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MECHANICAL PROPERTIES OF CONCRETE WITH 100 PERCENT COARSE RECYCLED CONCRETE AGGREGATE (RCA)

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by

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Dedication

This thesis is first dedicated to my wife, Dr. Hamideh Talafian, for her support throughout this journey. Thank you for your patience and love. I would also like to dedicate this work to my beautiful baby girl - Yalda - who showed me the beauty of life. Additionally, I thank my parents, brother, and twin sisters for their perpetual support and love.

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Abstract

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Recycled concrete aggregate (RCA) is a crushed concrete with the original aggregates' features and old mortar adhered to the original aggregate which makes it necessary to know the mechanical properties of the RCA. The objectives of this thesis are (a) to characterize RCA from different sources and of different proportions, (b) to measure the mechanical properties of concrete made with 100% RCA as coarse aggregates, and (c) to evaluate how the RCA properties affect the properties of new concrete. The study uses RCA with three types of original aggregates (limestone, dolomite, and granite) in two water-to-cement ratios 0.48 and 0.38 and also includes RCA collected from three recycling plants. The RCAs are graded with either 1 inch or ¾-inch nominal maximum aggregate size (NMAS). The resistance to abrasion, material finer than 75-µm, and the RCA's parent concrete compressive and flexural strength were characterized. The compressive and flexural strength of concrete with 100% RCA was determined at 7, 14, 28, and 90 days. The results shows that resistance to L.A. abrasion of RCAs range was between 21% and 43% which is within the natural aggregate acceptable ranges (up to 40%). The impact of particles finer than 75-µm on compressive strength was not significant. Also, 90 days compressive strength test of concrete with 100% control RCA in ¾ inch NMAS, and w/c ratio as of 0.38 reached 7,200 psi.

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Chapter 1

Introduction

Background

The rapid development and necessity for large-scale infrastructures result in the global exploitation of natural aggregates to fulfill the soaring demand. The global natural aggregate (NA) production was reported to be 21 billion tons in 2007. The corresponding production increased to 40 billion tons in 2014 [1]. Several countries are already facing a shortage of natural aggregates and are relying on imports to meet their demands, such as India [2]. On the other hand, many structures need to be demolished because they are approaching their end life, are damaged, or need to be upgraded.

The idea of using construction waste materials started after World War II in Europe [3], followed by developing technologies to search and recycle the waste materials as an eco-friendly approach. In the past, the demolished constructions would end up dumped in landfills. However, under new regulations, demolition contractors face penalties for dumping construction waste in landfills. Therefore, there is a worldwide concern to adopt greener technologies to recycle demolished concrete structures.

Extraction of natural aggregates requires exploitation of natural sources using heavy machinery with significant energy consumption such as fuel, electrical power, and equipment. Recycling concrete aggregates prevent exploitation of such sources and eliminate wasting of energy during exploitation. There are also economic benefits of recycled concrete aggregate (RCA). The process of producing RCA is cheaper than mining and extracting materials, and it can reduce construction costs which have a significant impact on project sponsors. In addition, recycling concrete aggregates and reusing them on-site also saves transportation costs [3].

Demolished concrete from structures such as pavement and bridges, in the form of blocks can be crushed and then screened to remove pollutants such as reinforcement, gypsum, and plastic. The crushed aggregates is sieved to obtain appropriate gradation of coarse and fine aggregates. ACI Committee 555 describes the production process of RCA [4].

Problem Statement

Natural coarse aggregate makes up around 70 to 80% of concrete’s volume. Therefore, the properties of aggregates are essential in influencing the mechanical properties of concrete. Properties of natural aggregates include shape and texture, porosity, specific gravity, LA abrasion loss, and other related material and geometric properties. Similar properties also apply to RCA, with additional properties exclusive to the RCA. One of the critical differences between NA and RCA is the fact that RCA contains adhered mortar. The adhered old mortar covers the aggregated surface of the NA. It means interfacial transition zones (ITZ) exist between NA and mortar, which is a weak link within the concrete.

The fresh and hardened properties and durability of the new concrete incorporating RCA can be significantly affected by the attached mortar. The differences are as follows: RCA has a rougher texture and more angular shape, lower specific gravity, higher water absorption, and higher porosity. An interfacial transition zone (ITZ) exists between NA and mortar, which bonds between the mortar and natural aggregates.

As concrete volume consists of 70 to 80% of natural aggregates and recycled concrete aggregates contain 20-30% mortar adhered to the crushed aggregates, concrete made with RCA has a higher mortar volume than concrete made with natural aggregates. The interfacial transition zone is known as a weak link within the concrete.

The amount of old mortar, the source of natural aggregate, and the original concrete mixture proportion are usually unknown factors in produced RCA. Furthermore, while the properties of similar types of aggregate from different sources are almost the same, RCA is produced and stockpiled together without considering the parent concrete quality and measuring the old mortar, which is adhered to the natural aggregates. Therefore, the mechanical properties of RCA and concrete having RCA are still unknown and more research is required to understand the properties of the RCA and new concrete with RCA.

Goals and Objectives

This research aims to increase the use of RCA in concrete by understanding the contributions of RCA properties to the mechanical properties of new concrete mixtures. The specific objectives of this research are:

1. To characterize the properties of RCA made from parent concrete with different types of virgin aggregates and water-to-cement ratios.
2. To determine the influence of RCA properties on the mechanical properties of concrete made with 100% RCA.

3. To provide recommendations for designing concrete mixtures with 100% RCA based on the properties of RCA and the required mechanical properties of the new concrete.

Scope and Limitations

In this study, concrete containing Dolomite (D), Granite (G), and Limestone (L) NAs with water-to-cement ratios of 0.38 and 0.48 were collected and tested for their mechanical properties. The concrete was crushed in the recycling yard to create recycled coarse concrete aggregate referred to as Manufactured RCA (control RCA). The manufactured RCA was then sieved to obtain aggregates with the nominal maximum size of aggregates (NMAS) of one inch and ¾ inch. In addition, three commercial RCAs (unknown source) were also collected from different States in the USA. These RCAs were also graded to obtain coarse aggregates with the nominal maximum size of one inch and ¾ inch and known as Commercial RCA (CRCA).

New concrete mixtures were manufactured with 100% RCA (1 and ¾ inches) and water to cement ratios of 0.38 and 0.48. In the last stage, the mechanical properties of concrete made by 100% manufactured and commercial (unknown sources) of RCAs in two different sizes and two different W/C ratios are determined.

Research Approach

To accomplish the study's aims and objectives, the following tasks were fulfilled:

Task 1. Conduct a comprehensive literature review: This task included a comprehensive review of existing literature pertaining to RCA. The task presents findings related to natural and recycled coarse aggregates' mechanical properties and properties for both fresh and hardened concrete evaluated by other researchers. The benefits and limitations of reusing aggregates in a new concrete mixture are discussed and presented under this task.

Task 2. Identify and select representative materials such as natural and recycled aggregate used in the laboratory environment for concrete batches. Aggregate properties, materials involved in the concrete mixture, and sample identifications are explained in this task.

Task 3. Investigate the performance of RCA mixtures: This task includes a series of mechanical properties tests of concrete mixtures that contain 100 percent recycled coarse aggregate to determine and evaluate the concrete mixture proportioning. Also, methodology of aggregate testing and fresh and hardened concrete mechanical properties are provided in this task.

Task 4. Test results comparison: In this task statistical analysis was conducted to examine the mechanical characteristics of RCA and the performance of concrete with 100% recycled coarse aggregate.

Chapter 2

Literature Review

Recycled Concrete Aggregate (RCA)

After demolishing a building, part of a pavement, or any other types of construction made by concrete, the concrete blocks are delivered to aggregate recycling plants. A motorized grinder is used to smash concrete blocks. Crushed concrete is recycled in two stages: screening and eliminating contaminants like reinforcement, gypsum, and plastics. Magnetic separation is also utilized to remove steel reinforcement. Water washing is used to eliminate dust and clean the aggregates as they are crushed [5] in recycling aggregate factories or concrete batching plants. The manufactured product will be categorized according to their sizes from coarse to fine aggregate size and will be called Recycled Concrete Aggregate (RCA) [6]. In this chapter, RCA's benefits, the impact of old adhered mortar on RCA, and some mechanical properties related to RCA are reviewed.

Benefits of Recycling Concrete

The advantages of replacing RCA with natural aggregates include reducing environmental pollution, energy usage, and economic gains. As the global population increases, landfill space is becoming scarcer, making it more difficult to dispose of solid waste generated by the construction market. One of the solutions is recycling waste concrete materials to decrease the need for landfills, which is a primary objective of most governments worldwide.

Energy consumption for the production and transportation of natural aggregate necessitates the expenditure of fuel and electrical power, both of which are considerable.

According to natural aggregate resources such as stone mines, it is also a procedure that increases the energy required to dig, extract, and transport the aggregate. In some cases, the expenses of RCA manufacturing may be compensated by savings in transportation and disposal costs, mainly if the RCA is manufactured on-site.

Economics is a significant factor in the decision to recycle concrete pavements. In highway construction, aggregate costs are one of the most significant expenses, accounting for between 20 and 30 percent of the total cost of materials and supplies [7]. The cost of generating RCA is restricted to crushing the concrete blocks, screening, and removing rebars from the RCA. The process of producing RCA is cheaper than mining and extracting materials, and it can reduce construction costs which have a significant impact on project sponsors. According to a report, in 2008, the Enterprise Park at Stapleton project in Denver, Colorado, used roughly 11,000 tons of ready-mixed concrete incorporating recycled concrete aggregate in foundations and tilt-up panels [8].

RCA Major Issue

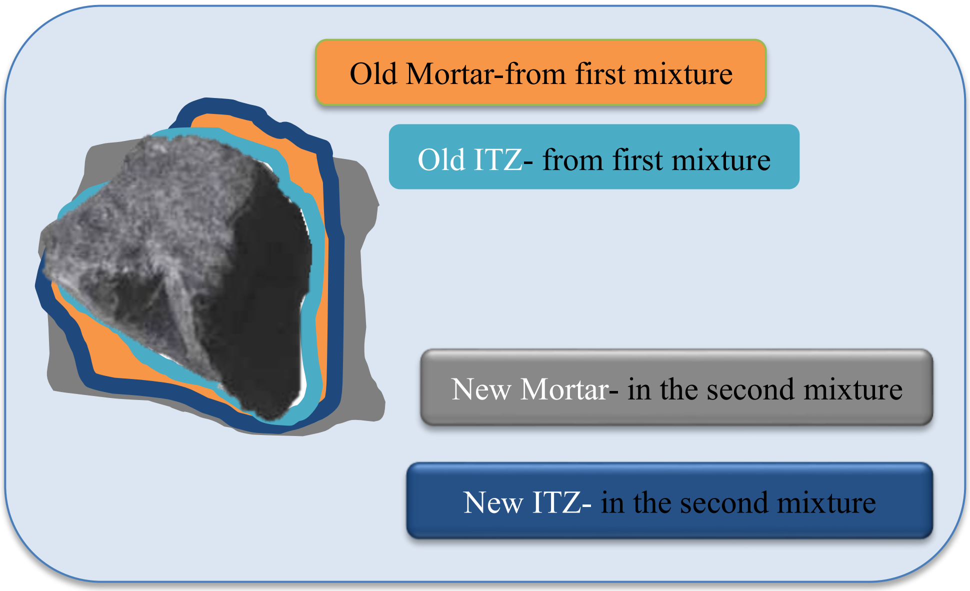
RCAs are mainly composed of natural aggregate, which is initially used during manufacturing parent concrete. After crushing and sieving parent concrete blocks, a quantity of adhered cement mortar will remain on the natural aggregate surface.

Old mortar from the previous parent concrete mixture is attached to RCA surface, and this may reduce the quality of recycled aggregates [9]. In general, adhered mortar has a greater absorption rate, a lower strength, and a poorer resistance to abrasion than most natural aggregates. Consequently, RCA has lower specific gravity and a greater absorption capacity than the virgin aggregate [10].

Due to the nature of the mortar, which is less dense and more porous than aggregate, RCA becomes weaker because of old mortar. Old mortar increases the absorption capacity and decreases the specific gravity on RCAs [11],[12], [9]. The microstructure of the old mortar attached to the natural aggregates depends on the properties of the hydrated cement paste. The area between the mortar and aggregate surface is called the Interfacial Transition Zone (ITZ). Manufacturing concrete with RCA creates two ITZs, one between old mortar and natural aggregate and new ITZ between old and new mortar [13]. Figure 1 shows the old and new mortar and ITZ zone locations in concrete made by RCA. It should be noted that original aggregate surface does not usually completely surround the old mortar.

Figure 1

Schematic of Old and New ITZ in RCA Concrete



RCA Properties

This research discussed the RCA mechanical properties and concrete properties made by 100% RCA. Some findings of other researchers are highlighted in this section. In order to examine the impact of attached old mortar on the concrete produced by RCA, several additional aggregate and concrete characteristics are discussed in this chapter.

Density

The lower specific gravity of the attached mortar in RCA results in a lesser density than natural aggregate density [13]. According to the literature, the specific gravity of natural aggregate is between 2.4 percent and 2.82 percent, while the specific gravity of RCA ranges between 2.1 percent and 2.6 percent. A comparison of the specific gravity of natural aggregate and recycled concrete is shown in Table 1.

Table 1

The Specific Gravity of Natural And Recycled Concrete Aggregate

Author	specific gravity %	
	RCA	NA
[6] J.M.V. Go´mez-Sobero´n, 2002	2.17 to 2.28	2.59 to 2.67
[14] C.S. Poon et al. 2004 (Granite)	2.33 to 2.37	2.62
[15] G. Fathifazl1 et al., 2009	2.42 to 2.5	2.71 to 2.74
[16] Shi Cong Kou et al., 2007	2.33 to 2.37	2.62
[17] K.Y. Ann et al. 2008	2.48	2.63
[18] J. Xiao et al. 2005	2.52	2.82

Absorption

The most critical difference between NA and RCA's concrete is that RCA has higher absorption and lower strength compared to NA [10]. The finding also proved a connection between specific gravity and the absorption of RCA, meaning that RCA with a lower specific gravity would have a greater absorption, as is shown in Figure B1 in the appendix B [13]. Some studies have demonstrated the absorption range between 0.4% to 1.49% for NA. Table 2 shows the absorption comparison between natural aggregate and RCA.

Table 2

Results of NA and RCA Absorptions by Other Studies

Reference	Absorption %	
	RCA	NA
[6] J.M.V. Go´mez-Sobero´n, 2002	5.83 to 8.16	0.88 to 1.49
[14] C.S. Poon et al. 2004 (Granite)	6.28 to 7.56	1.24 to 1.25
[15] G. Fathifazl1 et al., 2009	3.3 to 5.4	0.54 to 0.89
[16] Shi Cong Kouet et al., 2007	2.49 to 2.57	2.62
[17] K.Y. Ann et al. 2008	4.25	0.73
[18] J. Xiao et al. 2005	9.25	0.4

Aggregate Resistance to Abrasion

It has been discovered that the presence of old mortar attached to RCA makes it weaker, and the results of various types of research have shown that RCA has an increased percentage of abrasion loss than natural aggregate. Los Angeles abrasion (LA abrasion) is a test used to determine the relative quality of an aggregate in terms of deterioration caused by abrasion or impact. The Los Angeles test shows when adhered mortar content increases, the abrasion also increases significantly [10]. During the batching of concrete, the existing mortar may also begin to flake off the aggregate. Other investigations have shown that RCA has abrasion loss ranging from 15% to 51.5 percent, while natural aggregates have abrasion loss ranging from 15% to 45 percent, as mentioned in Table 3. In natural aggregate, losses of less than 15% are achievable (9.1% [19], and the maximum amount of abrasion loss, as shown in Table 3, may be high depending on NA quality. In a study on U.S. states specifications published by NJ DOT, it has been mentioned that the range of L.A. Abrasion loss in percentage is between 20 to 45% in the U.S. [20].

Table 3

The Range of Resistance to Abrasion of RCA and Natural Aggregate

Reference	**L.A. Abrasion results (% mass loss)**	
	NA	**RCA**
[21] Snyder et al. (1994)	15-30	20-45
[22] T.C. Hansen and H. Narud (1983)	20-30	22-41
[23] Yehia and Abdelfatah (2016)	19-25	21-35
[24] Verian et al.l (2013)	29-31	34-36
[25] Wen et al. (2014)	15	20-29
[26] Ait Mohamed Amer et al. (2016)	38.9	51.5
[27] Kurda et al (2017)	28	43
[28] Khaliq and Taimur (2018)	15.6	23.1
[29]Abedalqader et al. (2021)	26.4	40.4
[30] Arezoumandi et al. (2015)	43	41
[31] Katkhuda, Shatarat (2017)	28	31
[32] H. Mefteh et al, (2013) page 284	24	35
[33] A. Barbudo et al. 2013, page 94	27.25	40.4

A review study of specifications of resistance to abrasion for 49 states, FHWA, Federal Aviation Administration (FAA), and California District 2 specifications for a total of 52 "agencies" in America in 2003 has shown that the accepted value for the LA abrasion of recycled asphalt pavements (RAP) is reported between 25 percent and 55 percent. There are only two states which limit the acceptable results for 25% and 55%. Twenty-four states out of fifty have acceptable abrasion loss of less than 40%, and 12 states stand on 45% [34, 35, 36]. Equation 1 shows the calculation of the percentage loss as a percentage of the initial sample mass:

$$Loss = \left[\frac{M_{Original} - M_{Final}}{M_{Original}}\right] \times 100 \qquad (1)$$

Where:

M original = original sample mass (g)

M final = final sample mass (g)

Aggregate Gradation (Particles Finer than 75-µm)

American Standard Test Method (ASTM- C117) for materials finer than 75-µm (No. 200) sieved in mineral aggregates by washing with water determines the total amount of material finer than 75-µm by weight in aggregate. This test aims to determine the tiny particles mixed with aggregates. The number of materials finer than 75-µm, mixed with recycled coarse aggregate, impacts the workability of fresh concrete mixture and water to cement ratio [37]. The finer material could absorb more water in the concrete mixture and make the concrete mixture dry. Table 4 illustrates the amount of finer materials mixed with natural and recycled aggregate found by other researchers. It is recommended the RCA be washed before batching to reduce the quantity of small particles (less than #200 sieve or 75µm) and the risk of a mixed workability problem due to water absorption during the mixing process [4].

Ontario Provincial Standards Specification (OPSS) 1002 is the material specification for aggregates to use in a concrete mixture in Ontario. According to OPSS specification, the limitation for the range of particles finer than 75µm is up to 2% for natural aggregates. In the case of RCA, the only result mentioned in the article is 2.75% [9].

Table 4

The Range of Particles Finer Than 75µm In Coarse NA, RCA

Reference	NA Passing 75-µm (%)	RCA Passing 75-µm (%)
[38] Corinaldesi et al. (2009)	0.2	0.3
[19] C. J. Zega et al. 2010 (granite, w/c= 0.45) page 197,198	0.6	0.6
[39] G. Kumar Attri et al. 2021 (w/c=0.35), page 4332	0	0.1

Test Method for Sieve Analysis of Coarse Aggregates

Aggregate in concrete mixture volume ranges from 70% to 80%. The maximum nominal size of the RCA, form, texture, moisture content, specific gravity, and unit weight are associated variables influencing concrete mixture design. Therefore, recycled coarse aggregate has a significant impact on concrete characteristics. A gradation test is necessary for every concrete mixture design because recycled coarse aggregate gradation, such as maximum nominal aggregate size, influences the quantity of cement paste needed in a concrete mixture [40]. To determine the recycled coarse aggregate gradation, a sieve analysis test is conducted for coarse aggregate following ASTM C136 [41].

RCA: Fresh Concrete Properties

This section covers the fresh properties of concrete, such as the slump test, air content, concrete unit weight, and concrete mixture temperature.

Concrete Unit Weight (Density of Concrete)

ASTM C138 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete was followed [42]. The unit weight of concrete is calculated by dividing the weight of fresh concrete filled to the volumetric air bowl by its volume. Findings in some studies have shown the impact of cement content on the unit weight of fresh concrete mixture [43].

Slump Test (Workability)

Some factors such as water content, different types and sizes of aggregate, aggregate angularity, gradation, mixture proportion, surface texture, and mixture temperature affect the workability of concrete made using RCA [44]. The concrete mixture with RCA as a coarse aggregate has a lower slump than natural aggregate at the same concrete mixture design. Since the old mortar absorbs more water and makes the absorption higher, the slump decreases compared to the concrete mixture with natural aggregate and similar w/c [27]. Lower slump effect on the workability of fresh concrete properties, such as placing concrete and the fresh concrete density. In return, the solution is to use 5% to 15% additional mixing water into the concrete mixture or adding a water reducer/plasticizer as an admixture to the mix design [13, 45]. The workability of concrete may be estimated by slump test following ASTM C143 [46].

In general, a higher slump implies a more workable concrete mixture, whereas a lower slump indicates a stiffer concrete mixture with less workability. Some studies have shown that the presence of RCA in the concrete mixture has an impact on slump at the same w/c ratios [9, 47, 48, 12]. The water absorption in RCA is higher than natural aggregate because of adhered mortar which is attached to the RCA as it is shown in Table 2. Therefore, in the same w/c ratio, concrete incorporating natural aggregate has a higher slump than concrete with 100% RCA. Also, it is established that higher slump loss happens in oven-dried RCA compared to air dry RCA or saturated surface dry RCA [1,49].

Air Content

ASTM C173 [50] is used to determine the amount of air that exists in a freshly mixed concrete mixture. According to other studies, the air content of concrete produced by RCA is often up to 0.6 percent higher than the air content of a typical batch with natural aggregate [3]. Because of the old mortar that was connected to the RCA, the porosity of the concrete produced by 100 percent RCA is higher than the porosity in a natural concrete mixture[51, 52, 53]. Compared to other techniques, such as the super air meter method, studies have shown that the air values for the equivalent concrete mixture design are 4 percent to 5.5 percent higher [54], (ASTM C138 [42]).

Water freezing and salt crystal formation in concrete pores create osmotic, hydraulic, and internal stresses, which may be reduced by using an air-entraining admixture during batching. Compared to conventional concrete, adding air-entraining admixtures to concrete incorporating recycled aggregates had a comparable beneficial effect on freeze-thaw resistance. It is much more efficacious when a lower water-cement ratio is utilized to improve concrete performance [55, 56].

Mixture Temperature

Some studies showed that the higher temperature resulted in higher evaporation, water loss, air content, and the fresh concrete mixture's workability was also lower [57]. The temperature of a fresh concrete mixture does not affect the air content. However, the changes in fresh concrete temperature have a direct relationship with a slump [58].

RCA: Hardened Concrete Properties

In this section, hardened concrete properties of concrete using RCA coarse aggregate, including compressive strength and flexural strength, are discussed. The target strength of a concrete mixture design is dependent on the application. A high strength may be needed in a bridge construction or a lower strength for a walkway [59]. The concrete produced by RCA is still not well understood since it is limited in results and applications. Some studies have shown that the general properties of concrete which includes RCA is similar or almost the same as the properties of natural aggregate concrete with equal mixture design [61, 62, 63, 64, 65, 54].

Concrete Compressive Strength

Some studies have shown that the interfacial transition zone (ITZ), the bonds between the aggregate surface with old, adhered mortar, and the ITZ zone from new mortar in the concrete mixture significantly affect the strength. A mortar covers the aggregate's surface in concrete made by the natural aggregate. In contrast, in concrete made by RCA, ITZ includes bonds between aggregate's old mortar, aggregate's new mortar, and old mortar-new mortar, which can cause a lower strength for concrete made by RCA [66, 67, 68, 69]. Higher mortar content in RCA affects concrete strength [3].

Several studies have reported that RCA's strength is higher than similar concrete made by the natural aggregate as +25%, especially at 28 days [56]. The concrete incorporating RCA has higher air entrainment compared to the PC. Other studies have proven that the non-hydrated old cement, which is pasted on the surface of RCA, reacts with water in the new concrete mixture and increases the strength of concrete made from RCA compared to the concrete produced by natural aggregate [69, 14, 70, 66]. Some studies also show that replacing 100% RCA and design the concrete mixture for a lower w/c ratio gives concrete with a higher strength [71, 72, 22, 73, 9]. They also proved that aggregate moisture level could increase the strength up to 20% or decrease it up to 30% when replaced with a 100% RCA [68, 74]. Compressive strength is also significantly influenced by the w/c ratio.

In general, the lower w/c ratio produces a stronger concrete in terms of compressive strength. In a higher w/c ratio, not all of the water is consumed in hydration. It may then later evaporate and leave pore space behind. Designing concrete mixture with RCA in a lower w/c ratio than w/c ratio of the parent concrete with NA, resulted in a higher compressive strength in concrete with RCA. For instance, concrete with natural aggregate and w/c ratio of 0.48 after curing reached a compressive strength of 6,000 psi. This concrete was crushed to manufactured RCA with the same NMAS as the original

NA. This RCA is used in a new concrete mixture with a lower w/c ratio of 0.38 and the compressive strength of the concrete with RCA reached as high as 7,000 psi, compared to its relative concrete with NA [69]. Table 5 shows the highest strength achieved by other researchers for the compressive strength of concrete made by 100% RCA.

The compressive strength variations in concrete specimens where RCA is employed as a coarse aggregate in the new concrete mixture compared to the same concrete mixture with NA are also shown in Table 5. It should be noted that only the results of studies that used RCA as coarse aggregate with fine natural aggregate are collected. Other studies reported variations in strength ranging from 22% lower to 26% higher strength compared to the parent concrete mixture with NA as a coarse aggregate. However, the w/c ratio was the same in both concrete mixtures. It should be noted that in the case of increasing compressive strength to 26% higher strength [75], the specimens were tested at the age of 28 and 56 days. In this particular case, the compressive strength of the concrete mixture having RCA at 56 days was reduced by 9% compared to the compressive strength of the parent concrete mixture.

Table 5

Compressive Strength of Concrete Made By 100% RCA (28d, 90d)

Reference	RCA-Compressive strength on 28 days psi	RCA-Compressive strength on 90 days psi	NA-Compressive strength on 28 days psi	NA-Compressive strength on 90 days psi	RCA strength reduction compared to NA strength (%) 28 d	RCA strength reduction compared to NA strength (%) 90 d
[76]Kou et al. 2008 (w/c = 0.45) page 1196	7555	8920	9690	10490	-22%	-15%
[76]Kou et al. 2008 (w/c= 0.40) page 1196	8490	9355	10485	11330	-19%	-17%
[26]Adem Ait Mohamed Amer et al. 2016 (w/c=0.5) page 305	6380	7250	N/A	N/A	N/A	N/A
[18]Jianzhuang Xiao et al. 2005 (w/c=0.43) page 1190	3450	N/A	3900	N/A	-12%	N/A
[30]Arezoumandi et al. 2015 (w/c=0.40) page 157	4425	N/A	5400	N/A	-18%	N/A
[77]C. Zhou, Z. Che. 2017 (w/c=0.47) page 501	6420	N/A	6050	N/A	6%	N/A
[65]Etxeberria et al. 2007 (w/c= 0.55) page 737	5550	N/A	5150	N/A	8%	N/A
[78]Zaharieva et al. 2003 (w/c= 0.61) page 228	5715	N/A	6180	N/A	-8%	N/A
[38]V. Corinaldesi, G. Moricon. 2009 (w/c= 0.4) page 2871- report of cube specimens (NOT CYLINDER)	4600	N/A	4930	N/A	-7%	N/A

Reference	RCA-Compressive strength on 28 days psi	RCA-Compressive strength on 90 days psi	NA-Compressive strength on 28 days psi	NA-Compressive strength on 90 days psi	RCA strength reduction compared to NA strength (%) 28 d	RCA strength reduction compared to NA strength (%) 90 d
[27]Rawaz et al. 2017 (w/c=0.53) page 203	7540	N/A	8120	N/A	-7%	N/A
[79]Teerasak Yaowarat. 2018 (w/c= 0.40) page 4	6100	N/A	N/A	N/A	N/A	N/A
[75]Yong et al. 2009 (w/c= 0.41) page 4	8410	N/A	6670	N/A	26%	N/A
[38]Valeria Corinaldesi et al. 2009 (w/c=0.40) page 2873	4500	N/A	4920	N/A	-9%	N/A
[80]Thomas et al. 2018 (w/c= 0.50) page 352 (sample #25)	4380	N/A	5190	N/A	-16%	N/A
[14]Poon et al. 2004 (w/c = 0.77) page 35, crushed granite	6380	N/A	5800	N/A	10%	N/A
[81]Butler et al. 2013 (w/c = 0.4) page 1295	8730	N/A	8980	N/A	-3%	N/A
[80]Thomas et al. 2018 (w/c= 0.40) page 352 (sample #4)	4250	N/A	5050	N/A	-16%	N/A

Concrete Flexural Strength

There is a difference in strength reduction of concrete made by RCA in compressive strength with a flexural strength for a similar mix design. Some studies have shown that while the compressive strength of concrete made by recycled coarse aggregate decreased by approximately 25%, the flexural strength of concrete decreased about 10% compared to the concrete made by natural aggregate with the same mixture design [54]. Another study showed that concrete made by 100% RCA has a 7 to 17% decrease in flexural strength compared to similar concrete mix designs made by natural aggregate. In addition, increasing the w/c ratio resulted in flexural strength reduction [80]. To determine the flexural strength of concrete beams, the ASTM C78 [82] can be followed. The range of flexural strength changes in concrete with 100% RCA compared to concrete with NA is shown in Table 6. The range of flexural strength was between 42% lower strength to 18% higher strength. Flexural strength of concrete beams under two points loading is given by the equation below:

$$\text{Flexural Strength, fb}_2 = \frac{3PL}{2bd^2} \tag{2}$$

Where:

f_b = flexural strength (psi)
P = Load at failure (lbs.)
L = span length (inch)
b = average width (inch)
d = average depth (inch)

Table 6

Flexural Strength of Concrete Made by RCA With Different W/C Ratios

Reference	RCA-Flexural strength on 28 days psi	NA- Flexural strength on 28 days psi	RCA strength reduction compared to NA strength (%) 28 d
[30]Arezoumandi et al. 2015 (w/c=0.40) page 157	390	500	-22%
[77]C. Zhou, Z. Che. 2017 (w/c=0.49) page 501	735	625	18%
[80]Thomas et al. 2018 (w/c= 0.40) page 353 (sample #4)	565	610	-7%
[80]Thomas et al. 2018 (w/c= 0.50) page 352 (sample #25)	495	565	-12%
[83]Alexander et al. 2015 (w/c= 0.42) page 87	1625	2480	-34%
[29]Areej et al. 2021 (w/c=0.40) page 7	785	1090	-28%
[84]Mehmet et al. 2015 (w/c=0.43), page 337	580	695	-17%
[79]Teerasak Yaowarat. 2018 (w/c= 0.40) page 5	610	N/A	N/A
[75]Yong et al. 2009 (w/c= 0.00) page 5	900	985	-9%
[85]Saif I. Mohammed et al. 2020 (w/c= 0.44) page 38	435	755	-42%

Hardness Level of Concrete in Early Ages

In some applications of concrete, it is required to start the next step after concreting. For instance, in concrete foundation projects, the project has to continue once a concrete section has been placed and reached a required strength level. The project timeline is important for most of the projects. Therefore, it will be beneficial whether concrete with 100% RCA gains strength similar to concrete with natural aggregate. Other studies have shown a similar result, as is shown in Table 7.

Table 7

Hardness Of Concrete In Early Ages

Reference	w/c	7 days strength	28 days strength	7/28 days strength
[65] Etxeberria et al. 2007, (page 738)	0.52	5800	6240	93%
[65] Etxeberria et al. 2007, (page 739)	0.5	4640	5340	87%
[38]V. Corinaldesi, G. Moricon (p 2871)	0.4	3630	4210	86%
[14]C.S. Poon et al. 2004 (page 35)	0.68	4920	6790	72%
[16] Shi Cong Kou et al, 2018	0.3	4350	6380	68%
[26]A. Ait Mohamed Amer et al 2016	0.5	5080	5510	92%

Chapter 3

Concrete Materials

This chapter describes the materials used for this study. The materials used are Type I Portland cement, six manufactured coarse RCA, three commercial coarse RCA, concrete sand, and air-entraining admixture. The source of materials, natural aggregate properties, and sample identifications are discussed in the following sections.

Portland Cement

This study used Type I portland cement produced by Keystone Cement Company located in the state of Pennsylvania. This cement's chemical and physical properties, confirmed by ASTM specification C150 [86], are shown in Table 8, [87].

Table 8

Chemical and Physical Characteristics of Type I Cement

MILL TEST RESULTS		
Laboratory: Bath, Pennsylvania		
Date: June 2012, Cement Type: I Portland		
ITEM	**LIMIT**	**RESULT**
Silicon Dioxide (Si02) %	***	19.32
Aluminum Oxide (A1203) %	***	5.77
Loss of Ignition (LOI) %	<=3.0	2.50
Calcium Oxide (CaO) %	***	61.55
Blaine (cm2/g)	> =*2800*	3820
% Air Content	< = *12%*	9.2
Sodium Oxide (Na-,0) %	***	0.33

Note: This cement has been tested and is certified to meet the latest version of ASTM C-150. This cement is PENNDOT, DELDOT, NYSDOT, and NJDOT certified.

Coarse Aggregates

There are three categories of coarse aggregates used in the research: 1) Natural coarse aggregates (NA), 2) Control RCA and 3) Commercial RCA (CRCA). Natural coarse aggregates are dolomite (D), granite (G), and limestone (L), that were used for the manufacture of parent concrete used to produce the control RCA. Control RCAs are recycled concrete aggregate produced for this study by crushing parent concrete blocks with known concrete properties. The coarse control RCA was manufactured by Salamone, Inc. in Wayne, New Jersey [88]. The commercial aggregates are crushed concrete from commercial producers of RCA with unknown properties or mixed sources.

Coarse Natural Aggregates

Natural aggregates have a NMAS of 1 inch and were selected based on their expected difference in mechanical properties. The dolomite is typically the strongest of the three aggregates, and limestone is the least strong. Table 9 shows the NA properties and included in LA abrasion loss.

Table 9

Natural Aggregate Properties Used for Control RCA Parent Concrete

Sample Type	Natural aggregate Type	NMAS (inch)	Abrasion Loss %
coarse natural aggregate	Dolomite stone from Stavola	1”	21
	Gneiss from Tilcon	1”	25
	Limestone from Brean	1”	40
Fine aggregate	Concrete Sand	4”	N/A

Corse Control RCA

Parent concrete mixtures were produced using 100% natural coarse and fine aggregates in two water-to-cement ratios. The mixtures were cast and cured for 28 days, then crushed to produce 1” NMAS course RCA. After crushing, the RCAs were transported to the Civil Engineering laboratory at Rowan University, Glassboro, New Jersey.

The aggregates in both Types of NA and RCA met the graduation requirements of the ASTM C33 gradation method for chart number 56, 57 in 1 inch and #6 and #67 for ¾ inch NMAS[89]. Laboratory screen shaker was used to distribute ¾ out of 1 inch RCA, and the ASTM C136 has been followed to screen RCAs [90]. Control aggregates used in this study were regraded to produce NMAS 1 inch and ¾ inch, then each size of control RCAs was used in new concrete mixes in two different w/c ratios (0.48 and 0.38). The control RCA was thus batched into 24 distinct concrete mixtures. Figure 2 shows the coarse control aggregate gradation curves of 1-inch including dolomite and limestone with w/c ratio of 0.38, and granite in both w/c ratios 0.48 and 0.38 according to the ASTM/AASHTO method #57. Coarse control aggregate gradation curves of 1-inch included dolomite and limestone w/c ratio of 0.48 and Maryland, Nebraska based on ASTM/AASHTO method chart #56 are shown in Figure 3. Also, coarse control aggregate gradation curves of ¾ inches included dolomite w/c ratios of 0.48, and 0.38, limestone with w/c ratio of 0.48, and Colorado RCA due to the ASTM method chart #6 shows in Figure 4. According to the ASTM/AASHTO method for chart #67, coarse control aggregate gradation curves of ¾ inches included granite in both w/c ratios 0.48 and 0.38, and limestone in w/c ratio of 0.38 are shown in Figure 5. The distribution tables are shown in the Appendix A included Table A1 for RCAs under D56, Table A2 for RCAs under D57, Table A3 for RCAs under D6, and Table A4 for RCAs under D67.

Corse Commercial RCA (CRCA)

CRCAs were purchased and transported from other states across the U.S. to Rowan University and are referred to as Commercial RCA (CRCA) in this study. Since the manufacturers were not involved in any aggregate test properties or specific identification of the constructions they collected from, the properties are unknown and only sold as recycled coarse aggregates in recycling factories or mix plants. In recycling centers, concrete blocks are crushed, washed, sized, and stockpiled for commercial purposes. Commercial RCAs (CRCA) are used as coarse aggregate with two different maximum sizes and two w/c ratios to produce six concrete mixtures.

The CRCA was collected producers in Maryland (MD), Nebraska (NE), and Colorado (CO). RCAs in recycling plants often generate products according to the aggregate size required. There is no information regarding their parent concrete mix design, the age of the concrete, the water-to-cement ratios, the kind of application the concrete was used in, or the type of coarse and fine aggregate used in the mixture design. Recycling factories sell different sizes of RCA, and usually, the existing size of RCA is due to the supply and demand in that location or state. Also, it must follow the Department of Transportation (DOT) specifications in that state. CRCAs were collected from Maryland (MD) and Nebraska (NE) in 1 inch and sieved to make ¾ inch. CRCA purchased from Colorado (CO) in ¾ inch. Table 10 shows the size and location of CRCAs.

Table 10

Commercial RCA Sources

RCA source Type	RCA collected from	MSA
Commercial RCA	Maryland (MD)	1 inch
	Nebraska (NE)	1 inch
	Colorado (CO)	¾ inch

Sample Identification

Due to different types of RCA, sizes, and w/c in this study, a labeling scheme method is used for the RCA identification, shown in Table 11.

Table 11

Labeling Scheme Used for Samples and Concrete Mixtures

Variable Type (by contained natural aggregate mineral)	Designation	Variable Size (NMAS)	Designation	Variable w/c	Designation
Limestone	L	1”	100	0.38	A38
		0.75”	075	0.48	A48
Dolomite	D	1”	100	0.38	A38
		0.75”	075	0.48	A48
Granite Gneiss	G	1”	100	0.38	A38
		0.75”	075	0.48	A48
Designation for commercial Sources					
RCA collected from the state of Maryland, USA	MD	1”	100	N/A	
		0.75”	075		
RCA collected from the state of Nebraska, USA	NE	1”	100		
		0.75”	075		
RCA collected from the state of Colorado, USA	CO	0.75”	075		
Designation for concrete with RCA: w/b: RCA Type					
Concrete w/b	Designation	RCA Type	Example	N/A	
0.38	C38	Manufactured	C38L100A48		
0.48	C48	Externally Sourced	C48D100A38		

- Examples of parent concrete Type, w/c, and size:

L075A48 – indicates an RCA that is made from concrete with limestone aggregate and 0.48 w/c, crushed to 0.75” NMAS

- Example of concrete with RCA with different w/c ratios:

C48-L075A48 – indicates a 0.48 w/b concrete with 0.75” NMAS RCA made from limestone and 0.48 w/c concrete

Figure 2

Coarse Aggregate Gradations Curves Of 1 Inch, Chart #57

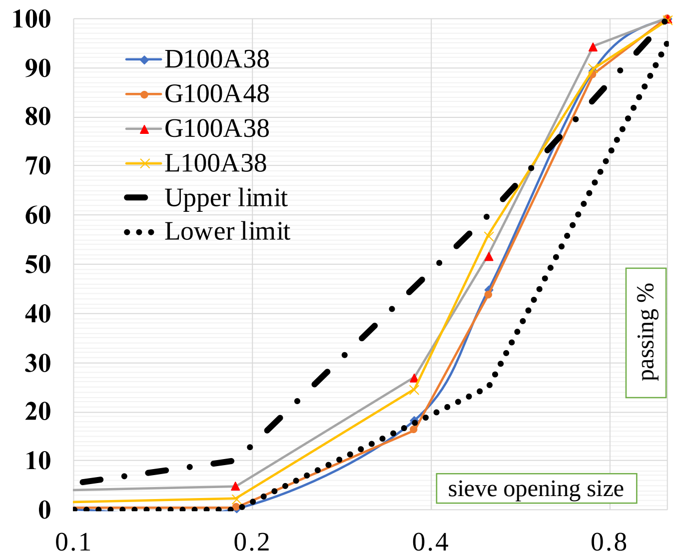


Figure 3

Coarse Aggregate Gradations Curves Of 1 Inch, Chart #56

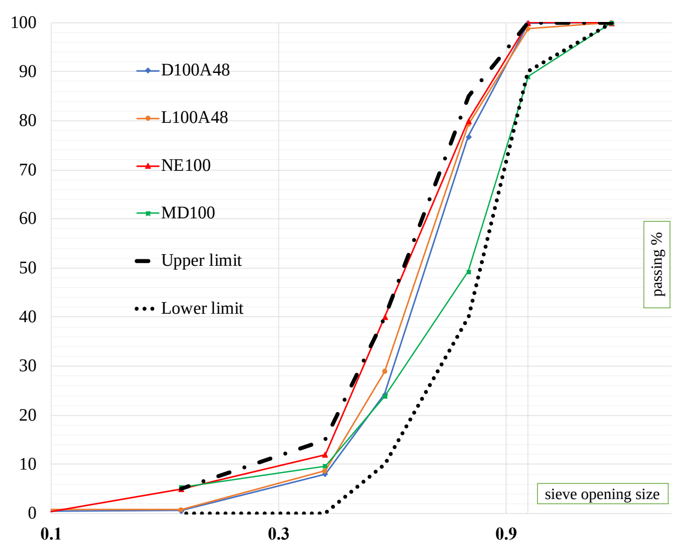


Figure 4

Coarse Aggregate Gradations Curves Of ¾ Inch, Chart #6

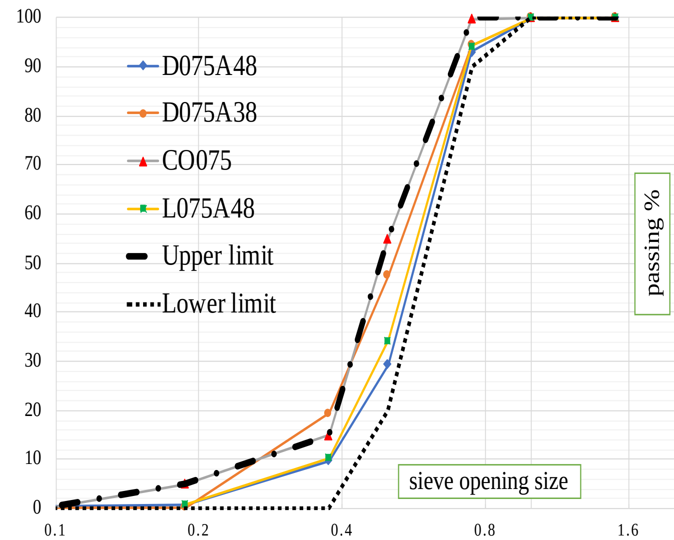
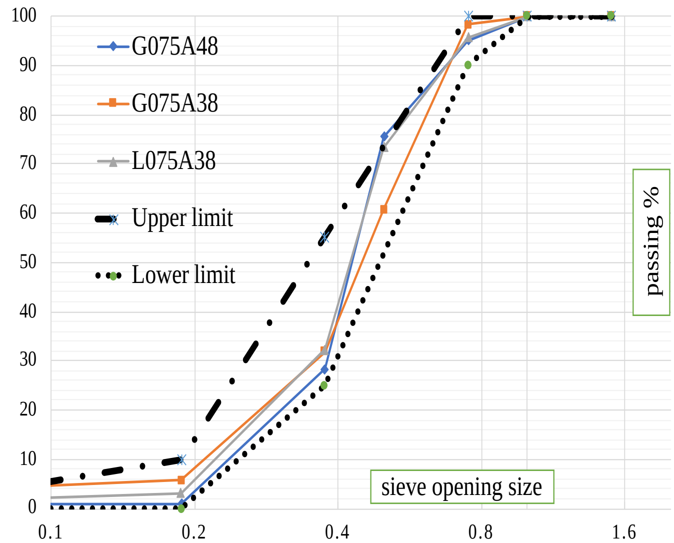


Figure 5

Coarse Aggregate Gradations Curves Of ¾ Inch, Chart #67



The mixture proportions of the parent concrete incorporating 100% NA as coarse aggregate are listed in Table 12.

Table 12

Parent Concrete Mixture Proportions

Water-to-cement	Cement (pcy)	Water (pcy)	NA* (pcy)	Sand (pcy)	AEA (oz/cwt)
0.48	575	276	1760	1310	0.55
0.38	730	276	1750	1180	0.45

**Dolomite, granite, or limestone*

The procedure of producing PC and manufacturing PC blocks to get control RCA in two w/c ratios is shown in Figure 6.

Figure 6

Producing Control RCAs from Dolomite, Granite, and Limestone

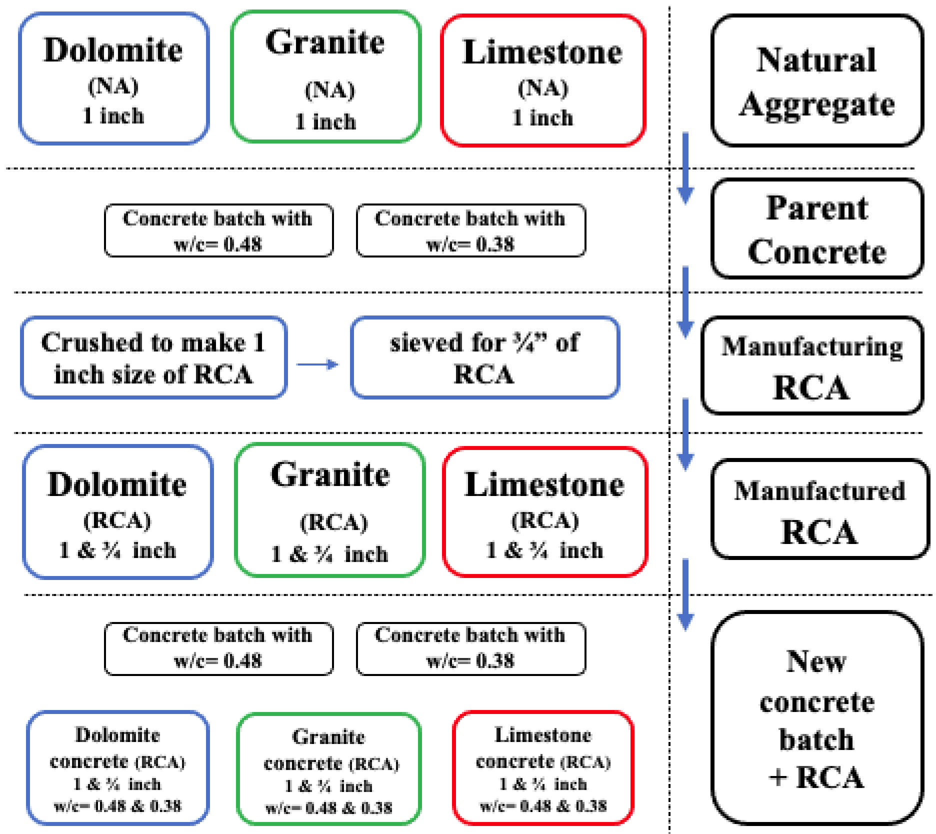


Table 13 compares the qualities of RCA based on specific gravity, absorption, and dry rodded unit weight, which reflect the physical characteristics of control RCA. The results of the durability tests are needed in some evaluations of the RCA properties.

Table 13

Physical Properties Of Control RCA Used In This Study

RCA	**Specific Gravity (**ASTM C127)	**Absorption % (**ASTM C127)	**DRUW pcf (**ASTM C29)
D100A48	2.49	3.81	88.84
D075A48	2.41	4.90	87.96
D100A38	2.46	4.44	83.55
G100A48	2.40	4.21	80.57
G075A38	2.49	3.81	83.46
L100A48	2.40	3.12	80.47
MD100	2.45	5.70	77.47
MD075	2.34	7.16	79.59
CO075	2.37	5.94	73.34

Figure 7

A View of the Control RCAs and CRCAs

A B C

(Limestone 1 inch) (Dolomite 1 inch) (Granite 1 inch)

D (MD 1 inch) E (NE 1 inch) F (CO ¾ inch)

Note. The general appearance of coarse aggregates used in the study with NMS A (Control RCA- Limestone 1”), B (Control RCA-Dolomite 1”), C (Control RCA- Granite 1”), D (Commercial RCA- MD), E (Commercial RCA- NE), F (Commercial RCA- CO)

As is shown in Figure 7, mortar sticks to the individual particles of manufactured and Commercial RCAs. Also, there were some particles (less than 2% of aggregate by weight) in Commercial RCA such as wood, asphalt, and other materials. Some physical properties of CRCAs, which may be used to analyze the other properties of RCA, are shown in Table 12.

Fine Aggregate

The fine aggregate used for the concrete mixtures in this study is concrete sand, a type of sand with the nominal maximum size of #4. This fine aggregate met the ASTM C33 standard and was purchased from a local aggregate supplier [91]. Table 14 shows the fine aggregate properties. Figure 8 shows the gradation of the sand.

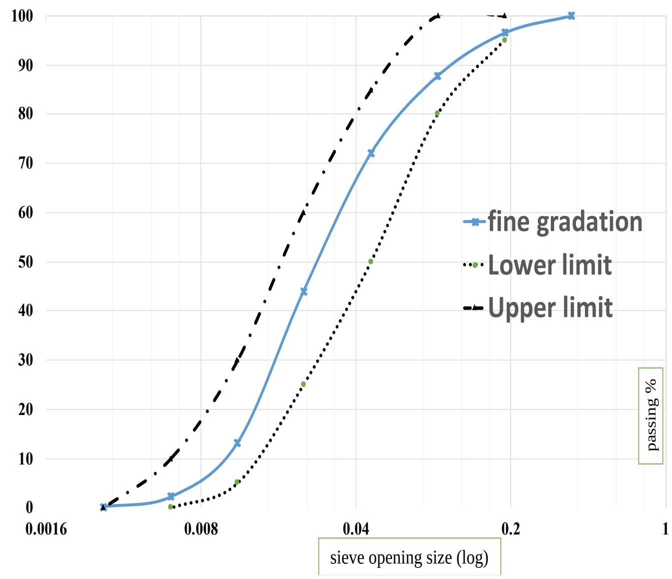
Table 14

Fine Aggregate Properties

aterial	Absorption (%)	Specific gravity	Fineness modulus	Bulk density (pcf)
Fine aggregate	1.4	2.6	2.8	83.9

Figure 8

Fine (NA) Aggregate Gradations Curves



Admixture

The only admixture used in this study for all concrete mixtures was the air-entraining agent (AEA). The AEA is Sika AEA-14. It is an aqueous solution based on tall oil. AEA-14 met the requirements of ASTM C-260 [92] for air-entraining admixtures [93].

Chapter 4

Methodology

This chapter describes the experimental procedures conducted to investigate the mechanical properties of concrete made with100% replacement of the coarse aggregate with RCA. According to task three which is mentioned in the introduction, two essential tasks include preparation of the concrete mixtures and testing samples to obtain the results. More than 200 ft^3 of concrete were batched as trial and target batches in this study.

Mixture Proportions

In this study, the basic proportioning of concrete made with 100% RCA coarse aggregates is similar to proportioning of normal concrete made with natural aggregates. This study's two different mixture designs are based on two different NMASs (1" and ¾ "). Also, two w/c (0.48 and 0.38) were adapted for each size of RCA.

Mixture Designation

The procedure of proportioning the mixture design of RCA concrete in this study is adopted from Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) [94]. Table 15 shows the requirements for concrete mixes used in this study.

Table 15

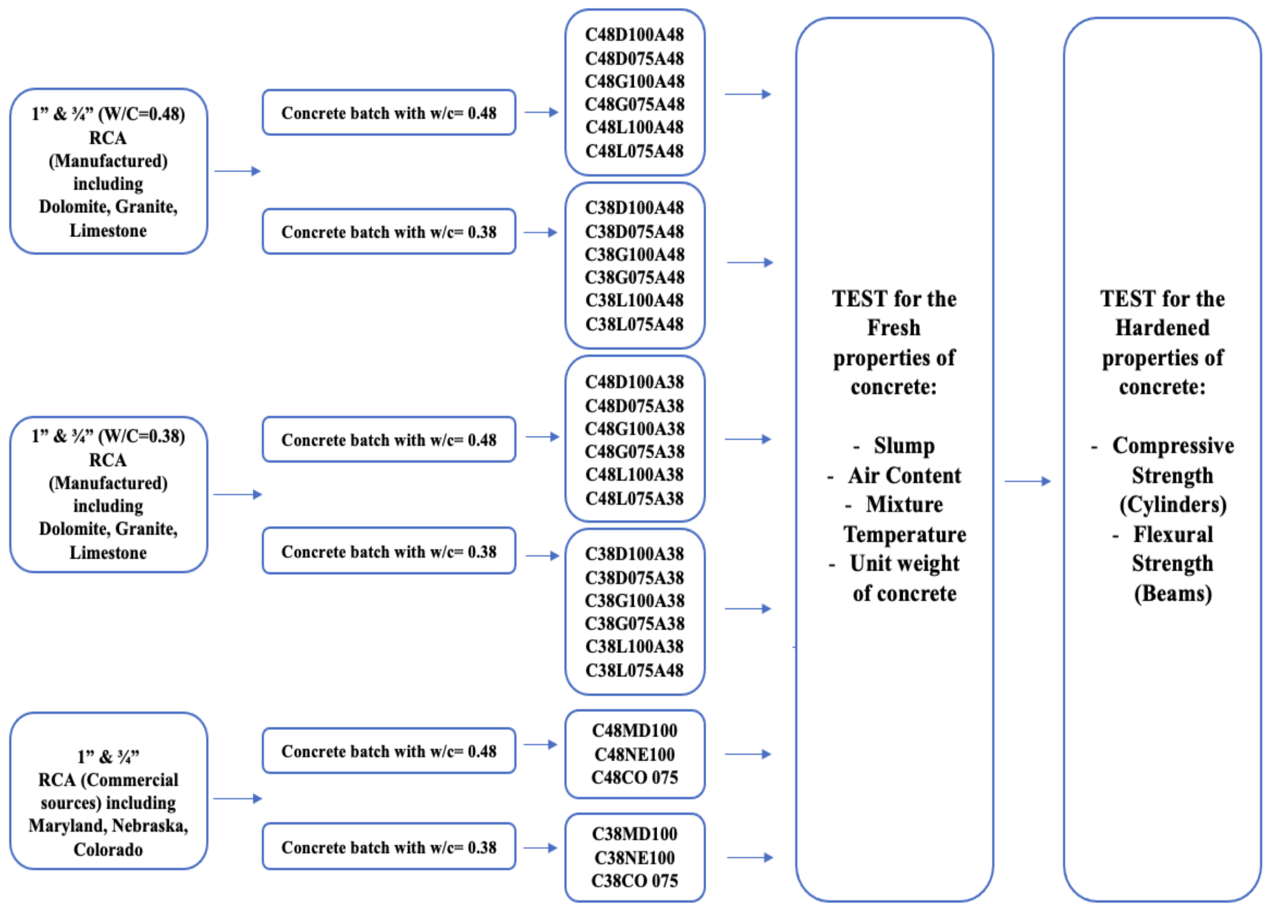
Parameters Applied For Designing Concrete Mixtures

Design Parameters	Target
Concrete mixture Slump	2±1 inch
Concrete Air content	6±2%
Nominal Maximum Aggregate Size	¾ inch and 1 inch

The process of using natural aggregate in parent concrete mixture and manufacturing the control RCA, and all concrete mixtures' name and the fresh and hardened properties which have been evaluated are shown in Figure 9.

Figure 9

Concrete Mixture with Control RCA & CRCAs in Different w/c Ratios



Mixture Compositions

Due to two different sizes of RCA (1” and ¾”) for both manufactured and external RCAs and two different water to cement ratios (0.48 and 0.38), in this study, two different mixture designs were used.

This subchapter presents the test results of the fresh and hardened properties of concrete used in this research. The mixture proportions of Parent Concrete are mentioned in table 16, and control RCA, CRCA mixture proportions are shown in Table 17.

Table 16

Parent Mixture Proportion

Sources	Mix Name*	Aggregate size (in)	Cement (pcy)	Water (pcy)	RCA (pcy)	Sand (pcy)	AEA (oz/cwt)
Parent Concrete	D100C48	1	575	276	1760	1310	0.55
	D100C38	1	730	276	1750	1180	0.45
	G100C48	1	575	276	1750	1310	0.50
	G100C38	1	730	276	1740	1180	0.45
	L100C48	1	575	276	1755	1310	0.50
	L100C38	1	730	276	1755	1180	0.50

Table 17

A) Concrete Mixture Proportions Of PC, Control RCA, B) Concrete Mixture Proportions Of CRCA

Sources	Mix Name*	Aggregate size (in)	Cement (pcy)	Water (pcy)	RCA (pcy)	Sand (pcy)	AEA (oz/cwt)
Concrete Made from Manufactured Dolomite RCA	C48D100A48	1	527	275	1401	1476	1.15
	C38D100A48	1	723	275	1401	1351	1.00
	C46D100A38	1	527	274	1567	1258	0.70
	C38D100A38	1	723	275	1567	1133	0.70
	C48D075A48	¾	590	283	1473	1321	0.65
	C38D075A48	¾	752	283	1473	1192	1.15
	C48D075A38	¾	590	283	1447	1391	0.70
	C38D075A38	¾	745	283	1447	1262	1.00
Concrete Made from Manufactured Granite RCA	C48G100A48	1	590	283	1363	1393	0.60
	C38G100A48	1	723	275	1473	1213	1.00
	C48G100A38	1	572	275	1513	1343	0.70
	C38G100A38	1	723	275	1513	1218	1.00
	C48G075A48	¾	590	283	1362	1394	0.60
	C38G075A48	¾	745	283	1362	1265	1.00
	C48G075A38	¾	590	283	1448	1388	0.70
	C38G075A38	¾	745	283	1448	1258	0.70

Sources	Mix Name*	Aggregate size (in)	Cement (pcy)	Water (pcy)	RCA (pcy)	Sand (pcy)	AEA (oz/cwt)
Concrete Made from Manufactured Limestone RCA	C48L100A48	1	572	275	1496	1314	0.65
	C38L100A48	1	723	275	1496	1118	1.00
	C48L100A38	1	572	275	1508	1325	0.65
	C38L100A38	1	723	275	1508	1199	1.00
	C48L075A38	¾	590	283	1395	1410	0.60
	C38L075A38	¾	745	283	1380	1315	0.60
	C48L075A48	¾	590	283	1384	1399	0.60
	C38L075A48	¾	745	283	1382	1285	1.00

*C48&C38= w/c of RCA mix design, 100=1" NMAS, 075= ¾" NMAS, A48&A38= w/c of Parent Concrete

B) Concrete mixture proportions of CRCA

Sources	Mix Name*	Aggregate size (in)	Cement (pcy)	Water (pcy)	RCA (pcy)	Sand (pcy)	AEA (oz/cwt)
Concrete Made from Commercial sources	C48-MD100	1	523	251	1454	1504	1.50
	C38-MD100	1	726	272	1401	1323	1.50
	C48-CO 075	¾	590	283	1320	1456	0.60
	C38-CO 075	¾	745	283	1320	1327	0.60
	C48-NE100	1	572	275	1503	1280	1.00
	C38NE100	1	723	275	1503	1154	1.00

Mixing Procedures

ASTM C192 [95] Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory was followed for concrete mixtures.

The first step of mixing concrete was loading RCAs into an oven for 24 hours to ensure aggregates have consistent, oven-dried moisture conditions. To avoid changing aggregate moisture, oven-dried materials were stored in sealed barrels (drums) to keep them dry during the research project.

Before batching, all the materials, including RCA, concrete sand, cement, and tap water, were placed in plastic containers separately to be weighed and sealed to minimize evaporation or avoid any harmful interactions. After determining the aggregates, cement, and tap water weight, the concrete batching began based on the procedure outlined in ASTM C192.

Laboratory Mixing Procedure. In this research, for the laboratory concrete mixes, ASTM C192 was followed. In this subchapter first laboratory mixing in three steps is reviewed, and the adjustments are explained. The concrete mixing procedure in the laboratory was outlined in the three steps below:

Step 1: RCA and fine aggregate (concrete sand), cement, AEA admixture, and tap water were weighed and placed in a plastic container. All the materials were sealed to minimize material evaporation in the room.

Step 2: The concrete mixer was charged with coarse aggregate. The mixer ran for 30 seconds while 10% of tap water including an AEA admixture was added to the mixer.

Step 3: After the first 30 seconds, all materials, including fine aggregate, cement, and water, are added to the running mixer. The first three minutes of mixing started when all the materials were added to the mixer. The first three minutes were running the mixer followed by another three minutes rest when the mixer was off, and the mixer was covered by plastic to avoid any evaporation. The final mixing was two minutes.

Modifications on The Laboratory Procedure. Some minor adjustments were added to the mixing procedure, which is mentioned below:

- During the 30 seconds of running the mixer with coarse aggregate and AEA, depending on the level of AEA interaction with aggregate, half of the small sample scoop of cement was added to increase the chemical interaction of AEA in the mixer (if needed).
- Instead of adding all of the water to the mixer, water was added gradually (10% by 10%) along with adding cement and fine aggregate, which helped concrete aggregates be wet during the mixing and interaction with cement in the mixer. Following batching, concrete test cylinders and beams were prepared following ASTM method.

Preparation of Test Specimens

All specimens were following ASTM C192, Section 8.3. All specimens, including cylinders and beams, were covered by plastic immediately after finishing to prevent water evaporation and were stored at room temperature for 24 hours. The type and the total number of specimens produced are listed in Table A5 in the appendix A.

The specimens, which were transported from the batching plant (parent concrete samples), as well as laboratory cast samples, were placed in curing boxes to stabilize the temperature and humidity of samples as is suggested in ASTM C192, section 9 [95], and ASTM C31, section 10.1.2 and 10.2.1 [96]. The isolated curing tank named Perfa-Cure Elite Xtreme concrete curing box for samples (cylinders and beams)[97] is shown in Figure 10. The temperature of curing tanks was set up for $72 \pm 2°$ F since the concrete was designed based on strength for 6,000 psi or greater. Cylinders were tested at 7, 14, 28, and 90 days. Each time samples were covered by plastic to prevent moisture loss during the test in the laboratory. It should be noted that the laboratory temperature was between 78° to 80° F.

Figure 10

Isolated Curing Tank for Samples (Cylinders and Beams)

Test Matrix

The test matrix for this study was divided into two parts, recycled concrete aggregate tests for mechanical properties and concrete tests including fresh and hardened properties. Table 18 shows the test matrix and the methods to measure the properties of recycled concrete aggregates in this study.

Table 18

Aggregate Tests Used In This Research For RCA

Aggregate test	ASTM standard	AASHTO standard
Resistance to abrasion	ASTM C 131	AASHTO T 96
Grading	ASTM C 117 ASTM C 136	AASHTO T 11 AASHTO T 27

Aggregate Tests

Several tests were conducted on the coarse aggregate for the RCA to determine aggregate mechanical properties that may affect concrete's performance. For resistance to abrasion, the Los Angeles machine (L.A. abrasion) was used. To determine the particles finer than 75-µm (sieve No. 200), sieve aggregate by washing was used [98]. To determine the aggregate gradation, sieve analysis of coarse aggregate was used [89]. In this section of chapter four, test procedures are reviewed.

Aggregate Gradation

Aggregate gradation is the distribution of a granular material's particles among various sizes, expressed in terms of cumulative percentages larger/smaller than each of a series of sieve opening sizes. The coarse aggregate was washed to determine the number of particles finer than 75-µm (sieve No. 200) and sieved to find the size distribution. The fine aggregate was sieved and tested for aggregate properties, also.

__Resistance to Abrasion__

To determine the resistance of RCAs to abrasion, ASTM C131 for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine was followed. Results are shown in Table A6 in the appendix A. The Humboldt abrasion machine [99] (H-3860D) is used to measure the degradation of the mineral aggregate of standard gradings resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres. The test is widely used to indicate the relative quality of various aggregate sources having similar mineral compositions. Figure 11 shows the Los Angeles machine used in this study.

Figure 11

The Los Angeles Test Machine

Particles Finer than 75-µm (Sieve No. 200)

To determine the amount of fine particles such as clay in the coarse aggregate, the RCA was washed with water, and the aggregate was weighed after 24 hours in the oven to measure the aggregate loss. Figure 12 shows the machine called small automatic aggregate washer (HM-52) used in this study [90]. The gradation results of the coarse aggregate are shown in Table A7 in the appendix A.

Figure 12

Small Automatic Aggregate Washer

Test Matrix for Concrete Mixtures

The standard tests used to measure the fresh and hardened concrete properties are shown in Table 19.

Table 19

Test Matrix Used In This Research For Concrete Made By 100% RCA

Concrete test		**ASTM standard**	**AASHTO standard**
Fresh concrete properties	Slump	ASTM C 143	AASHTO T 119
	Air content	ASTM C 173	AASHTO T 196
	Concrete mix temperature	ASTM C 1064	AASHTO T 11
	Concrete mixture Unit Weight	ASTM C 138	AASHTO T 121
Hardened concrete properties	Compressive strength	ASTM C 39	AASHTO T 22
	Flexural strength	ASTM C78	AASHTO T 97

Fresh Concrete Test Properties

In this study, tests conducted on fresh concrete properties included the determination of slump test, air content, concrete mixing temperature, and fresh concrete unit weight. The methodology used to conduct these tests is covered in this section.

Slump Test

For all 30 mixes in this research, slump test was performed in accordance with ASTM C143, Standard Test Method for Slump of Hydraulic-Cement Concrete [46], which is similar to AASHTO T 119 [100]. The study met the specification of the AASHTO T 119, which was a slump for concrete with coarse aggregate with a maximum size up to 1.5 inches (37.5 mm).

Air Content

As discussed in chapter two, since old mortar is attached to the RCA, the porosity of the concrete made with 100% coarse aggregate replacement with RCA could be high. In this study, the volumetric method, ASTM C173[50], was used to determine the air contained in the mortar fraction of the concrete because the results are not affected by air inside porous aggregate particles [101].

Because of the air trapped within porous aggregates, common techniques such as pressure methods might impact the air results. The volumetric method was used in this study to determine the air contained in the mortar fraction of the concrete, and the crucial fact with this method that caused it to be chosen over the pressure method is the results of the air volumetric method are unaffected by air that is inside porous aggregate particles. This study aimed to achieve air content for each concrete mixture of 6±2 percent.

Fresh Concrete Unit Weight

To measure the unit weight of fresh concrete ASTM C 138, Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete [42] was followed, which is similar to AASHTO T 121[102, p. 121]. The unit weight was calculated by dividing the weight of fresh concrete which filled the volumetric bowl by its volume.

Concrete Mixture Temperature

To determine the temperature of fresh concrete mixture, ASTM C1064 [103] was followed. The temperature of the fresh concrete mixture inside the mixer is collected for all mixtures. In this study, the range of concrete mixture temperature was between 60 and 86 F.

Hardened Concrete Test Properties

In this study, the mechanical properties of RCA are covered. The flexural strength and the compressive strength of the concrete was measured. Tests on hardened concrete are described in this section.

Compressive Strength

To determine the compressive strength of concrete specimens, ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens was followed. The compressive strength test was conducted in accordance with ASTM C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. The Loading Rate was 64 psi/sec for all the cylinders tested with this machine. Compressive strength results were obtained on 4 in x 8 in the cylinder after 7, 14, 28, and 90 days of curing in the isolated curing tank (no water in the curing tank). The cylinders were tested with steel retainers and unbonded neoprene pads. The test machine called Accu-Tek Touch 500 used in this experiment is shown in Figure 13.

Figure 13

Compressive Strength Machine

Flexural Strength

In this study, the Accu-Tek machine was used to determine the flexural strength of concrete specimens (beam). ASTM C 78, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) was followed [82]. Specimens using third-point loading followed the test procedure for beams. Three beams from each mix were tested at 14 and 28 days. Figure 14 shows the flexural machine called Accu-Tek Touch 500 used in this experiment.

Figure 14

The Flexural Machine

Chapter 5

Test Results and Analysis

This chapter covers the test results of control RCAs, CRCAs and fresh and hardened concrete properties which were studied in this research. Some statistical models of several concrete properties are based on regression analysis of the data discussed in this chapter.

RCA Properties (Aggregate)

Gradation of RCA

As described in Chapters 3 and 4, the RCA used in this study was included in two different NMAS (1 inch and ¾ inch). Aggregate gradation was sorted following ASTM methods, including D57, D56 for 1 inch aggregate, and D6 and D67 for ¾ inch aggregate.

Resistance to Abrasion

The L.A. abrasion test is used to determine the tendency of the aggregate to degrade when aggregates are inside a steel rotating drum for 500 rotations. The number of steel balls placed inside the machine was based on the oven dry aggregate weight remaining on specific sieve sizes [104]. The results of the L.A. abrasion loss test for the RCA study are shown in Figure 20.

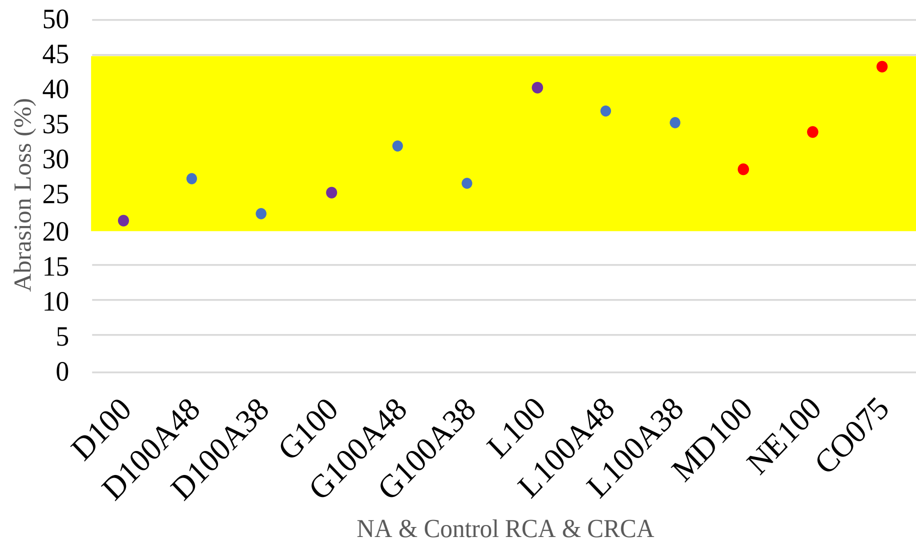
In Chapter 2, findings from other studies have been discussed. In summary, 1) due to the various test results mentioned in other studies, the range of L.A. abrasion test results based on a percentage of 100% RCA could be between 15% and 51.5%. Also, the range of L.A. abrasion test for natural aggregate in the same study and before producing RCA was between 15% and 43% (Table 3, Chapter 2). 2) Due to the variation in states specification within the United States for recycled concrete aggregates, which is mentioned in brief research by NJ DOT, many states accept the results of L.A. abrasion test between 20% and maximum 45%. For natural aggregate based on U.S. DOTs specification the range of acceptable L.A. abrasion test results is between 15% and 40% (many states accept the results up to 30%) [9]. Figure 15 shows the ranges of acceptable L.A. abrasion test results provided by some state DOTs.

Other concrete organizations have mentioned almost the same acceptable results. For instance, American Concrete Pavement Associated has mentioned that the maximum acceptable abrasion loss is 50% [9,112]. It should be noted that it is possible to have aggregate with a high quality, and the L.A. abrasion result could be even lower than 15%, as it was mentioned in Chapter 2 (9.1%). The ranges of L.A abrasion results for natural aggregate and recycled concrete aggregate in general are shown in Figure 16.

In this research, the result of mass loss in terms of L.A. abrasion test for selected natural aggregate included natural dolomite, granite, and limestone aggregate was between 21% and 40%. After manufacturing the RCA from parent concrete, control RCAs were tested to obtain the RCA resistance to abrasion and the results were between 21.1% and 36.6%, which is in the range of acceptable test results according to DOTs specification for both natural and recycled concrete aggregates. The results of selected CRCA from other states was between 28.5% and 43%, which is in the range of DOTs specification for RCA.

Figure 15

The L.A. Abrasion Results for NA & Control RCA & CRCA

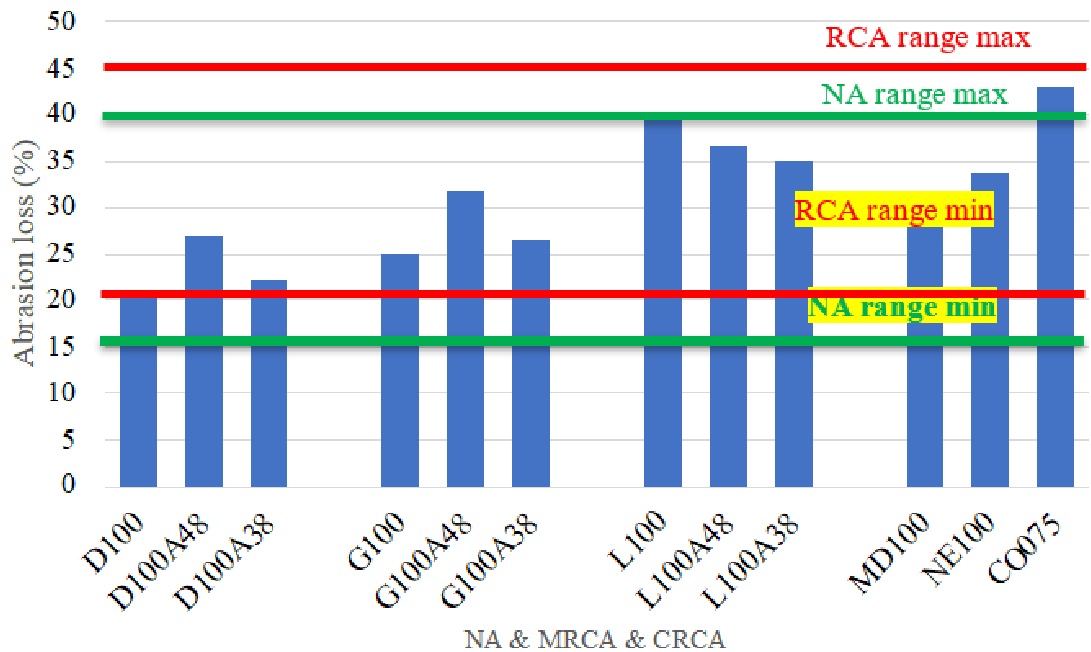


Note. Yellow bound= acceptable test results by some dots. Purple dots= NA. Blue dots= Control RCA. Red dots= CRCA.

Also, Figure 16 shows the abrasion test results, and the range of maximum acceptable loss results used by various agencies which is shown with the red lines. For example, D100 is natural aggregate, D100A48 is control RCA, and NE100 is CRCA. The ranges of L.A. abrasion loss in percentage for NA, control RCA, and CRCA are shown in Figure 15 and the results in detail in Table A6 in Appendix A.

Figure 16

The L.A. Abrasion of Control RCAs, and CRCAs in 1 Inch



Note. Red line= Range of test results for RCA in literature review/ Green line= Range of L.A. abrasion tests for natural aggregates (NA), (NJ DOT Maximum allowable L.A. abrasion test result is 40%).

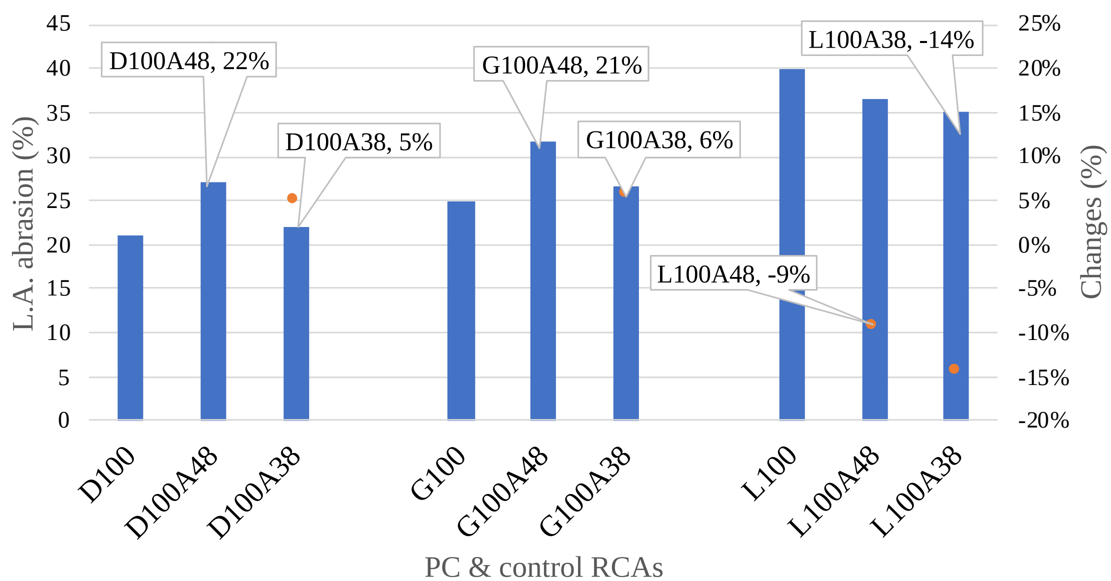
The results of L.A. abrasion indicate that Dolomite 1 inch with water to cement ratio of 0.38 was the most resistant to abrasion with 22.1%, while Colorado ¾ inch had the lowest resistance with 43%. It should be noted that the maximum mass loss among the 1 inch RCAs had limestone (L100A48) with 36% mass loss.

NA vs Control RCA Resistance to Abrasion. The comparison between L.A. abrasion test results of natural aggregates (D, G, L) that were used in the parent concrete and control RCA showed that control RCA abrasion loss is higher than selected natural aggregate in this study.

Comparison between the results of selected NA and control RCAs in terms of L.A. abrasion test showed that lowering the w/c ratio of concrete with NA can produce less mass loss in control RCA. For instance, the results of the L.A. abrasion for control RCAs in NMAS 1 inch after crushing the parent concrete blocks with w/c ratio of 0.48 showed 29% higher mass loss, while for 0.38 it was only 5% higher mass loss compared to natural dolomite NMAS 1 inch. A similar trend was found for granite. Figure 17 shows the comparison between natural aggregate and control RCA in terms of the L.A. abrasion test.

Figure 17

Comparison Between NA and Control RCA in L.A. Abrasion Test



Several studies have shown that the mass loss volume for RCA is greater than natural aggregate because weight loss occurs as a result of two factors: 1) loss of adhering mortar and 2) loss of original aggregate.[10, 107]. Natural aggregate used in parent concrete was included (dolomite, granite, limestone) with different quality of aggregate mass loss in terms of resistance to abrasion. Comparison between NA and RCA in two different w/c ratio in terms of mass loss is shown in table 20. Except in L100A48 with L.A. abrasion of 40% which turned out to a lower L.A. abrasion as of 35%, dolomite and granite have shown that mass loss in RCA is higher than its relative NA. Also, the results of lower w/c ratio showed less mass loss and improvement in RCA with a lower w/c ratio compared to its relative NA. For instance, Dolomite in 1 inch NMAS and w/c ratio as of 0.48.

Table 20

Comparison Between Aggregate Mechanical Properties of NA And RCA

Aggregate type (NMAS 1 inch)	***NA- L.A. abrasion- mass loss (%)***	***Control RCA (NMAS 1 inch)***	***RCA- L.A. abrasion- mass loss (%)***
D100	*21%*	*D100A48*	*27%*
		D100A38	*22.1%*
G100	*25%*	*G100A48*	*31.8%*
		G100A38	*26.5%*
L100	*40%*	*L100A48*	*36.5%*
		L100A38	*35%*

Abrasion and Specific Gravity Relationship. There is a relationship between the specific gravity of RCA and its resistance to abrasion. RCA with lower specific gravity has a higher L.A. abrasion loss in percentage. Figure 18, showing the relationship of specific gravity and the L.A. abrasion loss in percentage for control RCA and CRCA used in this study. Equation 4 gives the relationship between RCA specific gravity and abrasion loss.

Equation:

$$\mathbf{y = -89.61x + 247.82}$$

$$\mathbf{R^2 = 0.40}$$

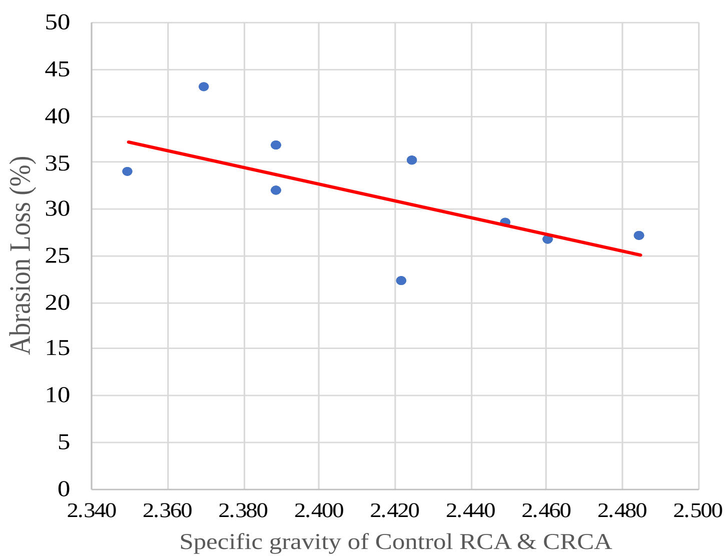
Where (4)

Y_1= control RCA and CRCA L.A. abrasion loss (%)

X_1= control RCA and CRCA Specific gravity

Figure 18

Control RCAs and CRCAs Abrasion Loss (%), vs. Specific Gravity

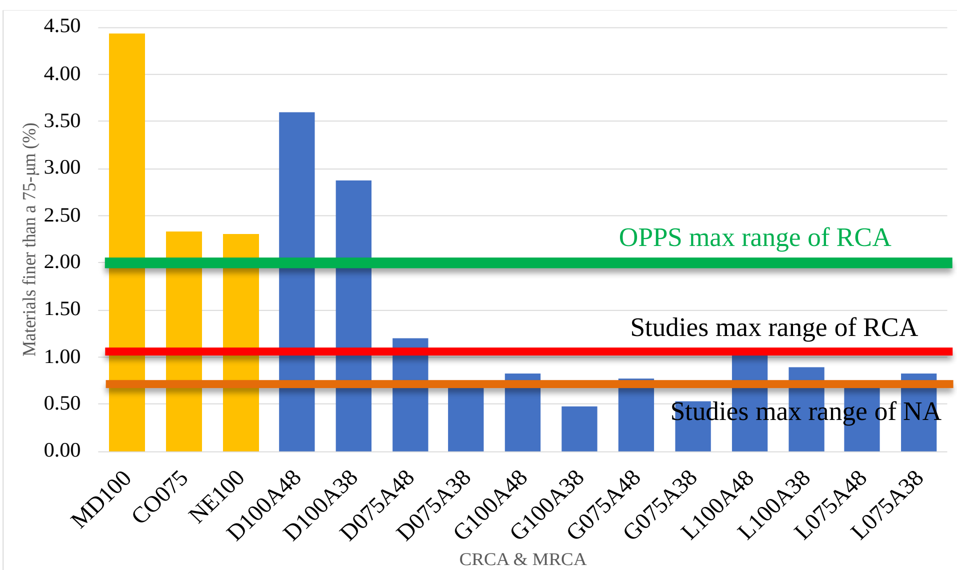


Materials Finer than 75-µm (Sieve No. 200)

The test results of particles finer than 75-µm showed that control RCA ranges were between 0.5% and 3.6%, and the commercial RCAs were ranging between 2.3% and 4.4%. It should be noted that Control RCA in NMAS ¾ inch was regraded aggregate from NMAS 1 inch of the same control RCA. Figure 18 shows the results of the washing aggregate test for control RCA and CRCA. Tables A8 and A9 in the appendix A, provide the results in more detail. The result of this test could be even less than the minimum line (which is mentioned in Figure 19 as it is mentioned in Chapter 2). This means that with a good quality of natural aggregate, the result of material finer than 75-µm test for 0% mass loss is also achievable.

Figure 19

CRCA & Control RCA Results of Fineness Mass Loss



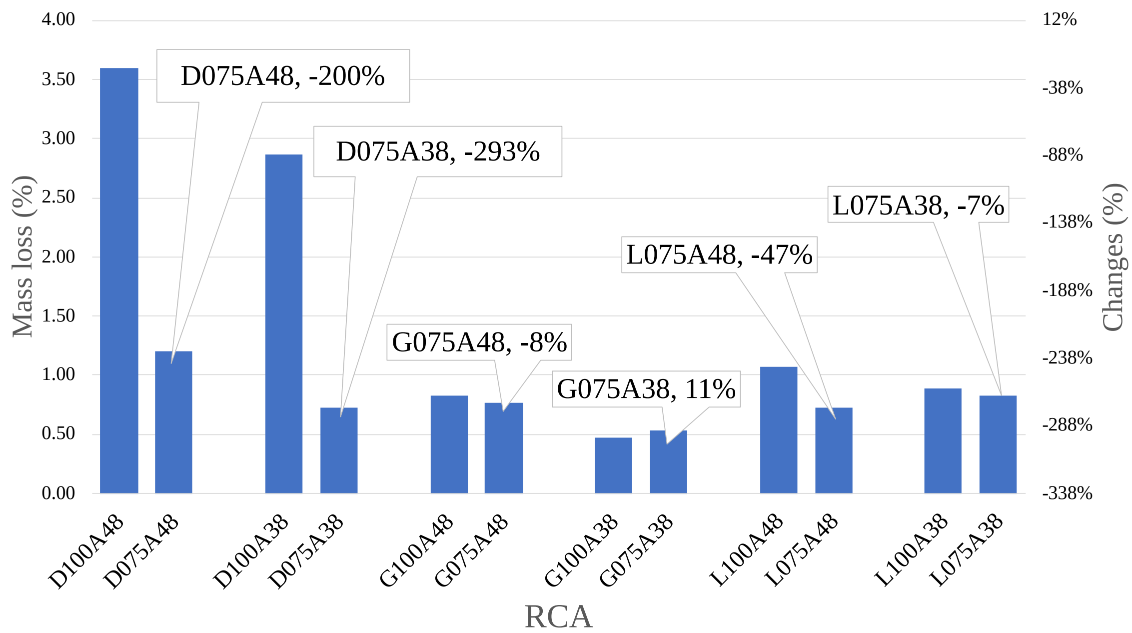
Note. Green line= maximum acceptable results of OPSS Canada, Red line= finding of other studies, orange line= maximum range of natural aggregate found by other studies.

Ontario Provincial Standards Specification (OPSS) 1002 is the material specification for aggregates which is being used in a concrete mixture in Ontario. According to OPSS specification, the limitation for the range of particles finer than 75μm is up to 2% for natural aggregates. In the case of RCA, the only result mentioned in the article is 2.75% [9]. OPSS maximum acceptable finer particle loss in coarse RCA and the other studies findings which are mentioned in Chapter 2, are shown in Figure 20.

In the same concrete mixture proportion where the w/c ratios of parent concrete and control RCA is the same, reducing NMAS from 1 inch to ¾ inch resulted in reduction of mass loss. This is because aggregate screening could separate some small particles and fine from aggregates. For example, RCA in D100A48 which had a mass loss of 3.6% and RCA in D075A48 which was regraded from D100A48 had a result of 1.2% mass loss, meaning 200% reduction. After regrading and washing the RCA, the mass loss showed to be lower. Figure 20 shows the impact of lowering NMAS on mass loss.

Figure 20

The Impact of Lowering NMAS on Mass Loss in Control RCA



Fresh Concrete Test Properties

In this study, concrete mixture design followed the ACI 211.1-81, and targeted the slump for 2 inches, air content for 6%, in two NMAS 1 inch and ¾ inch, and two w/c ratios 0.38 and 0.48. Also, the concrete mixture design was based on the aggregate properties and specific range which is mentioned in this study.

In order to determine the fresh properties of concrete some tests have been done in this study to measure the properties of control RCAs and CRCAs such as slump test, air content, and fresh concrete mixture unit weight. The results of parent concrete and the fresh property measurements of concrete with control RCA and CRCA coarse aggregate are shown in Table A10 in the Appendix A.

Slump Test Results

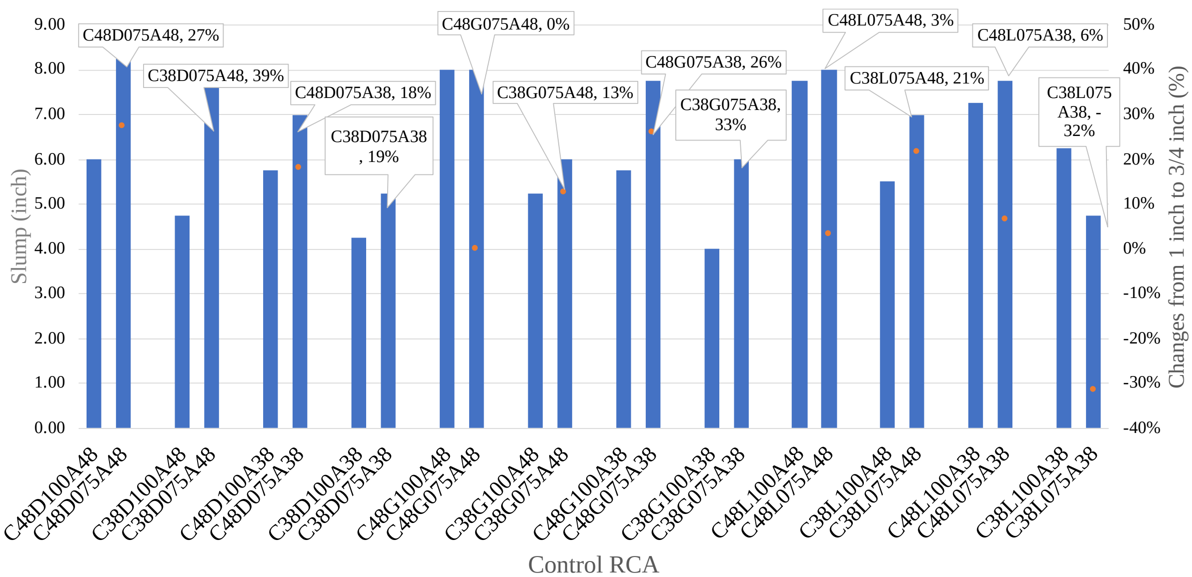
One of the RCA concerns is the workability of fresh concrete mixture. Generally, RCA as a coarse aggregate mixed with natural sand in a concrete mixture gives a 10% less slump than the normal concrete [114, 60].

Air Content

In this research, one of the target designs was air content, which was 6 ± 2 in percentage. The air entraining dosage for concrete with control RCAs and CRCAs were between 0.65 to 1.00 oz/cwt (a few cases up to 1.50 oz/cwt) for 1 inch NMAS, and 0.60 to 1.00 oz/cwt for ¾ inch NMAS of RCAs. Figure 21 shows the air content of both size and the percentage of difference where NMAS is reduced to ¾ inch. Other studies are showing that smaller coarse aggregate creates small voids that contain air bubbles in the concrete mixture. In other words, the smaller NMAS shows a higher air content compared to 1 inch NMAS [27].

Figure 21

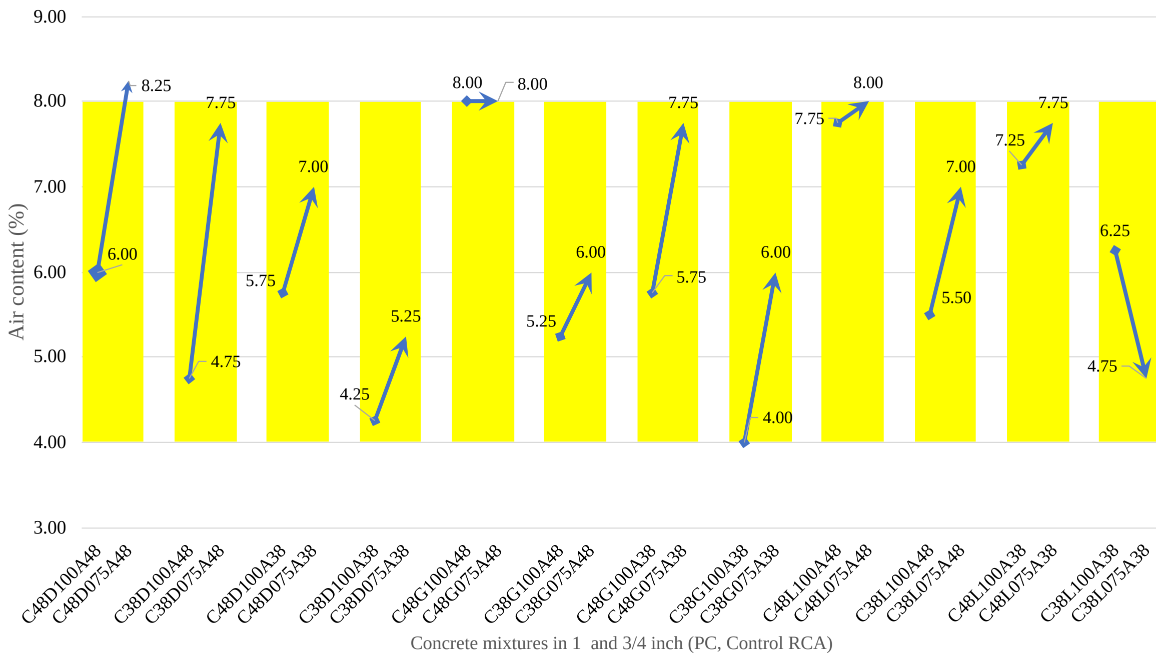
Air Content in Concrete Made with Control RCA



Impact of Aggregate NMAS on Air Content. Two different air contents have been obtained in this study, the air content of parent concrete and the air content of concrete with control RCA. The results of air content testing on concrete with control RCA are shown in Figure 22 (project air content design criteria were 6 ± 2 in percentage). In this study, an air volumetric device was used to determine the different air content in control RCA with two w/c ratios 0.48 and 0.38 and two NMAS 1 and ¾ inch and concrete with CRCA.

Figure 22

Air Content Test Results of Control RCA in 1 and ¾ inch NMAS



Note. project air content target was 6 ± 2 in percentage. Yellow bound shows the design criteria.

The comparison between the results of air content test for two NMAS 1 and ¾ inch showed that control RCAs with NMAS of ¾ inch was higher than 1 inch, where w/c ratios and other variables except NMAS were consistent. The results of control RCA in this study shows that in average 19% higher air content is achieved in ¾ inch NMAS compared to 1 inch NMAS in similar w/c ratios (except for C38L075A38). Figure 23 shows the comparison between control RCA in two NMAS.

Figure 23

Comparison Between Control RCA in Two NMAS

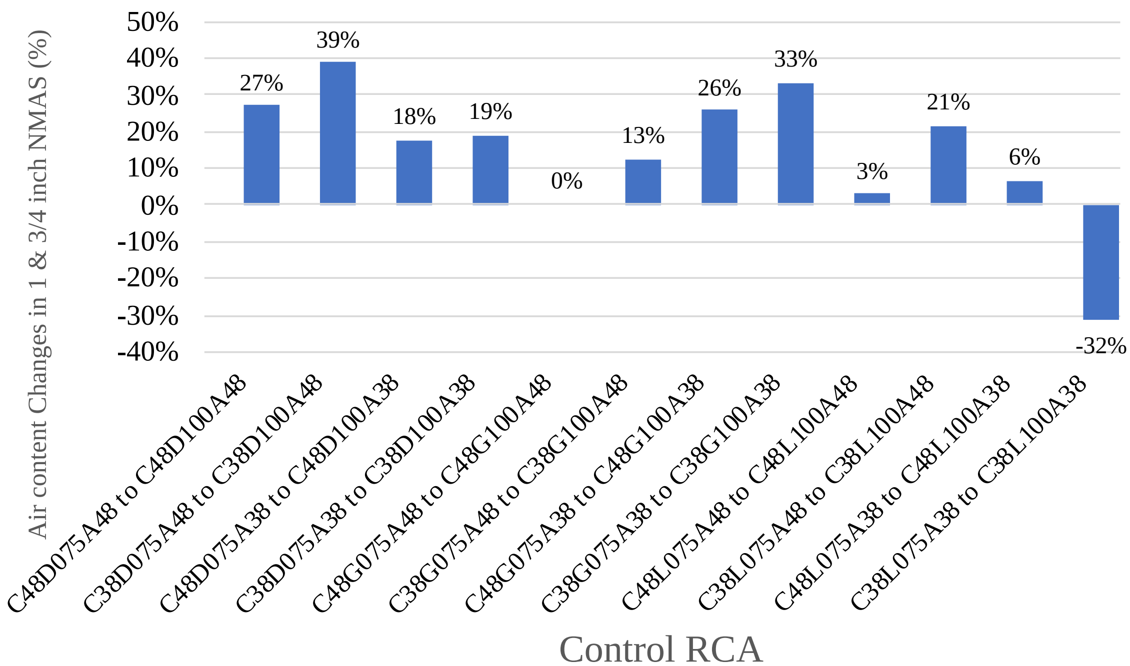


Figure 23 shows the comparison between control RCA in two NMAS and the average of results. Fresh concrete properties of parent concrete are shown in Table 21, and the fresh properties of control RCA and CRCA are shown in Table 22 as a reference.

Table 21

Parent Concrete Fresh Concrete Mixture Properties

Parent Concrete	**Slump** inch	**Air content** %	**Unit Wt** pcf	**190d Compressive strength,** psi
D100A48	5.5	6.0	145.6	6522
D100A38	5.5	5.4	146.8	7716
G100A49	8.0	7.2	147.4	5223
G100A39	4.0	4.5	148.2	8676
L100A48	6.5	6.8	142.2	5976
L100A39	4.0	5.0	149.4	8132

Table 22

Fresh Properties Of CRCA, And Control RCA

Sources	Aggregate	AEA (oz/cwt)	Slump inch	*Air content %	Unit Wt pcf	Concrete mixing Temp F
Commercial sources	C48-MD100	1.50	5.00	5.00	126.30	82
	C38-MD100	1.50	2.50	8.00	130.30	74
	C48-CO 075	0.60	5.00	7.00	140.68	70
	C38-CO 075	0.60	1.50	4.50	146.52	81
	C48-NE100	1.00	5.75	8.00	138.97	76
	C38NE100	1.00	3.25	4.25	145.17	82
Manufactured Dolomite	C48D100A48	1.15	8.50	9.00	137.69	78
	C38D100A48	1.00	2.00	4.75	149.66	82
	C48D100A38	0.70	2.25	5.75	147.27	86
	C38D100A38	0.70	1.75	4.25	151.16	81
	C48D075A48	0.65	5.25	8.25	139.18	80
	C38D075A48	1.15	6.00	7.75	133.20	61
	C48D075A38	0.70	5.75	7.00	145.17	79
	C38D075A38	1.00	1.50	5.25	145.53	79
Manufactured Granite	C48G100A48	0.60	4.50	8.00	141.70	79
	C38G100A48	1.00	2.25	5.25	141.43	63
	C48G100A38	0.70	2.50	5.75	145.26	71
	C38G100A38	1.00	1.50	4.00	149.24	68
	C48G075A48	0.60	4.50	8.00	141.70	80
	C38G075A48	1.00	2.25	6.00	144.42	79
	C48G075A38	0.70	6.50	7.75	143.07	78
	C38G075A38	0.70	3.25	6.00	142.33	82
Manufactured Limestone	C48L100A48	0.65	6.50	7.75	142.03	60
	C38L100A48	1.00	3.00	5.50	145.17	72
	C48L100A38	0.65	4.75	7.25	142.57	79
	C38L100A38	1.00	6.50	6.25	144.93	68
	C48L075A38	0.60	5.00	7.75	143.28	80
	C38L075A38	0.60	2.00	4.75	151.01	74
	C48L075A48	0.60	5.75	8.00	140.38	85
	C38L075A48	1.00	3.00	7.00	145.59	77

*Results of volumetric air test of the fresh concrete mixture.

Hardened Concrete Test Properties

In this research, the mechanical properties and test results of compressive strength and flexural strength are covered. More than 540 specimens, including PC, control RCA, and CRCA, were tested in terms of compression in 7, 14, 28, and 90 days of age. And for the flexural strength, control RCA and CRCA beams were tested at 14 and 28 days of age. The results are discussed in this subchapter.

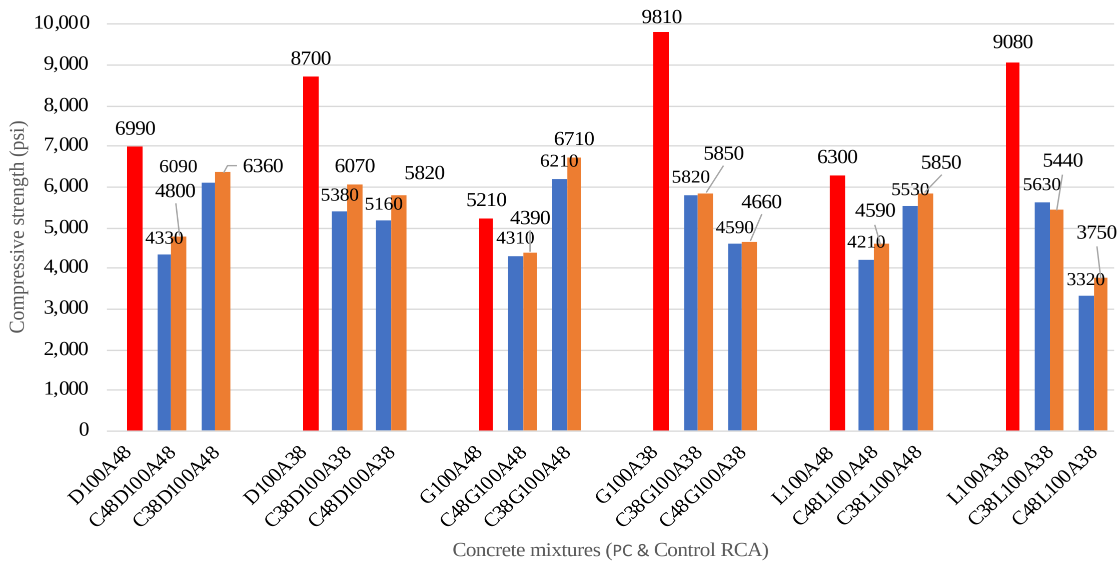
Compressive Strength

In this study, compressive strength is determined via testing 4×8 in cylinders. The following section discusses the impact of recycled concrete aggregate properties and other factors on the compressive strength of a new concrete with 100% RCA.

Parent Concrete. In this subsection, the compressive strength test results of parent concrete are discussed. Parent concrete specimens were tested at 190 days old because of school and laboratory closure during the COVID-19 quarantine. Figure 24 shows the compressive strength of parent concrete at the age of 190 days old compared to the compressive strength of concrete made from control RCAs in the same NMAS, w/c ratios, and mixture proportions at the age of 90 days old. Table A11 in the appendix A, shows the test results of dolomite, limestone, and granite in 1 inch with two water to cement ratios (0.38 and 0.48).

Figure 24

Comparison Between Compressive Strength of PC and Control RCA

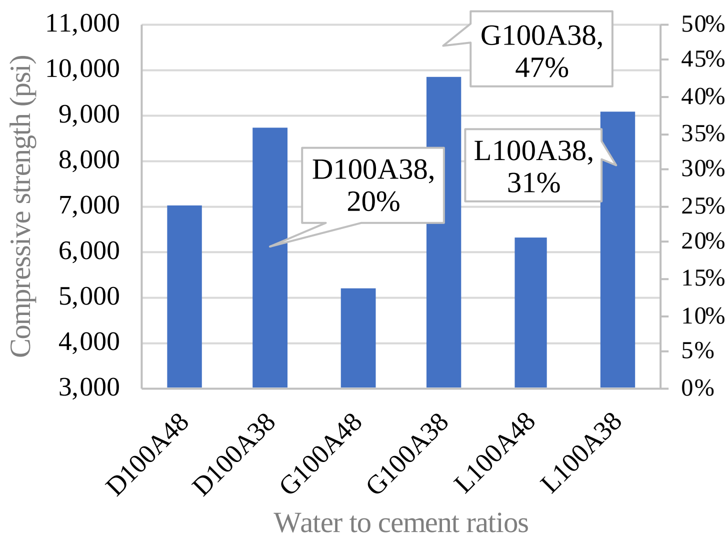


Note. Red=parent concrete at 190 days old, Blue=Control RCA in 28 days old, Orange= Control RCA in 90 days old.

The compressive strength of parent concrete with natural aggregate in 1 inch of NMAS was between 5,990 and 6,990 psi for w/c=0.48, and the range for w/c= 0.38 was between 8,700 and 9,810 psi. In general, the lower the w/c, the higher the compressive strength [69]. It should be noted that because of the pandemic continuing the mixes were also delayed. Therefore, 28 days test results have been used in data analysis and in some cases if 90 days test results have been considered if enough data was available. Figure 25 shows the impact of lowering w/c ratio in parent concrete with NA.

Figure 25

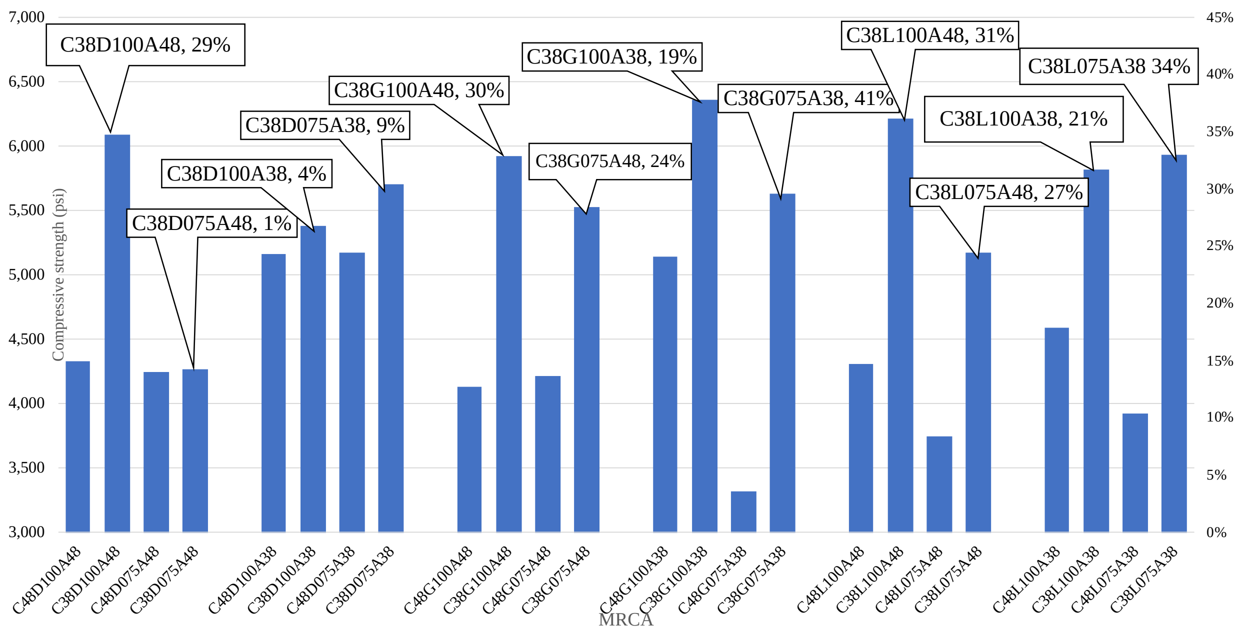
PC Compressive Strength Difference in Percentage vs. w/c Ratios



There is a benefit of using a low w/c ratio such as 0.38 in concrete with control RCA in terms of compressive strength. The impact of lowering the w/c ratio of concrete with control RCAs from 0.48 to 0.38 resulted in a concrete with a higher compressive strength as 22% on average when the NMAS and parent concrete w/c ratio were consistent. In this research, lowering the w/c ratio from 0.48 to 0.38 has shown that the 28 days compressive strength test results of w/c ratio of 0.38 was higher than concrete mixture with w/c ratio of 0.48. Also, it has been discovered that lowering w/c ratio can be more beneficial when the RCA is mixed with the new concrete having a lower w/c ratio compared to its relative parent concrete w/c ratio. For instance, after crushing the concrete blocks of G100A48 (parent concrete) with compressive strength of 5,210 psi, coarse control RCA was mixed in a new concrete with a w/c ratio of 0.48 (C48G100A48), while the parent concrete w/c ratio (A48) was similar to w/c ratio of new concrete with control RCA (C48). The result shows a lower strength as 4,310 psi since the mixture included control RCA with adhered mortar. However, mixing control RCA with a lower w/c ratio of 0.38 (C38G100A48) resulted in a higher strength as 5,920 psi, which is 30% higher than strength in w/c ratio 0.48. Also, 28 days old test results of lower w/c ratio were higher than its relative parent concrete strength with the same w/c ratio in 190 days. Figure 26 shows the strength improvement in lowering w/c ratio for control RCA samples.

Figure 26

Strength Improvement in Concrete with a Low w/c Ratio



Control RCA Compressive Strength. The compressive strength test results of concrete made with control RCA are discussed in two subsections. The first section is about the impact of w/c ratios of the parent concrete on the new concrete having 100%

RCA (control RCA). The second subsection is about the impact of other NA and parent concrete properties such as volume of RCA on new concrete mixture compression strength. Figure 27 shows the 1 inch control RCA test results of compressive strength, and Figure 28 shows the compressive test results of control RCA in ¾ inch.

Figure 27

Compressive Strength Test Results At 28, 90 Days Old, NMAS 1"

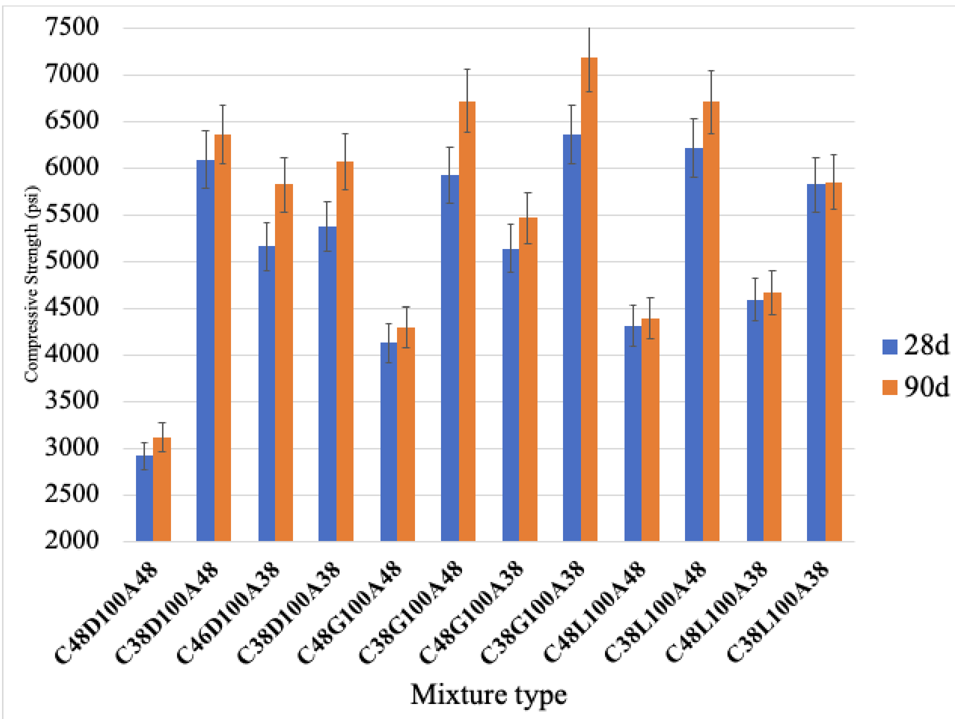
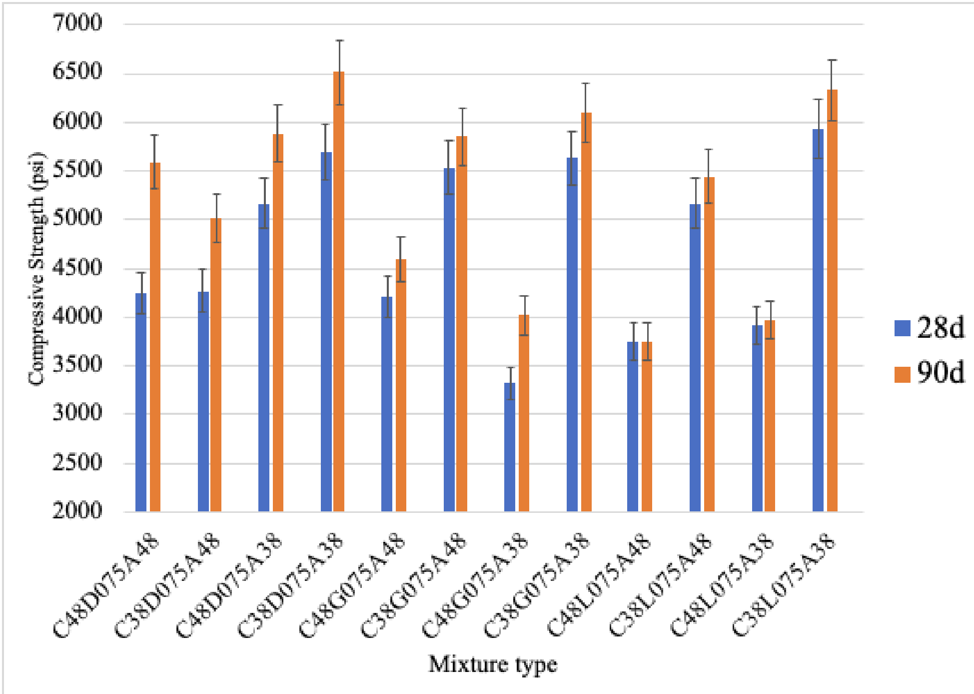


Figure 28

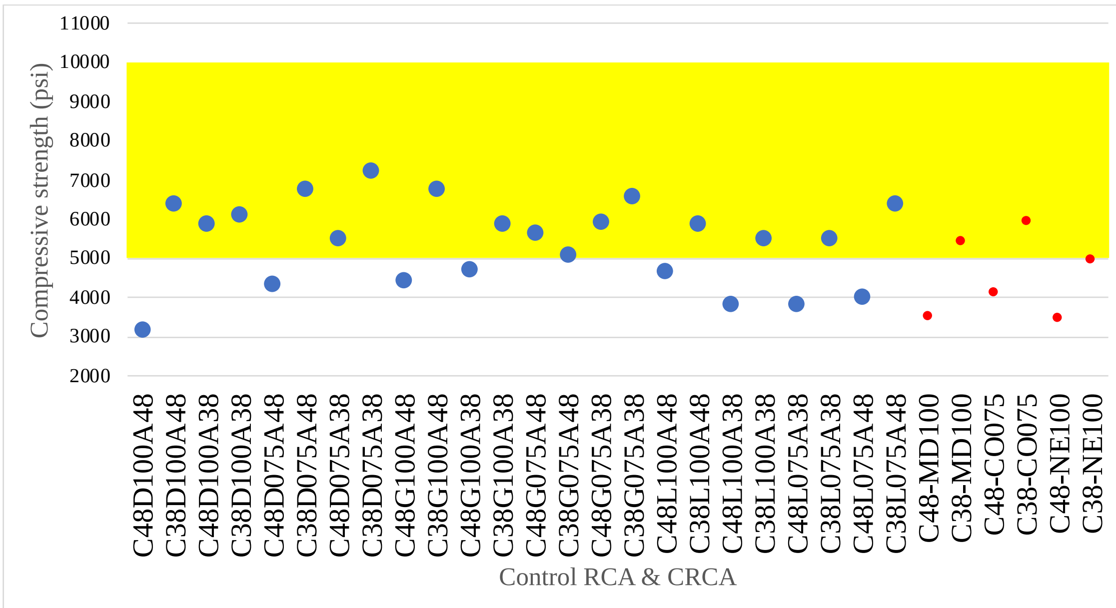
Compressive Strength Test Results At 28, 90 Days Old, NMAS ¾"



One of the study's objectives was to provide recommendations for designing concrete mixtures with 100% RCA based on the properties of RCA and the required mechanical properties of the new concrete. The concrete mixture design was targeted for a slump in 2 inch, air content for 6% and w/c ratios as of 0.38 and 0.48 in NMAS of 1 inch and ¾ inch, and the NA and RCA properties which is required for the mixture design. According to the mixture design, the results of compressive strength of concrete with 100% RCA in both control RCAs and CRCAs produced the strength in the range of parent concrete with natural aggregate. Figure 29 shows the results of control RCA in blue dots and CRCAs in red dots. The lower limit and upper limit of yellow bound shows the lowest and highest compressive strength of concrete with natural aggregate.

Figure 29

Compressive Strength of Control RCA and CRCA



The Impact of w/c Ratios of PC on Concrete with 100% Control RCA. In this study, there were two different w/c ratios in each parent concrete with natural aggregate (0.38 and 0.48). Control RCA from the parent concrete mixture with w/c=0.48 was mixed in new concrete in two w/c ratios (0.38 & 0.48). Also, control RCA from the parent concrete with w/c=0.38 was mixed in a new concrete with two w/c ratio (0.38 &0.48). In chapter two of this study, Table 5 shows the percentage reduction of compressive strength in new concrete with 100% RCA up to 22% reduction at 28 days old [76], and 15% strength reduction at the age of 90 days in previous studies.

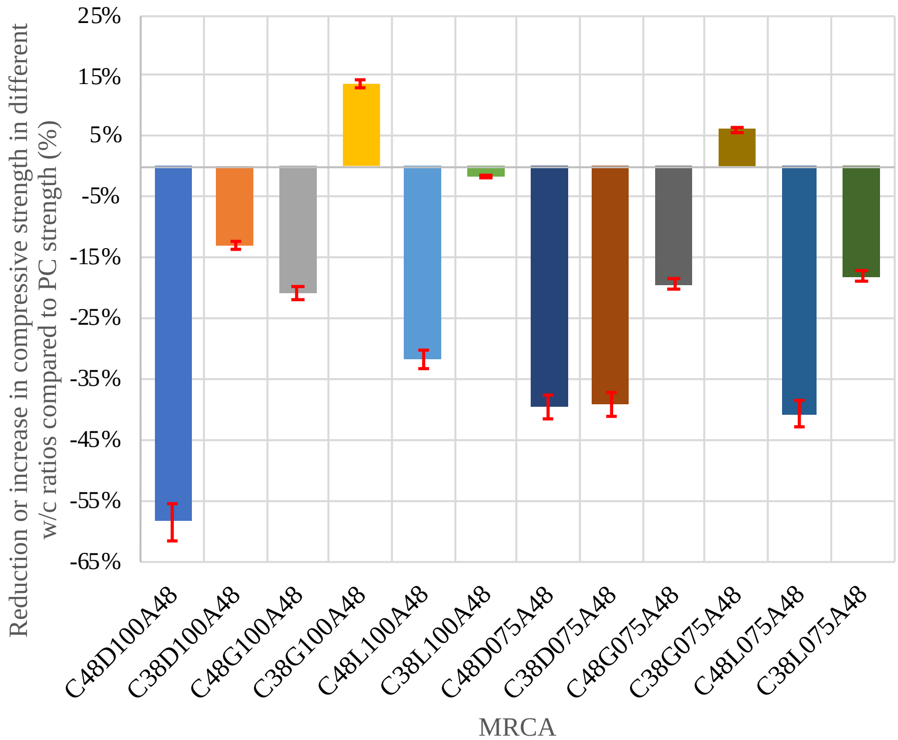
The compressive strength test results for control RCA samples with the same w/c ratio as parent concrete mixture design shows a compressive strength reduction of 34% in average (comparison between control RCA in 90 days old with parent concrete in 190 days old).For example, if coarse control RCA which is a RCA manufactured from a parent concrete G100A48 (5,210 psi compressive strength) used in a new concrete mixture with a w/c ratio of 0.48 and the same NMAS 1 inch (4,300 psi compressive strength), the strength result could show 17% reduction compared to the parent concrete. In other concrete with RCA in this study, the reduction was higher or lower. However, the average was 34%.

In this study, the comparison between compressive strength test results of parent concrete w/c 0.48 and NMAS 1 inch, and control RCA with w/c ratio of 0.38 in the same NMAS 1 inch shows an increase in strength as 9% in average. Therefore, new concrete incorporating 100% RCA with a lower w/c ratio compared to its parent concrete with a higher w/c ratio could result in a higher compressive strength. Other studies also have found the same results, which are shown in Table 5, Chapter 2. Figure 30 shows the reduction of compressive strength of control RCAs. Also, Table 34 in the appendix shows the results for each control RCA.

On the other hand, RCA produced from parent concrete with a lower w/c ratio as 0.38 which was used in new concrete mixture with low w/c ratio of 0.38, could result in 31% reduction in terms of compressive strength. The reason for reduction is because the parent concrete with a low w/c ratio had earned its highest strength with natural aggregate and in the new concrete mixture with 100% RCA with no additional strength improvement the results will always be lower than parent concrete compressive strength. For instance, RCA in a concrete mixture as C38L100A38 with a low w/c ratio will present a compressive strength of 5,850 psi. However, the results of parent concrete in w/c of 0.38 (L100A38) presented a high strength of 9,080 psi. Therefore, achieving close strength results to the relative parent concrete with NA where parent concrete presented a high strength test result could be very hard.

Figure 30

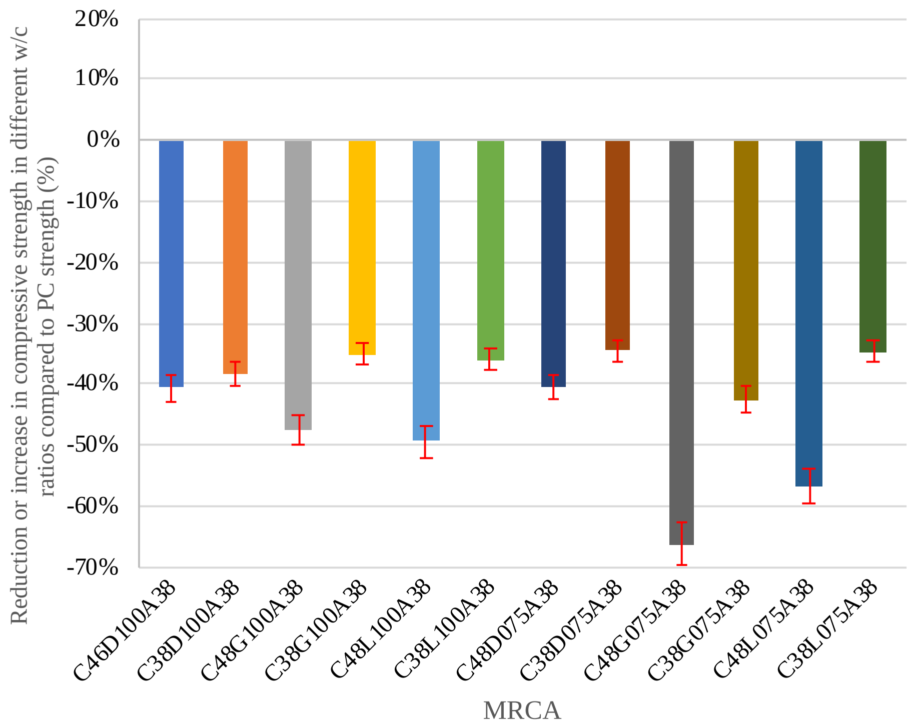
Compressive Strength Reduction of Control RCAs Concrete Mixtures



Mixing control RCA with w/c ratio of 0.48 while its parent concrete w/c ratio was 0.38 resulted in 42% on average compressive strength reduction compared to its parent concrete strength. Also, mixing control RCA with w/c ratio of 0.38 while its parent concrete w/c ratio was 0.38 resulted in 31% on average compressive strength reduction compared to its parent concrete strength. Therefore, even using lower w/c ratio in the case of parent concrete with a low w/c ratio as of 0.38 resulted in higher strength because of using a lower w/c ratio produced a lower reduction in compressive strength (41% reduction compared to 31% reduction). Figure 31 shows the compressive strength reduction of control RCA made of PC with w/c=0.38.

Figure 31

Compressive Strength Reduction of Control RCA Made of PC w/c=0.38



The compressive strength test results and comparison between parent concrete with control RCA shows that:

- Compressive strength of concrete with 100% RCA in the same NMAS and w/c ratio is lower than strength in parent concrete. However, the strength results showed that concrete with 100% RCA is necessary to achieve capable strength for concrete applications in industry. The range of compressive strength in the case of similar w/c ratio and NMAS in concrete with RCA is between 3,000 psi and 5,000 psi.
- Compressive strength of concrete with 100% RCA in lower w/c ratio than its parent concrete w/c ratio showed a suitable strength improvement of 9% where the NMAS is 1 inch in both concrete mixtures and only the w/c ratio is reduced. The results are important in industry where the highest strength of concrete with RCA is needed. The range of compressive strength in the case of similar NMAS but lower w/c ratio as 0.38 in concrete with RCA is between 6,000 psi and 7,000 psi.

NMAS Impact on Compressive Strength of Concrete with Control RCA. In general, a reduction in the natural aggregates' NMAS in concrete mix design makes the compressive strength of concrete higher because of less severe stress distributions surrounding the particles [116, 117, 118]. An insignificant trend was detected when control RCAs were used as the aggregate and the NMAS was reduced from 1 to ¾ inch. The results are shown in Table 23 and Figure 33. In Figure 34, reducing the NMAS from 1 inch to ¾ inch in concrete mixtures with the same w/c ratio had no substantial effect on the compressive strength values. Also, mixing concrete with a lower w/c ratio improves the strength along with reducing the NMAS. According to the small compressive strength improvement in case of using a smaller size of coarse aggregate, the results showed that engineers in industry can use 100% RCA in NMAS of 1 inch if smaller coarse aggregate was not available.

Table 23

Impact Of Reduction In NMAS On Control RCAs

CONTROL RCA	1 inch (28 d) strength	3/4 inch (28d) strength	compressive strength reduction or increase (%)
C48D075A48	2920	4130	29%
C38D075A48	6090	5920	-3%
C48D075A38	5160	5140	0%
C38D075A38	5380	6360	15%
C48G075A48	4310	4240	-2%
C38G075A48	6210	4270	-45%
C48G075A38	4590	5170	11%
C38G075A38	5820	5700	-2%
C48L075A38	4210	3750	-12%
C38L075A38	5530	5170	-7%
C48L075A48	3320	3920	15%
C38L075A48	5630	5930	5%

CRCA Compressive Strength. In this research, aggregate properties of three RCAs transported from MD, NE, CO with no history and mixture information were tested and the concrete mixture with 100% CRCA was evaluated in terms of fresh and hardened properties. The results of mixtures made with CRCAs' compressive strength with the results of control RCAs are shown in a different color in Figure 32.

Figure 32

Comparison Between CRCA and Control RCA Strength Results

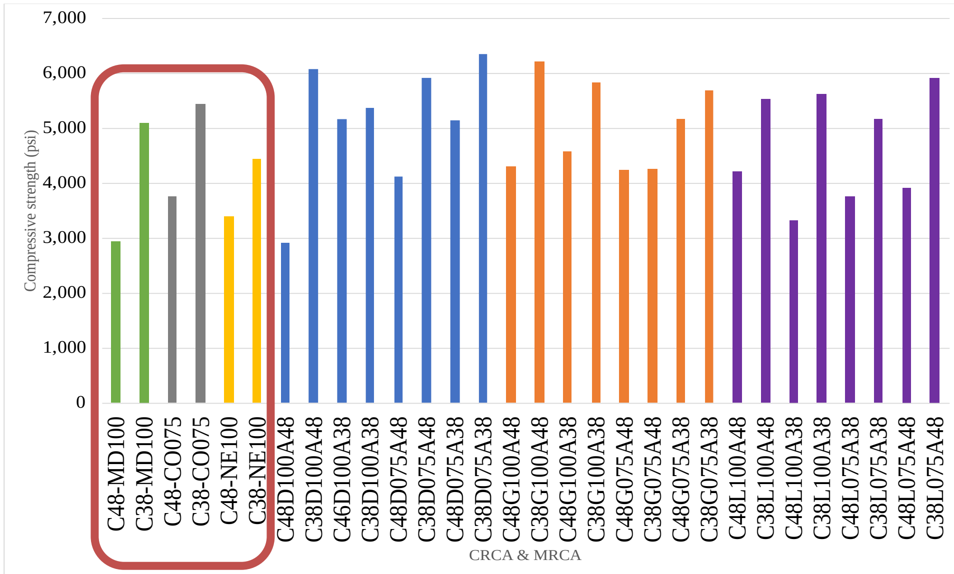
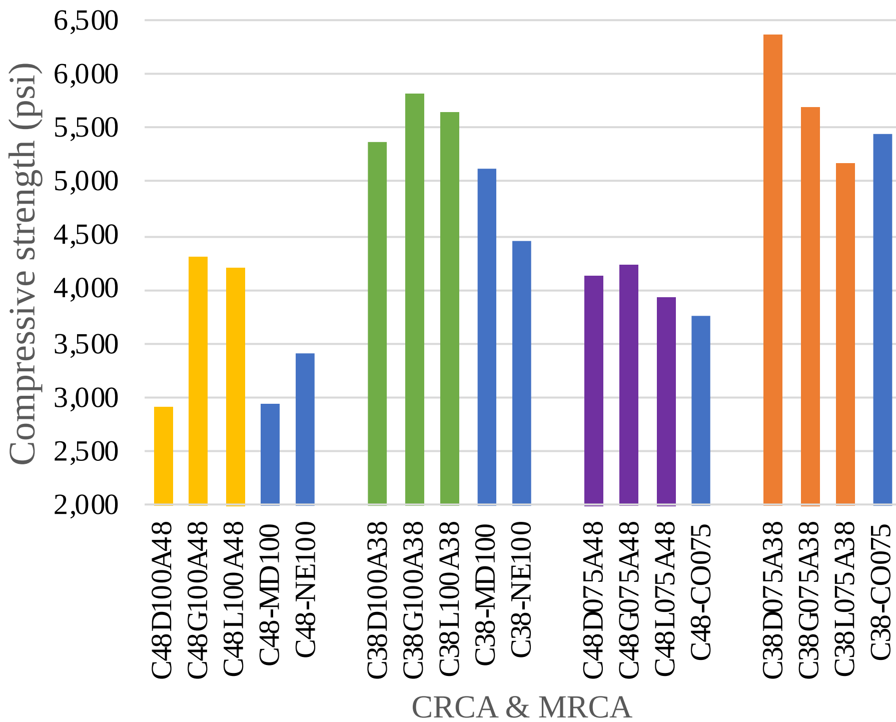


Figure 33 shows the compressive strength due to a similar w/c ratio between parent concrete and new concrete. In this chart, control RCA samples with the same w/c ratios of new concrete are compared with CRCAs. CRCA with a low w/c as of 0.38 could achieve 5,000 psi in a similar control RCA mixture proportion. Also, the highest compressive strength was achieved (5,500 psi) when CRCA in ¾ inch of NMAS was used in a similar control RCA mixture proportion. It is notable that RCA with no history of parent concrete mix proportion and W/C ratio is capable of achieving a high strength when mixed in an appropriate mixture proportion, small size of coarse aggregate, and lower w/c ratio.

Figure 33

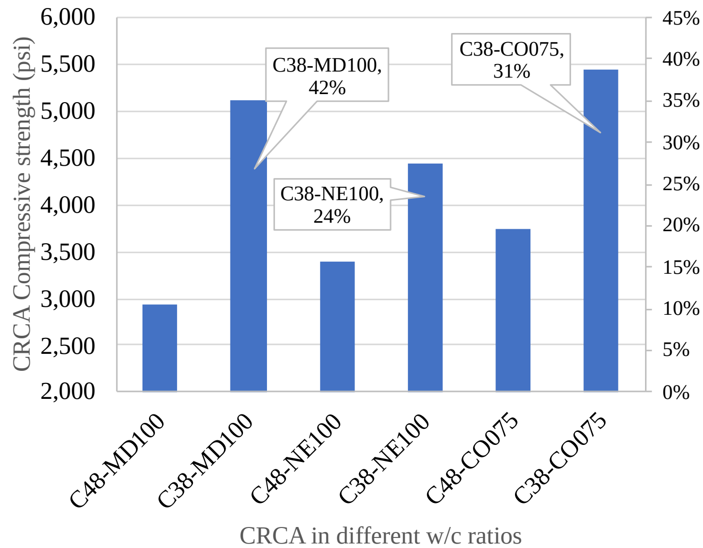
Similar w/c Ratio Results for Control RCA & CRCA



CRCA and w/c Ratio. In the previous section, the impact of changing the w/c ratio in concrete made from manufactured RCA was discussed. There is a similar relationship between the compressive strength of CRCA and lowering the w/c ratio in concrete mixture. Although CRCA is an aggregate with no history of parent concrete proportion or aggregate type, designing the new concrete mixture with a lower w/c ratio such as 0.38 resulted in increasing the compressive strength. If ACI.211.1-81 concrete mixture design guidelines for NA is being followed for a stockpile of RCA, one can evaluate the aggregate properties, target the slump for 2 inch, NMAS for 1 inch, and use a lower w/c ratio such as 0.38, which is presented in this study. This will produce a suitable compressive strength with many applications in construction due to range of strength between 3,000 psi and 6,000 psi. Figure 34 shows the relationship between CRCA and w/c ratios in percentage.

Figure 34

Relationship Between CRCA and w/c Ratios in Percentage

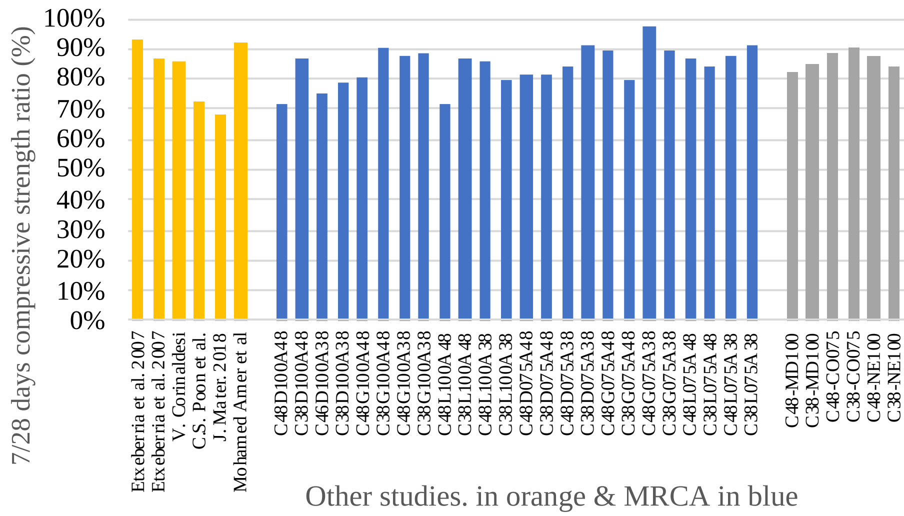


Achieving the Compressive Strength Target in Concrete with RCA in Early Age. In this research, due to the mixture proportions and concrete mix design, the compressive strength test results of 30 concrete mixes (control RCA & CRCA) tested at 7 days could achieve an average of 84% at 28 days compressive strength for the identical specimens (Min= 72% and Max= 97%). Also, control RCA specimens at 7 days of age achieved an average of 74% of compressive strength at 90 days (Min= 62% and Max= 87%). In the case of concrete with CRCA with a similar w/c ratio and mixture proportions the strength at 7 days was an average of 86% of the 28 day strength and 79%

of the 90 days strength. Figure 35 shows the ratio of 7 days compressive strength and 28 days for control RCA, CRCA, and other studies. Other studies findings in detail are shown in Table A13 in the Appendix A.

Figure 35

Ratio of Compressive Strength in 7 Days and 28 Days Age

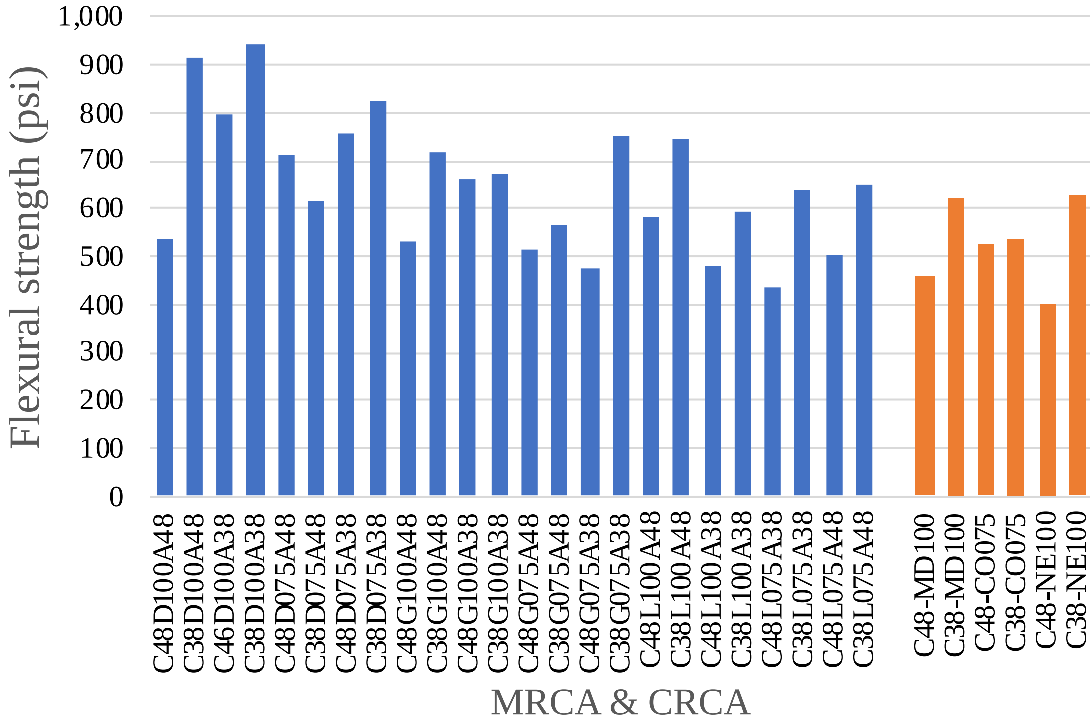


Flexural Strength

This research tested the flexural strength of control RCA and CRCA beams at 14 and 28 days of concrete aging. The results of control RCA and CRCA are shown in Figure 36. In this figure the flexural strengths are shown from high to low. Similar results are observed for concrete with CRCA and concrete with control RCA. The test results are shown in table A12 in the appendix A.

Figure 36

Flexural Strength of Control RCA (Blue) & CRCA (Orange)



NMAS of Control RCA Impact on Flexural Strength. In this study, an increase in NMAS from ¾ to 1 inch for control RCA shows 11% increase in flexural strength. Other studies also found that

the greater dimension of RCA are usually orientated along the longitudinal direction of th e prism specimen, which aids in the formation of a stronger connection with the surround ing mortar [111]. Figure 37 shows the impact of aggregate size on flexural strength of control RCA by percentage. Figure 38 shows the results of flexural strength for 1 inch and ¾ inch of concrete. Flexural strength test result is shown a benefit of concrete with 100% RCA when high strength is demanded and the larger NMAS of RCA is available.

C38G100A38 and C38L100A38 had a reduction in terms of having a higher volume of RCA in mixture proportion compared to the same w/c ratio of ¾ inch (for instance, C38G100A38 had RCA as 1513 pcy while C38G075A38 had RCA as 1448 pcy).

Figure 37

Percentage Change in Flexural Strength with Respect to NMAS

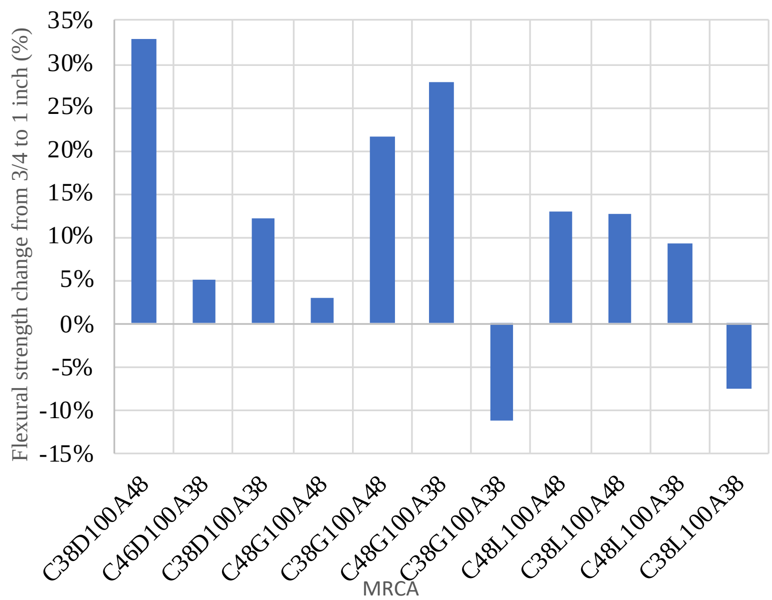
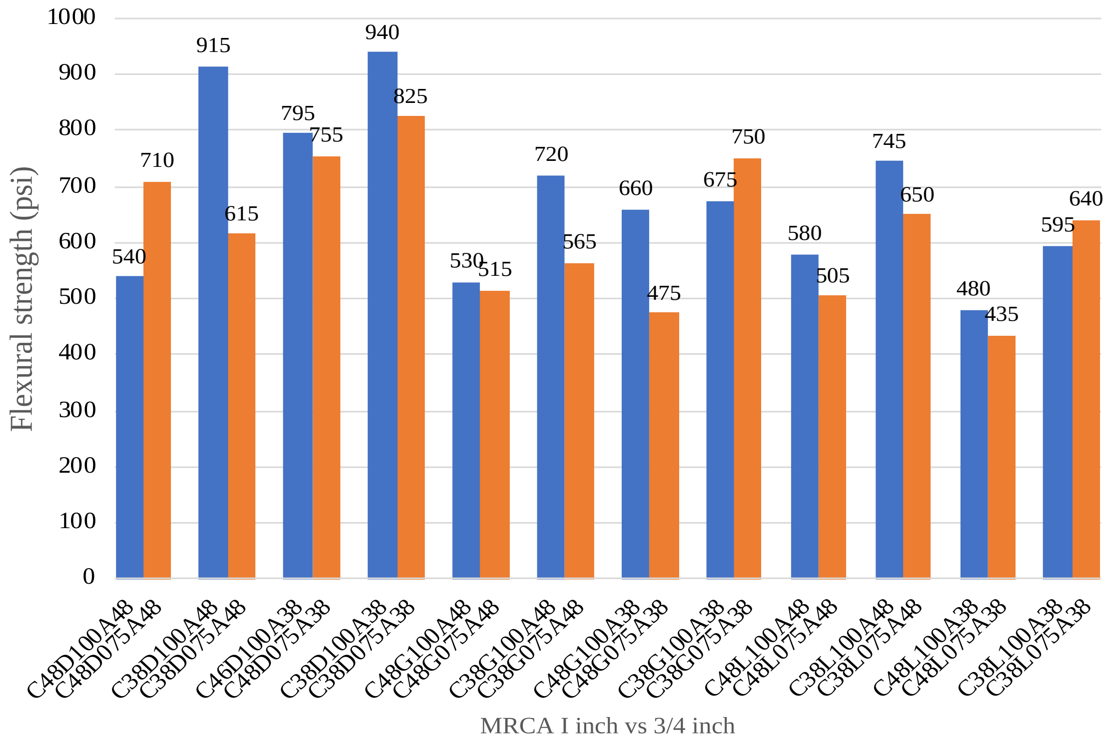


Figure 38

Flexural Strength for 1 inch and ¾ inch NMAS Concrete



W/C Ratio vs. Flexural Strength of Control RCA. In this study, the impact of the w/c ratio on the flexural strength of concrete was almost similar to compressive strength. Figure 39 shows the flexural strength of control RCA in different w/c ratios. The comparison between two types of new concrete showed 18% increase in flexural strength on average. The first type was new concrete with w/c ratio of 0.38 where its parent concrete had w/c ratio of 0.48. For instance, PC with a w/c ratio of 0.48 named D100A48 was mixed with a new concrete incorporating control RCA with a w/c ratio as of 0.38 named C38D100A48, and the results showed 18% increase in flexural strength. The second type was the new concrete with a w/c ratio 0.48 and its parent concrete w/c ratio 0.48 (example: C48D100A48). In other words, mixing RCA in a concrete mixture with a lower w/c could increase the flexural strength of concrete by 18%. Other studies found similar results where flexural strength falls as the w/c ratio rises, flexural strength was reduced by 2–14% when the water to cement ratio was raised from 0.4 to 0.5, the flexural strength of RCA mixes with the same cement amount decreased by 2–19%. Increased cement concentration results in a denser paste and a stronger transition zone, which enhances the concrete's flexural strength [80].

Figure 39

Flexural Strength of Control RCA in Different w/c Ratios

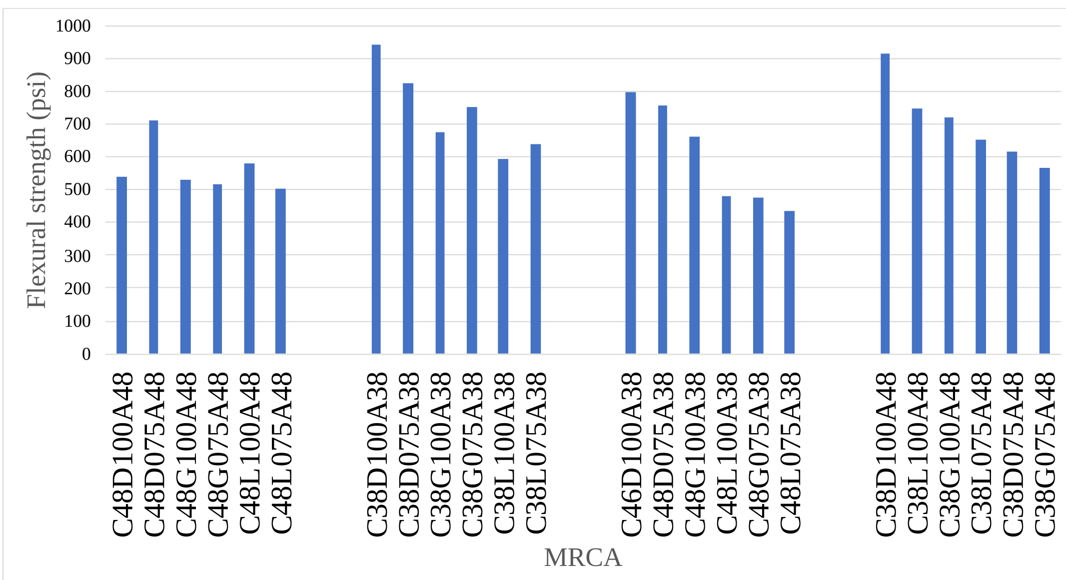
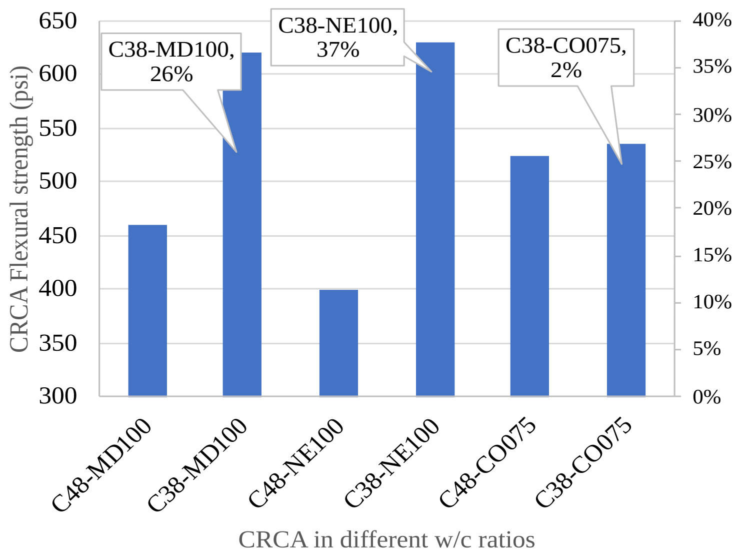


Figure 40 shows the impact of high and low w/c ratio on the flexural strength of CRCA concrete.

Figure 40

Impact of High and Low w/c Ratio on Flexural Strength of CRCA



Chapter 6

Summary and Conclusions

The goal of this research project was (a) to evaluate and characterize RCA from different sources and of different proportions, (b) to measure the mechanical properties of concrete incorporating 100% RCA as coarse aggregates, and (c) to evaluate how the RCA properties affect the properties of new concrete. According to the laboratory experimental findings and the subsequent statistical analyses, the following conclusions were drawn:

Mechanical Properties of Aggregate

- Evaluating RCA resistance to abrasion for the CRCA and control RCA indicates that RCA had resistance to abrasion ranging from 22 to 43%, which is in the range of natural aggregate (15% to 45%).
- There is a significant impact of natural aggregate L.A. abrasion loss on manufactured recycled concrete aggregate. The higher NA abrasion, the higher RCA abrasion.
- Evaluating the CRCA and control RCA which was manufactured in this research indicates that RCA has a higher finer mass loss (%) than natural aggregate that has an effect on aggregate degradation and fresh slump properties.
- Evaluating the selected commercial RCA from other states and control RCAs which was manufactured from parent concrete with selected natural aggregate for this study (dolomite, limestone, granite) indicates that CRCA, which was randomly selected, had higher fine mass loss (%) test results than control RCA.

- The impact of particles finer than 75-µm on compressive strength was not significant. In this study, the range of finer particles mass loss of control RCAs up to 1.25% had a compressive strength range between 3,000 to 6,000 psi. CRCAs had a higher mass loss by washing aggregate as high as 4.43%. However, mixing a CRCA in a lower w/c ratio as 0.38 produced a compressive strength of 5,000 psi while strength of w/c ratio of 0.48 for the same CRCA produced a compressive strength as 3,000 psi.
- Control RCAs and CRCAs properties which were selected specifically for this study, upon review, could help engineers in industry to compare their aggregates properties to predict the concrete strength if the type of aggregate or other related properties of RCA are similar to RCAs in this study.

Mechanical Properties of Concrete

- The results of compressive strength test on concrete with 100% RCA at 28 days old with w/c ratio of 0.48 and NMAS 1 inch achieved 5,000 psi. The results can encourage engineers in industry to use 100% RCA with the specific mixture design target and take advantage of RCA in suitable strength.
- The results of a compressive strength test on concrete with 100% RCA at 28 days old with w/c ratio of 0.38 and NMAS 1 inch achieved 6,000 psi. The results will encourage concrete mixtures designers in industry to use a lower w/c ratio in concrete mixture to achieve higher compressive strength.
- The compressive strength test on concrete with 100% RCA with w/c ratio of 0.38 and NMAS ¾ inch at 90 days old achieved 7,200 psi. This strength has applications in concrete construction projects which is equal to concrete with NA.

- This study recommends using a lower w/c ratio as 0.38 to achieve a suitable compressive strength as 6,000 psi in order to provide the concrete construction requirement.
- Compressive strength of control RCAs have shown that there is no significant impact of reducing NMAS from 1 inch to ¾ inch.
- The larger coarse aggregate (NMAS 1 inch) had a higher flexural strength in average 11% since the greater dimension of RCA is usually orientated along the longitudinal direction of the prism specimen, which aids in the formation of a stronger connection with the surrounding mortar.

Future Work

This study was part of a comprehensive research of Classification and Production of Recycled Concrete Aggregates Based on Concrete Performance. The mechanical properties of manufactured RCA and commercial RCA were studied, and through field testing, the following specific topics can be observed or evaluated:

- Three types of CRCAs were obtained and tested to compare the properties of concrete mixtures with control RCA to commercial RCA. Collecting more CRCA and using them in new concrete to compare with the result of concrete mixes with control RCA will further validate the present results
- Evaluating the alkali-silica reaction and cyclic freezing and thawing of concrete with control RCA will be beneficial in identifying the suitability of the concrete for different environments.

- Determining the properties of concrete with 100% RCA in a wide range of w/c ratios such as 0.3, 0.5, or 0.7, and different NMASs will help to improve the accuracy of RCA properties prediction in new concrete mixtures.

References

[1] Vivian W. Y. Tam, M. Soomro, and A. C. J. Evangelista, "A review of recycled aggregate in concrete applications (2000–2017)," *Constr. Build. Mater.*, vol. 172, pp. 272–292, May 2018, doi: 10.1016/j.conbuildmat.2018.03.240.

[2] G. K. Attri, R. C. Gupta, and S. Shrivastava, "Impact of recycled concrete aggregate on mechanical and durability properties of concrete paver blocks," *Mater. Today Proc.*, vol. 42, pp. 975–981, Jan. 2021, doi: 10.1016/j.matpr.2020.11.977.

[3] "Recycling-Concrete-Pavement-ACPA.pdf." Accessed: Sep. 19, 2021. [Online]. Available: https://www.antigoconstruction.com/wp-content/uploads/Recycling-Concrete-Pavement-ACPA.pdf

[4] "555R-01 Removal and Reuse of Hardened Concrete," p. 26.

[5] "Comparative environmental assessment of natural and recycled aggregate concrete - ScienceDirect." https://www.sciencedirect.com/science/article/pii/S0956053X10002217 (accessed Sep. 19, 2021).

[6] J. M. V. Gómez-Soberón, "Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study," *Cem. Concr. Res.*, vol. 32, no. 8, pp. 1301–1311, Aug. 2002, doi: 10.1016/S0008-8846(02)00795-0.

[7] H. J. Halm, "CONCRETE RECYCLING," *Transp. Res. News*, no. 89, 1980, Accessed: Sep. 19, 2021. [Online]. Available: https://trid.trb.org/view/159773

[8] "Case Histories | Construction & Demolition Recycling Association." https://cdrecycling.org/materials/concrete/case-histories/ (accessed Oct. 26, 2021).

[9] J. T. Smith, "Recycled Concrete Aggregate – A Viable Aggregate Source For Concrete Pavements," p. 224.

[10] "Study on the influence of attached mortar content on the properties of recycled concrete aggregate - ScienceDirect." https://www.sciencedirect.com/science/article/pii/S0950061808001086 (accessed Sep. 19, 2021).

[11] N. Kisku, H. Joshi, M. Ansari, S. K. Panda, S. Nayak, and S. C. Dutta, "A critical review and assessment for usage of recycled aggregate as sustainable construction material," *Constr. Build. Mater.*, vol. 131, pp. 721–740, Jan. 2017, doi: 10.1016/j.conbuildmat.2016.11.029.

[12] V. Shah, A. Aijaz, K. Naidu, S. Francis, and K. Kayam, "Waste Aggregate in Concrete Pavement – A Review," vol. 01, pp. 2455–7137, Jan. 2017.

[13] K. P. Verian, W. Ashraf, and Y. Cao, “Properties of recycled concrete aggregate and their influence in new concrete production,” *Resour. Conserv. Recycl.*, vol. 133, pp. 30–49, Jun. 2018, doi: 10.1016/j.resconrec.2018.02.005.

[14] C. S. Poon, Z. H. Shui, L. Lam, H. Fok, and S. C. Kou, “Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete,” *Cem. Concr. Res.*, vol. 34, no. 1, pp. 31–36, Jan. 2004, doi: 10.1016/S0008-8846(03)00186-8.

[15] G. Fathifazl, A. Abbas, A. G. Razaqpur, O. B. Isgor, B. Fournier, and S. Foo, “New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate,” *J. Mater. Civ. Eng.*, vol. 21, no. 10, pp. 601–611, Oct. 2009, doi: 10.1061/(ASCE)0899-1561(2009)21:10(601).

[16] “Influence of Fly Ash as Cement Replacement on the Properties of Recycled Aggregate Concrete | Journal of Materials in Civil Engineering | Vol 19, No 9.” https://ascelibrary-org.ezproxy.rowan.edu/doi/full/10.1061/%28ASCE%290899-1561%282007%2919%3A9%28709%29 (accessed Sep. 19, 2021).

[17] K. Y. Ann, H. Y. Moon, Y. B. Kim, and J. Ryou, “Durability of recycled aggregate concrete using pozzolanic materials,” *Waste Manag.*, vol. 28, no. 6, pp. 993–999, Jan. 2008, doi: 10.1016/j.wasman.2007.03.003.

[18] J. Xiao, J. Li, and Ch. Zhang, “Mechanical properties of recycled aggregate concrete under uniaxial loading,” *Cem. Concr. Res.*, vol. 35, no. 6, pp. 1187–1194, Jun. 2005, doi: 10.1016/j.cemconres.2004.09.020.

[19] C. Zega, Y. Villagrán-Zaccardi, and A. Maio, “Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates,” *Mater. Struct.*, vol. 43, pp. 195–202, Jan. 2010, doi: 10.1617/s11527-009-9480-4.

[20] D. B. Cleary, “FINAL REPORT January, 2013,” p. 100.

[21] M. B. Snyder, J. M. Vandenbossche, K. D. Smith, and M. Wade, “Synthesis on Recycled Concrete Aggregate. Interim Report-Task A,” *Fed. Highw. Adm. FHWA Wash. DC*, 1994.

[22] T. C. Hansen and H. Narud, “Strength of Recycled Concrete Made From Crushed Concrete Coarse Aggregate,” *Concr. Int.*, vol. 5, no. 1, pp. 79–83, Jan. 1983.

[23] “Examining the Variability of Recycled Concrete Aggregate Properties,” presented at the 4th International Conference on Advances in Agricultural, Biological & Ecological Sciences, Dec. 2016. doi: 10.15242/IICBE.DIR1216403.

[24] K. P. Verian, N. M. Whiting, J. Olek, J. Jain, M. B. Snyder, and Purdue University. Joint Transportation Research Program, “Using recycled concrete as aggregate in concrete pavements to reduce materials cost.,” FHWA/IN/JTRP-2013/18, Aug. 2013. Accessed: Sep. 19, 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/26862

[25] H. Wen, D. I. McLean, and K. Willoughby, “Evaluation of Recycled Concrete as Aggregates in New Concrete Pavements,” *Transp. Res. Rec.*, vol. 2508, no. 1, pp. 73–78, Jan. 2015, doi: 10.3141/2508-09.

[26] A. Ait Mohamed Amer, K. Ezziane, A. Bougara, and M. Adjoudj, “Rheological and mechanical behavior of concrete made with pre-saturated and dried recycled concrete aggregates,” *Constr. Build. Mater.*, vol. 123, pp. 300–308, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.06.107.

[27] R. Kurda, J. de Brito, and J. D. Silvestre, “Influence of recycled aggregates and high contents of fly ash on concrete fresh properties,” *Cem. Concr. Compos.*, vol. 84, pp. 198–213, Nov. 2017, doi: 10.1016/j.cemconcomp.2017.09.009.

[28] W. Khaliq and Taimur, “Mechanical and physical response of recycled aggregates high-strength concrete at elevated temperatures,” *Fire Saf. J.*, vol. 96, pp. 203–214, Mar. 2018, doi: 10.1016/j.firesaf.2018.01.009.

[29] A. Abedalqader, N. Shatarat, A. Ashteyat, and H. Katkhuda, “Influence of temperature on mechanical properties of recycled asphalt pavement aggregate and recycled coarse aggregate concrete,” *Constr. Build. Mater.*, vol. 269, p. 121285, Feb. 2021, doi: 10.1016/j.conbuildmat.2020.121285.

[30] M. Arezoumandi, A. Smith, J. S. Volz, and K. H. Khayat, “An experimental study on flexural strength of reinforced concrete beams with 100% recycled concrete aggregate,” *Eng. Struct.*, vol. 88, pp. 154–162, Apr. 2015, doi: 10.1016/j.engstruct.2015.01.043.

[31] H. Katkhuda and N. Shatarat, “Improving the mechanical properties of recycled concrete aggregate using chopped basalt fibers and acid treatment,” *Constr. Build. Mater.*, vol. 140, pp. 328–335, Jun. 2017, doi: 10.1016/j.conbuildmat.2017.02.128.

[32] H. Mefteh, O. Kebaïli, H. Oucief, L. Berredjem, and N. Arabi, “Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete,” *J. Clean. Prod.*, vol. 54, pp. 282–288, Sep. 2013, doi: 10.1016/j.jclepro.2013.05.009.

[33] “Influence of water-reducing admixtures on the mechanical performance of recycled concrete - ScienceDirect.” https://www.sciencedirect.com/science/article/pii/S0959652613004034 (accessed Sep. 19, 2021).

[34] J. Han, S. C. Thakur, O. Chong, R. L. Parsons, and E. and A. E. University of Kansas. Dept. of Civil, “Laboratory evaluation of characteristics of recycled asphalt pavement in Kansas.,” K-TRAN: KU-09-2, Sep. 2011. Accessed: Sep. 20, 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/23380

[35] Transportation Research Board and National Academies of Sciences, Engineering, and Medicine, *Aggregate Properties and the Performance of Superpave-Designed Hot-Mix Asphalt*. Washington, DC: The National Academies Press, 2005. doi: 10.17226/13844.

[36]“NovaChip | WSDOT.” https://wsdot.wa.gov/tags/novachip (accessed Sep. 20, 2021).

[37] L. F. R. Miranda and S. M. S. Selmo, “CDW recycled aggregate renderings: Part I – Analysis of the effect of materials finer than 75μm on mortar properties,” *Constr. Build. Mater.*, vol. 20, no. 9, pp. 615–624, Nov. 2006, doi: 10.1016/j.conbuildmat.2005.02.025.

[38] V. Corinaldesi and G. Moriconi, “Influence of mineral additions on the performance of 100% recycled aggregate concrete,” *Constr. Build. Mater.*, vol. 23, no. 8, pp. 2869–2876, Aug. 2009, doi: 10.1016/j.conbuildmat.2009.02.004.

[39] G. Kumar Attri, R. C. Gupta, and S. Shrivastava, “Effect of demolished concrete and stone crusher dust on properties of M−40 grade paver blocks,” *Mater. Today Proc.*, vol. 44, pp. 4330–4336, Jan. 2021, doi: 10.1016/j.matpr.2020.10.553.

[40] M. G. Alexander, “Aggregates and the Deformation Properties of Concrete,” *Mater. J.*, vol. 93, no. 6, pp. 569–577, Nov. 1996, doi: 10.14359/9863.

[41] “compass.” Accessed: Sep. 20, 2021. [Online]. Available: https://compass.astm.org/document/?contentCode=ASTM%7CC0136_C0136M-19%7Cen-US

[42] C09 Committee, “Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete,” ASTM International. doi: 10.1520/C0138_C0138M-17A.

[43] K. Marar and Ö. Eren, “Effect of cement content and water/cement ratio on fresh concrete properties without admixtures,” *Int J Phys Sci*, p. 14.

[44] J. R. Roesler and J. G. Huntley, “PERFORMANCE OF I-57 RECYCLED CONCRETE PAVEMENTS,” p. 89.

[45] R. Kurda, J. de Brito, and J. D. Silvestre, "Combined influence of recycled concrete aggregates and high contents of fly ash on concrete properties," *Constr. Build. Mater.*, vol. 157, pp. 554–572, Dec. 2017, doi: 10.1016/j.conbuildmat.2017.09.128.

[46] C09 Committee, "Test Method for Slump of Hydraulic-Cement Concrete," ASTM International. doi: 10.1520/C0143_C0143M-20.

[47] "Performance of rigid pavements containing recycled concrete aggregates - ProQuest. " https://www.proquest.com/openview/f43e44fee77b6907d600568f4c8c5e3a/1?pq-origsite=gscholar&cbl=18750 (accessed Sep. 20, 2021).

[48] J. Liu and B. Chen, "Property of High Strength Concrete Made with Field-Demolished Concrete Aggregates," presented at the Transportation Research Board 87th Annual MeetingTransportation Research Board, 2008. Accessed: Sep. 20, 2021. [Online]. Available: https://trid.trb.org/view/848193

[49] İ. B. Topçu, "Properties of heavyweight concrete produced with barite," *Cem. Concr. Res.*, vol. 33, no. 6, pp. 815–822, Jun. 2003, doi: 10.1016/S0008-8846(02)01063-3.

[50] C09 Committee, "Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method," ASTM International. doi: 10.1520/C0173_C0173M-16.

[51] "AASHTO - Highway Safety Manual - Contact." http://www.highwaysafetymanual.org/Pages/Contact.aspx (accessed Sep. 20, 2021).

[52] K. Obla, H. Kim, and C. Lobo, *Crushed Returned Concrete as Aggregates for New*. 2007.

[53] M. J. Wade, G. D. Cuttell, J. M. Vandenbossche, H. T. Yu, K. D. Smith, and M. B. Snyder, "PERFORMANCE OF CONCRETE PAVEMENTS CONTAINING RECYCLED CONCRETE AGGREGATE," Art. no. FHWA-RD-96-164, Mar. 1997, Accessed: Sep. 20, 2021. [Online]. Available: https://trid.trb.org/view/478512

[54] A. Katz, "Properties of concrete made with recycled aggregate from partially hydrated old concrete," *Cem. Concr. Res.*, vol. 33, no. 5, pp. 703–711, May 2003, doi: 10.1016/S0008-8846(02)01033-5.

[55] P. R. Speare and B. Ben-Othman, "Recycled concrete coarse aggregates and their influence on durability," in *Concrete 2000; Economic and durable construction through excellence: Proceedings of the international conference held at the University of Dundee, Scotland, UK*, 1993, pp. 419–432.

[56] R. M. Salem, E. G. Burdette, and N. M. Jackson, “Resistance to freezing and thawing of recycled aggregate concrete,” *Mater. J.*, vol. 100, no. 3, pp. 216–221, 2003.

[57] M. F. M. Zain, M. Safiuddin, and K. M. Yusof, “A study on the properties offreshly mixed high performance concrete,” *Cem. Concr. Res.*, vol. 29, no. 9, pp. 1427–1432, Sep. 1999, doi: 10.1016/S0008-8846(99)00108-8.

[58] V. Sampebulu, “Influence of High Temperatures on the Workability of Fresh Ready-Mixed Concrete,” *J. Eng. Technol. Sci.*, vol. 44, no. 1, Art. no. 1, 2012, doi: 10.5614/itbj.eng.sci.2012.44.1.2.

[59] R. Movassaghi, “Durability of reinforced concrete incorporating recycled concrete as aggregate (RCA),” Master’s Thesis, University of Waterloo, 2006.

[60] A. Masood, T. Ahmad, M. Arif, and F. Mahdi, “Waste management strategies for concrete,” *Environ. Eng. Policy*, vol. 3, no. 1, pp. 15–18, Mar. 2001, doi: 10.1007/s100220100034.

[61] İ. B. Topçu and S. Şengel, “Properties of concretes produced with waste concrete aggregate,” *Cem. Concr. Res.*, vol. 34, no. 8, pp. 1307–1312, Aug. 2004, doi: 10.1016/j.cemconres.2003.12.019.

[62] Y.-H. Lin, Y.-Y. Tyan, T.-P. Chang, and C.-Y. Chang, “An assessment of optimal mixture for concrete made with recycled concrete aggregates,” *Cem. Concr. Res.*, vol. 34, no. 8, pp. 1373–1380, Aug. 2004, doi: 10.1016/j.cemconres.2003.12.032.

[63] “PWTB 200-1-27 Reuse of Concrete Materials From Building Demolition | WBDG - Whole Building Design Guide.” https://www.wbdg.org/ffc/army-coe/public-works-technical-bulletins-pwtb/pwtb-200-1-27 (accessed Aug. 17, 2021).

[64] Y. J. Li, S. Q. Zhou, J. Yin, and J. Li, “Study on the Workability and Mechanical Properties of Recycled Aggregate Concrete Containing Ultra-Fine Fly Ash,” *Key Eng. Mater.*, vol. 302–303, pp. 314–320, 2006, doi: 10.4028/www.scientific.net/KEM.302-303.314.

[65] “(2) Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete | Request PDF.” https://www.researchgate.net/publication/223597298_Influence_of_amount_of_recycled_coarse_aggregates_and_production_process_on_properties_of_recycled_aggregate_concrete (accessed Sep. 20, 2021).

[66] L. Zhang, Y. Zhang, C. Liu, L. Liu, and K. Tang, “Study on microstructure and bond strength of interfacial transition zone between cement paste and high-performance lightweight aggregates prepared from ferrochromium slag,” *Constr. Build. Mater.*, vol. C, no. 142, pp. 31–41, 2017, doi: 10.1016/j.conbuildmat.2017.03.083.

[67] D. Kong, T. Lei, J. Zheng, C. Ma, J. Jiang, and J. Jiang, "Effect and mechanism of surface-coating pozzalanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete," *Constr. Build. Mater.*, vol. 24, no. 5, pp. 701–708, May 2010, doi: 10.1016/j.conbuildmat.2009.10.038.

[68] V. Tam, X. Gao, and C. Tam, "Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach," *Cem. Concr. Res.*, vol. 35, pp. 1195–1203, Jun. 2005, doi: 10.1016/j.cemconres.2004.10.025.

[69] R. Kurad, J. D. Silvestre, J. de Brito, and H. Ahmed, "Effect of incorporation of high volume of recycled concrete aggregates and fly ash on the strength and global warming potential of concrete," *J. Clean. Prod.*, vol. 166, pp. 485–502, Nov. 2017, doi: 10.1016/j.jclepro.2017.07.236.

[70] J. Brito, "Mechanical behaviour of concrete made with fine recycled concrete aggregates," *Cem. Concr. Compos.*, Accessed: Sep. 20, 2021. [Online]. Available: https://www.academia.edu/30668717/Mechanical_behaviour_of_concrete_made_with_fine_recycled_concrete_aggregates

[71] M. Tavakoli and P. Soroushian, "Strengths of Recycled Aggregate Concrete Made Using Field-Demolished Concrete as Aggregate," *Mater. J.*, vol. 93, no. 2, pp. 178–181, Mar. 1996, doi: 10.14359/9802.

[72] A. K. Padmini, K. Ramamurthy, and M. S. Mathews, "Influence of parent concrete on the properties of recycled aggregate concrete," *Constr. Build. Mater.*, vol. 23, no. 2, pp. 829–836, Feb. 2009, doi: 10.1016/j.conbuildmat.2008.03.006.

[73] I. B. Topçu, "Physical and mechanical properties of concretes produced with waste concrete," *Cem. Concr. Res.*, vol. 27, no. 12, pp. 1817–1823, Dec. 1997, doi: 10.1016/S0008-8846(97)00190-7.

[74]S. Lotfi, J. Deja, P. Rem, R. Mróz, E. van Roekel, and H. van der Stelt, "Mechanical recycling of EOL concrete into high-grade aggregates," *Resour. Conserv. Recycl.*, vol. 87, pp. 117–125, Jun. 2014, doi: 10.1016/j.resconrec.2014.03.010.

[75] "Utilisation of Recycled Aggregate as Coarse Aggregate in Concrete | Journal of Civil Engineering, Science and Technology." https://publisher.unimas.my/ojs-training/index.php/JCEST/article/view/60 (accessed Sep. 20, 2021).

[76] S. C. Kou, C. S. Poon, and D. Chan, "Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete," *Mater. Struct.*, vol. 41, no. 7, pp. 1191–1201, Aug. 2008, doi: 10.1617/s11527-007-9317-y.

[77] C. Zhou and Z. Chen, "Mechanical properties of recycled concrete made with different types of coarse aggregate," *Constr. Build. Mater.*, vol. 134, pp. 497–506, Mar. 2017, doi: 10.1016/j.conbuildmat.2016.12.163.

[78] R. Zaharieva, F. Buyle-Bodin, F. Skoczylas, and E. Wirquin, “Assessment of the surface permeation properties of recycled aggregate concrete,” *Cem. Concr. Compos.*, vol. 25, no. 2, pp. 223–232, Feb. 2003, doi: 10.1016/S0958-9465(02)00010-0.

[79] T. Yaowarat, A. Arulrajah, M. Mirzababaei, A. Safuan, and A. S. A Rashid, “Compressive and Flexural Strength of Polyvinyl Alcohol-Modified Pavement Concrete Using Recycled Concrete Aggregates,” *J. Mater. Civ. Eng.*, vol. 30, p. 04018046, Jan. 2018, doi: 10.1061/(ASCE)MT.1943-5533.0002233.

[80] J. Thomas, N. N. Thaickavil, and P. M. Wilson, “Strength and durability of concrete containing recycled concrete aggregates,” *J. Build. Eng.*, vol. 19, pp. 349–365, Sep. 2018, doi: 10.1016/j.jobe.2018.05.007.

[81] L. Butler, J. S. West, and S. L. Tighe, “Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength,” *Constr. Build. Mater.*, vol. 47, pp. 1292–1301, Oct. 2013, doi: 10.1016/j.conbuildmat.2013.05.074.

[82] C09 Committee, “Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),” ASTM International. doi: 10.1520/C0078_C0078M-21.

[83] A. S. Brand, J. R. Roesler, and A. Salas, “Initial moisture and mixing effects on higher quality recycled coarse aggregate concrete,” *Constr. Build. Mater.*, vol. 79, pp. 83–89, Mar. 2015, doi: 10.1016/j.conbuildmat.2015.01.047.

[84] M. Gesoglu, E. Güneyisi, H. Ö. Öz, I. Taha, and M. T. Yasemin, “Failure characteristics of self-compacting concretes made with recycled aggregates,” *Constr. Build. Mater.*, vol. 98, pp. 334–344, Nov. 2015, doi: 10.1016/j.conbuildmat.2015.08.036.

[85] S. I. Mohammed and K. B. Najim, “Mechanical strength, flexural behavior and fracture energy of Recycled Concrete Aggregate self-compacting concrete,” *Structures*, vol. 23, pp. 34–43, Feb. 2020, doi: 10.1016/j.istruc.2019.09.010.

[86] C01 Committee, “Specification for Portland Cement,” ASTM International. doi: 10.1520/C0150_C0150M-20.

[87] “Keystone Type I MILL TESTS AND CERTS 2012.pdf.” Accessed: Sep. 20, 2021. [Online]. Available: http://www.cavabuilding.com/wp-content/uploads/2014/04/Keystone%20Type%20I%20MILL%20TESTS%20AND%20CERTS%202012.pdf

[88] “Welcome to Salomone Redi Mix.” http://www.salomoneredimix.com/index.php (accessed Sep. 20, 2021).

[89] C09 Committee, “Test Method for Sieve Analysis of Fine and Coarse Aggregates,” ASTM International. doi: 10.1520/C0136_C0136M-19.

[90] “Gilson Test-Master® Testing Screens,” *GlobalGilson.com*. https://www.globalgilson.com/gilson-test-master-testing-screens (accessed Sep. 20, 2021).

[91] “Sand Stone & Gravel,” *Frank J Fazzio & Sons Inc*. http://fazzioconcrete.com/materials/ (accessed Sep. 20, 2021).

[92] C09 Committee, “Specification for Air-Entraining Admixtures for Concrete,” ASTM International. doi: 10.1520/C0260_C0260M-10AR16.

[93] “Sika USA.” https://usa.sika.com/en/home.html (accessed Sep. 20, 2021).

[94] “ACI PRC-211.1-91: Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (Reapproved 2009).” https://www.concrete.org/store/productdetail.aspx?ItemID=211191&Language=English&Units=US_Units (accessed Sep. 20, 2021).

[95] C09 Committee, “Practice for Making and Curing Concrete Test Specimens in the Laboratory,” ASTM International. doi: 10.1520/C0192_C0192M-19.

[96] C09 Committee, “Practice for Making and Curing Concrete Test Specimens in the Field,” ASTM International. doi: 10.1520/C0031_C0031M-21A.

[97] “Perfa-Cure Concrete Curing Boxes,” *GlobalGilson.com*. https://www.globalgilson.com/perfa-cure-concrete-curing-boxes (accessed Sep. 20, 2021).

[98] C09 Committee, “Test Method for Materials Finer than 75-m (No. 200) Sieve in Mineral Aggregates by Washing,” ASTM International. doi: 10.1520/C0117-17.

[99] “Los Angeles Abrasion Machine.” https://www.humboldtmfg.com/los-angeles-abrasion-machine.html (accessed Sep. 20, 2021).

[100] “AASHTO T 119M/T 119 : Standard Method of Test for Slump of Hydraulic Cement Concrete.” https://global.ihs.com/doc_detail.cfm?document_name=AASHTO%20T%20119M%2FT%20119&item_s_key=00489018 (accessed Sep. 20, 2021).

[101] “AASHTO T 196M/T 196 - Standard Method of Test for Air Content of Freshly Mixed Concrete by the Volumetric Method | Engineering360.” https://standards.globalspec.com/std/13344835/aashto-t-196m-t-196 (accessed Sep. 20, 2021).

[102] “AASHTO T 121M/T 121 - Standard Method of Test for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete | Engineering360.” https://standards.globalspec.com/std/13344869/aashto-t-121m-t-121 (accessed Sep. 20, 2021).

[103] C09 Committee, “Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete,” ASTM International. doi: 10.1520/C1064_C1064M-17.

[104] M. Alexander and S. Mindess, *Aggregates in Concrete*. CRC Press, 2010.

[105] J. Liu, A. Mullin, and J. Rein, “Use of the Micro-Deval Test for Assessing Alaska Aggregates,” p. 61.

[106] I. González-Taboada, B. González-Fonteboa, F. Martínez-Abella, and D. Carro-López, “Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis,” *Mater. Constr.*, vol. 66, no. 323, p. e089, Sep. 2016, doi: 10.3989/mc.2016.06415.

[107] T. Mukai, M. Kikuchi, and H. Koizumi, “Fundamental study on bond properties between recycled aggregate concrete and steel bars,” *Cem. Assoc. Jpn.*, vol. 32, 1978.

[108] L. Jin, W. Yu, D. Li, and X. Du, “Numerical and theoretical investigation on the size effect of concrete compressive strength considering the maximum aggregate size,” *Int. J. Mech. Sci.*, vol. 192, p. 106130, Feb. 2021, doi: 10.1016/j.ijmecsci.2020.106130.

[109] F. Yu, D. Sun, J. Wang, and M. Hu, “Influence of aggregate size on compressive strength of pervious concrete,” *Constr. Build. Mater.*, vol. 209, pp. 463–475, Jun. 2019, doi: 10.1016/j.conbuildmat.2019.03.140.

[110] G. D. Tsiskreli and A. N. Dzhavakhidze, “The effect of aggregate size on strength and deformation of concrete,” *Hydrotech. Constr.*, vol. 4, no. 5, pp. 448–453, May 1970, doi: 10.1007/BF02376145.

[111] Safiuddin, U. J. Alengaram, A. Salam, M. Z. Jumaat, F. F. Jaafar, and H. B. Saad, “Properties of high-workability concrete with recycled concrete aggregate,” *Mater. Res.*, vol. 14, no. 2, pp. 248–255, Jun. 2011, doi: 10.1590/S1516-14392011005000039.

Appendix A

Complete Test Results

Table A1

Aggregate Distributions For RCAs Due To The ASTM Method Under D56

Size (in)	Sieve Size	D100A48	L100A48	NE100	MD100	**#56 (1")**
		%Passing	%Passing	%Passing	%Passing	**%Passing**
1.500	1 1/2"	100	100	100	100	**100**
1.000	1"	99.88	98.73	100.00	88.99	**90-100**
0.750	3/4"	76.78	79.21	80.00	49.26	**40 - 85**
0.500	1/2"	24.27	28.87	40.00	23.89	**14885**
0.375	3/8"	8.03	8.72	12.00	9.64	**0 - 15**
0.187	#4	0.57	0.77	5.00	5.31	**0 - 5**
0.094	#8	0.51	0.77	0	0	**-**
Pan		0	0	0	0	**-**

Table A2

Aggregate Distributions For RCAs Due To The ASTM Method Under D57

Size (in)	Sieve Size	D100A38	G100A48	G100A38	L100A38	**#57 (1")**
		%Passing	%Passing	%Passing	%Passing	**%Passing**
1.500	1 1/2"	100	100	100	100	**100**
1.000	1"	99.84	100.00	100.00	99.58	**95-100**
0.750	3/4"	89.31	88.59	94.30	89.88	**-**
0.500	1/2"	44.95	43.64	51.67	55.83	**25-60**
0.375	3/8"	18.35	16.34	27.06	24.62	**-**
0.187	#4	0.32	0.57	4.90	2.34	**0-10**
0.094	#8	0.28	0.52	3.88	1.67	**0-5**
Pan		0	0	0	0	

Table A3

Aggregate Distributions For RCAs Due To The ASTM Method Under D56

Size (in)	Sieve Size	D075A48	D075A38	L075A48	CO 075	**#6 (3/4")**
		%Passing	%Passing	%Passing	%Passing	**%Passing**
1.500	1 1/2"	100	100	100	100	**-**
1.000	1"	100	100	100	100	**-**
0.750	3/4"	93.00	94.43	94.19	99.70	**100**
0.500	1/2"	29.39	47.53	34.33	55.00	**90-100**
0.375	3/8"	9.73	19.40	10.37	15.00	**20 - 55**
0.187	#4	0.69	0.33	0.92	5.00	**0 - 15**
0.094	#8	0.61	0.29	0.92	0.00	**0 - 5**
Pan		0	0	0	0	**-**

Table A4

Aggregate Distributions For RCAs Due To The ASTM Method Under D67

Size (in)	Sieve Size	G075A48	G075A38	L075A38	**#67 (3/4")**
		%Passing	%Passing	%Passing	**%Passing**
1.500	1 1/2"	100	100	100	**-**
1.000	1"	100	100	100	**100**
0.750	3/4"	95.06	98.32	95.75	**90-100**
0.500	1/2"	75.59	60.74	73.38	**-**
0.375	3/8"	28.30	31.81	32.36	**25-55**
0.187	#4	0.99	5.76	3.08	**0-10**
0.094	#8	0.90	4.56	2.20	**0-5**
Pan		0	0	0	-

Table A5

Type And The Total Number Of Specimens Produced

Test	Type of specimens*	Number of specimens	Total specimens per mix
Compressive strength	Cylinder (4x8)	3(per 7,14,28,90 days)	12
Flexural strength	Beam (6x6x21)	3 (14 days, 28 days)	6
Total specimens per mix			18
Total specimens for 30 mixes			540

Note. Size in inches.

Table A6

L.A. Abrasion Test Results (Control RCA & CRCA)

Aggregate	LA Abrasion (%) ASTM no.C131
D100	21
G100	25
L100	40
MD100	28.50
MD075	37.40
CO 075	43.00
NE100	33.80
D100A48	27.00
D100A38	22.10
G100A48	24.30
G100A38	26.50
L100A48	36.60
L100A38	35.00

Table A7

Test Results Of Materials Finer Than 75-Mm By Percentage

Aggregate	Finer than a 75-µm (%) ASTM no.C117
MD100	4.43
CO 075	2.33
NE100	2.30
D100A48	3.60
D100A38	2.87
D075A48	1.20
D075A38	0.73
G100A48	0.83
G100A38	0.47
G075A48	0.77
G075A38	0.53
L100A48	1.07
L100A38	0.89
L075A48	0.73
L075A38	0.83

Table A8

Material Finer than 75-μm - Control RCA and CRCA (ASTM C944)

Sample Name	Average Mass Loss (g)
C48MD100	1.70
C38MD100	0.73
C48D100A48	0.70
C38D100A48	0.50
C48D100A38	0.45
C38D100A38	0.43
C48D075A48	1.20
C38D075A48	0.73
C38D075A38	0.30
C48D075A38	1.40
C48G100A48	0.80
C38G100A38	0.43
C48G100A38	0.17
C38G100A38	0.10
C48L100A48	0.23
C38L100A48	0.33
C48L100A38	0.47
C38L100A38	0.30

Table A9

Materials Finer than 75-μm

Aggregate Type	original dry mass (gr)	dry mass after washing (gr)	% Finer than **75-μm** Passing (No. 200)
MD100	3000	2866	4.43
CO075	3001	2930	2.35
NE100	3000	2931	2.30
D100A48	3002	2892	3.60
D100A38	3001	2914	2.90
D075A48	3000	2964	1.20
D075A38	3002	2978	0.75
G100A48	3001	2975	0.85
G100A38	3002	2985	0.47
L100A48	3000	2974	0.90
L100A38	3001	2975	0.83

Table A10

Mixture Proportions Of 30 Concrete Batches

Sources	Aggregate	Cement pcy	Water pcy	RCA pcy	Sand pcy	AEA (oz/cwt)
External sources	C48-MD100	523	251	1454	1504	1.50
	C38-MD100	726	272	1401	1323	1.50
	C48-CO 075	590	283	1320	1456	0.60
	C38-CO 075	745	283	1320	1327	0.60
	C48-NE100	572	275	1503	1280	1.00
	C38NE100	723	275	1503	1154	1.00
Manufactured Dolomite	C48D100A48	527	275	1401	1476	1.15
	C38D100A48	723	275	1401	1351	1.00
	C46D100A38	527	274	1567	1258	0.70
	C38D100A38	723	275	1567	1133	0.70
	C48D075A48	590	283	1473	1321	0.65
	C38D075A48	752	283	1473	1192	1.15
	C48D075A38	590	283	1447	1391	0.70
	C38D075A38	745	283	1447	1262	1.00
Manufactured Granite	C48G100A48	590	283	1363	1393	0.60
	C38G100A48	723	275	1473	1213	1.00
	C48G100A38	572	275	1513	1343	0.70
	C38G100A38	723	275	1513	1218	1.00
	C48G075A48	590	283	1362	1394	0.60
	C38G075A48	745	283	1362	1265	1.00
	C48G075A38	590	283	1448	1388	0.70
	C38G075A38	745	283	1448	1258	0.70

Sources	Aggregate	Cement	Water	RCA	Sand	AEA (oz/cwt)
		pcy	pcy	pcy	pcy	
Manufactured Limestone	C48L100A48	572	275	1496	1314	0.65
	C38L100A48	723	275	1496	1118	1.00
	C48L100A38	572	275	1508	1325	0.65
	C38L100A38	723	275	1508	1199	1.00
	C48L075A38	590	283	1395	1410	0.60
	C38L075A38	745	283	1380	1315	0.60
	C48L075A48	590	283	1384	1399	0.60
	C38L075A48	745	283	1382	1285	1.00

Note. AEA: Air Entraining Agent. pcy: Weight (lbs.)/yd^3.

Table A11

Compressive Strength Test Results

Aggregate	Compressive strength, psi			
	ASTM C39			
	7d	14d	28d	90d
C48-MD100	2410	2710	2940	3490
C38-MD100	4330	4190	5110	5410
C48-CO075	3310	3550	3750	4090
C38-CO075	4930	5395	5440	5920
C48-NE100	2980	3430	3400	3440
C38-NE100	3740	4210	4450	4930
C48D100A48	3650	4120	4330	4850
C38D100A48	5270	5730	6090	6360
C46D100A38	3890	4640	5160	5820
C38D100A38	4250	5020	5380	6070
C48G100A48	3310	3800	4130	4300
C38G100A48	5350	5790	5920	6720
C48G100A38	4500	4760	5140	5470
C38G100A38	5620	5990	6360	7180
C48L100A48	3090	3820	4310	4390
C38L100A48	5360	5730	6210	6710
C48L100A38	3950	4430	4590	4660
C38L100A38	4630	4980	5820	5850
C48D075A48	3460	3990	4240	5590
C38D075A48	3470	3900	4270	5020
C48D075A38	4340	4840	5170	5880
C38D075A38	5190	5420	5700	6510
C48G075A48	3760	4060	4210	4590
C38G075A48	4410	5190	5530	5850
C48G075A38	3230	3320	3320	5880
C38G075A38	5040	5520	5630	6510
C48L075A48	3260	3350	3750	3750
C38L075A48	4330	5140	5170	5440
C48L075A38	3450	3860	3920	3970
C38L075A38	5380	5400	5930	6330

Table A12

Flexural Strength Test Results

Aggregate	Flexural strength, psi ASTM C78	
	14d	28d
C48-MD100		460
C38-MD100		615
C48-CO075	480	525
C38-CO075	520	535
C48-NE100	380	400
C38-NE100	530	630
C48D100A48	540	605
C38D100A48	910	915
C46D100A38	765	795
C38D100A38	880	940
C48G100A48	525	530
C38G100A48	670	720
C48G100A38	550	660
C38G100A38	640	675
C48L100A48	555	580
C38L100A48	616	745
C48L100A38	455	480
C38L100A38	585	595
C48D075A48	665	710
C38D075A48	540	615
C48D075A38	555	755
C38D075A38	605	810
C48G075A48	495	515
C38G075A48	496	560
C48G075A38	465	475
C38G075A38	700	750
C48L075A48	425	435
C38L075A48	635	640
C48L075A38	505	505
C38L075A38	640	650

Table A13

Increase (+) Or Decrease (-) In Compressive Strength (%)

PC	PC w/c	190-day Compressive strength of Parent Concrete (psi)	CONTROL RCA	Compressive strength, psi				Ratio of strength for PC & CONTROL RCA in 90 d	Ratio of 0.48 & 0.38
				ASTM C39					
				7d	14d	28d	90 d		
Dolomite	0.48	6990	C48D100A48	3650	4120	4330	4850	-31%	22%
			C38D100A48	5270	5730	6090	6360	-9%	
	0.38	8700	C46D100A38	3890	4640	5160	5820	-33%	3%
			C38D100A38	4250	5020	5380	6070	-30%	
Granite	0.48	5210	C48G100A48	3310	3800	4130	4300	-17%	46%
			C38G100A48	5350	5790	5920	6720	29%	
	0.38	9810	C48G100A38	4500	4760	5140	5470	-44%	17%
			C38G100A38	5620	5990	6360	7180	-27%	
Limestone	0.48	6300	C48L100A48	3090	3820	4310	4390	-30%	37%
			C38L100A48	5360	5730	6210	6710	7%	
	0.38	9080	C48L100A38	3950	4430	4590	4660	-49%	13%
			C38L100A38	4630	4980	5820	5850	-36%	
Dolomite	0.48	6990	C48D075A48	3460	3990	4240	5590	-20%	-8%
			C38D075A48	3470	3900	4270	5020	-28%	
	0.38	8700	C48D075A38	4340	4840	5170	5880	-32%	7%
			C38D075A38	5190	5420	5700	6510	-25%	
Granite	0.48	5210	C48G075A48	3760	4060	4210	4590	-12%	24%
			C38G075A48	4410	5190	5530	5850	12%	
	0.38	9810	C48G075A38	3230	3320	3320	4020	-59%	21%
			C38G075A38	5040	5690	5630	6095	-38%	
Limestone	0.48	6300	C48L075A48	3260	3350	3750	3750	-40%	27%
			C38L075A48	4330	5140	5170	5440	-14%	
	0.38	9080	C48L075A38	3450	3850	3920	3970	-56%	26%
			C38L075A38	5380	5400	5930	6330	-30%	
Average ratio of reducing w/c ratio from 0.48 to 0.38 for CONTROL RCAs									22%

Appendix B

Figures as Reference

Figure B1

Relationship Between Absorption and Specific Gravity of Concrete