the bivariate tables presented in Figure 15 to initially design and batch concrete mixtures.
3. The mixture design tools presented in this report should not be relied upon for finalized mixture designs. The tools presented are for preliminary trial batching and should be tested in the laboratory prior to being utilized in the field. Exact proportions of field concrete will likely need to be modified to meet the needs of local products and designs standards.
4. The variability study should be reviewed by engineers to understand how different RCA and concrete properties impact the properties of concrete made with RCA.

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