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# DURABILITY PROPERTIES OF CONCRETE WITH 100 PERCENT COARSE RECYCLED CONCRETE AGGREGATES

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# DURABILITY PROPERTIES OF CONCRETE WITH 100 PERCENT COARSE RECYCLED CONCRETE AGGREGATES

by

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## Dedications

I want to thank my parents Shahabuddin Khan and Afsana Perven, for always giving me the strength to achieve my goal. I would also like to thank my sister Tajrian Khan for always being there for me.

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**Abstract**

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The supplies of concrete aggregates from natural sources are rapidly reducing. Recycled concrete aggregates (RCA) are produced by crushing the concrete obtained from demolished concrete structures. The purpose of this study is to determine the durability properties of concrete with 100% recycled concrete coarse aggregates and relate the durability of such concrete to the physical, mechanical, and durability properties of RCA and the RCA parent concrete. The correlations of several properties are determined by developing model equations to predict RCA properties. The parent concrete is crushed and graded at two nominal maximum sizes, 1" and 0.75", to determine the RCA production effects on new concrete. Six varieties of RCA were manufactured for the study. Concrete mixtures with RCA coarse aggregate have water-to-cement ratios of 0.38 and 0.48. Physical properties of aggregates tested in the lab include bulk density, specific gravity, absorption, and residual mortar. The concrete durability is obtained by measurement of resistance to degradation, resistivity test, density, absorption, and voids in the hardened concrete. A regression model for the surface resistivity of RCA showed that the surface resistivity increases when the absorption of RCA, w/c of concrete, and the volume of mortar decrease. The research results contribute to increasing RCA use through an improved understanding of its influence to concrete durability.

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# Chapter I

# Background

## 1.1 Introduction

Concrete is the most commonly used material in constructing infrastructures, including roads, bridges, and even skyscrapers. It is widely used due to its strength, durability, low cost, and good resistance against high temperature. Concrete is a composite material that is made of coarse and fine aggregates bound together with a mixture of cement and water which hardens over time [1]. Aggregates are the essential component that makes up 60% to 80% of the volume of concrete [2].

Generally, natural aggregate (NA) such as crushed stone, sand, and gravel are used to make concrete. However, the excavation process of mining these natural aggregates involves blasting and operating heavy equipment to develop quarries. This is a costly process and consumes a significant amount of energy [3]. Furthermore, the supplies of natural aggregates are limited, and with the increasing demand for concrete, the collections of high-quality aggregates are rapidly depleting. Due to the lack of sources, using NA has become an issue in construction. Hence there is an urgency to find ways to mitigate the continued depletion of this natural resource [2].

Recycled concrete aggregates (RCA), also known as recycled crushed aggregates, are made from crushed old concrete. Recycled concrete aggregate is made by crushing the parent concrete of pavement and other structures. Due to this process, the shape of the RCA may be changed from the shape of NA. Different instruments have been used to break structures to make the RCA, such as jaw crusher, pneumatic breakers, spring-action hammer, wrecking ball and crane, resonant frequency breaker, and many more. Approximately 95% reinforcement steel is usually eliminated by hydraulic shears [4]. Crushed concrete is then placed in the RCA processing plant. The remaining portion of the reinforcement steel, other contaminants such as plaster, wood, plastic, and non-metallic structural substances are removed in the plant. Before processing, the aggregate size is generally 12" to 16", which is reduced to ¾" to 1" after processing in the plant. The final RCA product produced has commonly less than 2% passing the No. 200 sieve [4]. While coarser RCA is widely used to replace the natural aggregates, finer RCA can replace finer aggregates [9]. It is essential to remove the contaminants of RCA to reach the goal of having good quality concrete made of RCA. Because of the attached residual mortar, RCA has lower specific gravity than NA [2]. RCA has higher absorption than NA because the attached porous mortar absorbs more water. Characteristics of RCA are also influenced by the type and maximum size of parent aggregate and the strength of parent concrete. Because of the mortar and other contaminants, the strength of the concrete with RCA may be lower than with NA, and it has less resistance to abrasion than NA. The resistance to abrasion increases with the increase in aggregate size [5].

In practice, most applications of RCA limit coarse aggregate replacement to 30% in the concrete mixture. However, this limit can go higher if the mix design, batching methodology, and RCA's moisture condition are suitably managed [2].

Using RCA instead of NA is the most effective way to reduce the consumption of natural aggregates. This method is also environmentally friendly as it reduces the amount of construction waste, old concrete is recycled and efficiently utilized instead of transporting and placing them in landfills. Furthermore, using RCA can also reduce the demand for opening new mining areas for NA. Recycled concrete aggregates are also economically feasible, as the unit weight of RCA is less than NA. The transportation of RCA consumes less energy than NA for the same hauling distance, which decreases the cost of construction [6]. According to the report given by Verian et al.[7], RCA can reduce the cost by nearly $2.26-$2.93 per ton of pavement concrete [7]. From an estimation study by the Environmental Council of Concrete Organizations, it has been known that the replacement of NA by RCA can save up to 60% of the total construction cost [8]. The RCA products cost around $1 to $18 per ton, which varies [9]. In the United Kingdom, 10% RCA is used in the total aggregates [10].

## 1.2 Objectives

The goal of this research is to have durable structures made of concrete with RCA. To achieve the goal, this research measures the properties of coarse RCA and determines how the durability of new concrete changes when coarse recycled concrete aggregates are incorporated into the mix. The coarse RCA was manufactured from concrete with different natural aggregates and water-to-cement ratios. New concrete mixtures with the coarse RCA were then tested for durability. In this thesis, the specific objectives of the study are:

1) To determine the durability properties of concrete with 100% recycled concrete coarse aggregates.
2) To study the effects of RCA's physical, mechanical, and durability properties and the RCA parent concrete on the durability of new concrete with 100% coarse RCA.

Six manufactured RCA were obtained. Concrete mixtures with coarse RCA had water-to-cement ratios of 0.38 and 0.48. Physical properties of aggregates tested in the lab included bulk density, specific gravity, absorption, and residual mortar. The concrete durability was obtained by measurement of resistance to degradation, electrical resistivity testing, and voids in hardened concrete.

# Chapter II

# Literature Review

## 2.1 Concrete Demolition

Concrete structures last for a long time. However, sometimes a structure needs to be demolished to create space for building new concrete structures. About 60-70% of aggregates are used in structural works, and around 20-30% are used in other road construction and maintenance work [11]. But every day, the world is being polluted with concrete waste [2]. The rise in industrial development is creating the problem of disposing of construction and demolition waste materials. Furthermore, demolished concrete produced from antiquated and collapsed structures causes environmental and ecological issues [11].

On the other hand, the use of natural aggregates (NA) for producing new concrete increases the transport and landfilling costs. Moreover, the natural resources for producing aggregate are inadequate [11]. As a solution, recycled concrete aggregate (RCA) can be a suitable substitute for building concrete structures and pavements [11]. To get the recycled concrete aggregate (RCA), old concrete needs to be crushed, screened, graded, and stored together. These aggregates could be contaminated by the attached cement paste, salt, wastes of brick, timber, sand, plastics, paper, cardboard, and metals [11]. After separating these wastes and appropriate sieving, these aggregates can replace natural aggregates [11].

Aggregates found from concrete demolition can be used as boulder heads to prevent erosion and floor-filling materials. Using RCA in renewing highways and airfield runways reduces the carrying cost of the old concrete materials and the transportation cost by building an aggregate producing center at the site [11]. Furthermore, after a destructive earthquake, the waste found from the demolished concrete can be used in reconstructing these houses [11]. That is the way of reducing cost by not using new aggregates. However, before using the RCA from demolished concrete, RCA needs to be tested for grain size, specific gravity, density, water absorption, and abrasion resistance to evaluate and compare the quality of RCA with natural aggregates [4, 11].

## 2.2 Methods of Demolishing Concrete

There are various methods used to demolished concrete structures and crush it to produce RCA. Several types of tools can be used to demolish concrete. Some of the tools include pneumatic impact brakers, spring-action brakers, concrete crushers, ripper and resonant frequency breaker.

### *2.2.1 Hydraulic/Pneumatic Impact Breakers/Hammers*

The size of the hydraulic hammer should be selected in such a way so that it will go with the size of the conveyor it will be mounted on. Different sizes of hydraulic impact hammers have different amounts of energy. The range of the energy is 125ft-lb (169 J) to more than 20,000 ft-lb (27,000 J). The size of the hammer should be selected based on the impact rate, working weight, hydraulic pressure, and design details. The frequency rate of the hammer depends on the type and degree of removal [12].

### *2.2.2 Spring-Action Hammers*

This tool is also known as a mechanical sledgehammer. Mechanical sledgehammers or spring-action hammers are boom-mounted tools used for shuttering concrete walls, decks, pavements, and other thin members. The wing of the mallet is powered hydraulically, and the impact-head is spring-powered. It is of different sizes. The energy of this equipment is 300,000 ft.lb [12].

## 2.3 Demolition Method by Type of Concrete

Concrete structures can be categorized into four types. They are: a) Mass concrete structures, b) Underground structures, c) Reinforced concrete structures, d) Prestressed/ Post-tensioned structures [12].

### *2.3.1 Mass Concrete Structures*

Large mat foundations, dams, bridge piers, thick walls, hydraulic structures are included in the mass concrete structures [12]. Some removal methods are applied, such as explosive blasting, diamond wire sawing, presplitting using nonvolatile demolition agents, rotary head cutting, stitch cutting, and drilling. Remote-controlled thermal lance cutting, abrasive water-jet blasting, electrical heating of steel reinforcement, and microwave heating of cover concrete are the methods that have been applied less [12].

### *2.3.2 Prestressed/Post-Tensioned Structures*

Thermal lance, hydraulic breaker, drop ball, and a jackhammer removes prestressed/post-tensioned concrete structures. Structural failure can be caused by the stored energy that is released from the tendon. That is why proper steps should be taken. Laborers should not be permitted to work near the anchorages at the time of any form of removal [12]. The removal of prestressed/post-tensioned concrete structural elements may be done using a hydraulic breaker, thermal lance, jackhammer, and drop ball. There is a need for being careful while undertaking destruction because the mechanical energy within the tendons may, if released abruptly, result in structural failure or tensionwhiplash upon components of the anchorage. Workers should never be allowed near anchorages at the time of any type of removal except in detention that is controlled. The Technical Manual of OSHA (Occupational Safety and Health Administration 1991b) points out four principal classes of prestressed members. There is a need to recognize categories or categories before any destruction, remembering that any prestressed structure might have features from more than a single category [12].

Category 1- These include prestressed members before using the superimposed loads and all tendons wholly bonded to the concrete or grouted in the ducts [12].

Category 2-. Category 2 is similar to Category 1, but the tendons are not grouted. This type of erection may sometimes be identified from the points of access that may have been arranged to examine the anchors and cables. Tendons that are not bonded are used in the manufacture of slabs, beams, and other members. These tendons are safeguarded by grease and could be covered by sheathing made of plastic instead of the typical duct made of metal [12].

### *2.3.3 Monolithic Structures*

There is a need for engineer expertise before uncovering the anchorages or tendons of constructions where two or more members are stressed together. Temporary supports are usually a prerequisite for the anchorages and tendons to be discovered with caution. In these types of situations, there is a need to avoid random distress and uncover the anchorages and tendons [12].

## 2.4 Crushing and Screening Demolition Waste to Produce RCA

To manufacture recycled concrete aggregates, crushing needs to be done in specific processes. First, after arriving at the plant, the rocks were broken by using a mighty hammer, metal jaws. Then all the reinforcing steel, plaster, wood, plastic, fibers are removed. After that, the product was again reduced by using a smaller jaw crusher to produce a final product of ¾ to 1in top size. The final aggregate produced has less than 2%, passing the No. 200 sieve [12].

By screening, very fine particles such as dirt, gypsum, and plaster can be removed. The crushed debris can be eliminated by a wet screening process. When the contaminants are heavier than water, a dry screening process can be applied [12].

## 2.5 RCA Properties

### *2.5.1 Mortar Content*

The recycled concrete aggregate produced by crushing concrete is the combination original natural aggregates that are coated with cement paste. RCA has high absorption because the existing cement paste absorbs water due to having porosity. To remove the adhesive cement-paste from the RCA, $CO_2$ can be used to pretreat RCA, this process is called the carbonation method. In this process, CO2 reacts with the adhering paste on the RCA to form $CaCO_3$ and silica gel. Mortar content control the quality of aggregate. The adhered mortar makes an aggregate weaker due to having pores. Therefore, the quality of RCA is lower than the virgin aggregate. The mortar also affects the density, absorption, LA abrasion of aggregate. The higher the mortar the lower the density, higher the absorption and LA abrasion of aggregates. Removing mortar content can depend on the crushing and screening process of the concrete. The cost of the removal of mortar will depend on the stages of the crushing process.[13]

### *2.5.2 Absorption Capacity*

The amount of water absorbed by aggregate is known as the absorption capacity. The features of recycled concrete aggregate may vary with the natural aggregate, which is found from natural sources. The main difference between recycled aggregate and natural aggregate is the presence of cement mortar in recycled aggregate [14]. Mortar porosity can influence the bulk density of aggregate [14]. The recycled concrete aggregate has old cement mortar, which has a high porosity. The water absorption at 24 h of RCA is 23 times higher than that of NA [15]. Thus, more water is needed when preparing recycled aggregate concrete (RAC) in a mixed proportion compared to NA. The high-water absorption of RCA is generally regarded as the most significant characteristic of RCA. The bulk density of recycled concrete aggregate is lower than natural aggregate due to having more old mortar. The old mortar decreases the bulk density of recycled aggregate [14], and therefore, removing old mortar increases bulk density. Compared to NCA, the bulk density and the apparent density of RCA decrease by 12 and 10%, respectively [15]. The attached old, hardened mortar on RCA is the main reason for this decline.

Furthermore, this leads to a declination of concrete's density and elastic modulus when prepared with RCA [20]. Because of high porosity, the water-holding or absorption capacity is more significant in recycled aggregate than natural aggregate. In RAC, there are two types of interfacial transition zone [14]. One exists in old cement mortar aggregate, and the other one is a newly mixed aggregate. These are the main reasons for increasing the water absorption of RCA. Only one interfacial transition zone exists for concrete made with NA [16].

The absorption capacity of RCA can range from 2% to 10% (Hiller et al., 2011), and it is claimed to be up to 8 times that of virgin aggregates (Army Corps, 2004). In Hong Kong, crushed granite aggregate is used, with a density of approximately 2600-2650 kg/m^3 and a water absorption capacity of roughly 1% [16]. However, due to the adhered mortar, the density of recycled aggregate varies from 2200 to 2400 kg/m^3, and the water absorption capacity may vary from 5 to 15% [16].

### *2.5.3 Residual Mortar*

The reuse of aggregate from existing structures that have been demolished has become a more prominent concept in the field of civil engineering. It is important to know the amount of residual mortar present in an aggregate sample to allow the aggregate to bind correctly to the other concrete components. Since RCA is sourced from previously cast concrete, the aggregates are either fully or partially coated in residual mortar. Since the residual mortar is not the same as, or as vital as, the virgin aggregates themselves, it is crucial to measure how this adhered mortar affects the aggregates themselves, as well as the concrete made with RCA. Since there is not a current standard procedure to measure the amount of residual mortar in effect, an experimental technique published by the ASTM International Journal describes a novel way to identify the amount of residual mortar. The method proposed includes submerging the oven-dried RCA in a sodium sulfate solution and repeatedly allowing the aggregate to undergo freeze-thaw [17]. After the last freeze-thaw cycle, the solution is drained, and the aggregate, now free of residual mortar, is massed and compared to the original oven-dried mass [17, 18]. The difference in the two masses represents the mass of the residual mortar of the RCA sample.

### *2.5.4 Bulk Density*

The bulk density of coarse aggregate refers to the overall density of coarse aggregate and aids in determining the percent air voids that exist in a sample of aggregate. Understanding the air void percentage of a coarse aggregate sample is essential in selecting an appropriate aggregate for a specific project or undertaking. Knowing the air void percentage enables decisions regarding permeability and infiltration to be made. Quantifying the air voids present in an aggregate sample is also helpful in predicting how the aggregate will react to external stimuli in the field, such as how certain aggregate will perform under pressure when used in asphalt for pavements.

Due to a higher porosity in the mortar layer of concrete, the bulk density of recycled aggregate is lower than the bulk density of natural aggregates [18]. The differences between these properties decrease if the recycling of concrete is done at an advanced technology center. The old cement mortar is effectively removed from the aggregate as recycled concrete aggregate. Bulk densities of recycled aggregate are on average 10 percent lower compared to the bulk density of natural aggregates [19]. According to the University of Novi Sad, an increase in the share of recycled aggregate in the total mass of the component aggregate reduces the bulk density of fresh concrete [19]. The bulk density test of concrete with RCA showed a 5 to 10 percent lower bulk density than the natural aggregate concrete. Concretes made with RCA and natural aggregates gave 1 to 5 percent lower densities than natural aggregate concrete.

### *2.5.5 Specific Gravity*

The specific gravity of recycled concrete aggregate is usually lower than the specific gravity of natural aggregates. The adhered mortar to the RCA is responsible for this reduction. A decrease in the water to cement ratio increases the specific gravity of RCA.

Engineers in New Hampshire have determined that fine RCA will tend to have a lower specific gravity due to the high percentage of paste content present in the aggregate. The paste is attached to the recycled concrete before and after it is crushed into recycled concrete aggregate. The paste used in concrete mixes typically has a specific gravity between 1.43 and 1.74, with values that increase for higher strength concrete mixtures due to higher cement contents [20].

## 2.6 The Durability of Concrete with RCA

The durability of concrete is defined as the ability of concrete to withstand abrasion, weathering, and chemical action and maintain the desired properties of concrete. Different concrete has different degrees of durability. Concrete durability generally depends on the concrete properties and environmental conditions.

### *2.6.1 Resistance to Degradation*

Surface abrasion of concrete can be defined as the continuous mass loss due to friction on a solid concrete surface. Abrasion can be a spontaneous attack on a concrete surface, and sometimes the concrete can be entirely abraded from any structural constituent. The ability of the concrete surface to withstand the relative wearing is called abrasion resistance [21]. The aggregate type plays a vital role in concrete's resisting to abrasion. According to researchers from the LA abrasion test result, limestone faces more mass loss than granite because granite is harder than limestone [21]. The condition of curing and concrete permeability are also significant factors of degradation—these influence the capacity of concrete to withstand abrasion during freezing and thawing. The air-void system, soundness of the aggregate, and concrete maturity are other factors that affect the concrete's deterioration in the long run [22]. Concrete having a larger size of aggregates is more resistant to abrasion than concrete with smaller aggregate [21]. The increased abrasion resistance is because the larger aggregate takes a more significant portion of the surface area than the mortar area of the concrete. Additional energy is needed to deteriorate the area which has a more substantial size of aggregates. The greater the aggregate size, the greater the abrasion resistance for low strength concrete [21].

The abrasion resistance of aggregate is generally measured to justify the characteristics and quality of the aggregate. The usual test is the Los Angeles abrasion ASTM C-131 method, from which the percentage of mass loss of aggregates can be determined. The test result shows the stiffness and brittleness of the aggregate particles, the mineral's cleavage, and the intergranular bond's strength can be discussed. Since most concrete is aggregate, it is essential to have rigid, durable, strong, voids-free, and fracture-resistant aggregates. In addition, the aggregate should have high abrasion resistance so that the concrete in roads, and airports can be protected from deterioration [23].

### *2.6.2 Resistivity Test*

The electrical resistivity test is essential when characterizing the hardened properties of concrete made from RCA. The test shows the degree to which concrete cylinders can prevent the passage of an electrical current [24]. An often over looked aspect of hardened concrete is its ability to resist an electrical current. When a concrete sample, like cylindrical concrete, is moist on its surface, the concrete itself can conduct electricity both on the surface and through the interior of the concrete. Electricity can pass through the cement paste of a concrete sample due to the moisture that can result from the mixing process or freeze-thaw. Suppose concrete is reinforced with rebar, for example, and has a low resistance to electric currents. In that case, the interior rebar has the potential of rusting, which causes internal expansion of the concrete, leading to exterior cracking and other defects in the concrete. To prevent this from occurring, resistivity tests are performed on concrete samples.

To correctly perform the test on concrete samples, moistened electrodes are placed at opposite ends of the concrete specimen, and the resistivity of the concrete is measured in ohmmeters. The recording for the resistivity of the concrete sample may only be recorded once the value of resistivity has remained unchanged for two to five seconds. Obtaining these recordings is essential because the resistivity of the concrete sample can indicate whether or not the concrete sample is also resistant to the chloride ion, which is detrimental to the quality of the concrete [19].

### 2.6.3 Permeability of Hardened Concrete

In terms of permeability, concrete samples with coarse RCA have a 200% to 500% increase in change of permeability from virgin aggregate samples, and concrete samples that incorporated coarse RCA and fine RCA saw a 200% to 500% increase in change of permeability compared to virgin aggregate concrete samples [25]. West Virginia does not provide exact values for the standard requirements for permeability of hardened concrete. However, the state does mandate that tests for permeability, including chlorine permeability, must take place after the concrete samples have been cured for 28 days [26]. Similarly, the specifications for testing methods for durable highways for Wisconsin do not mention specific maximum or minimum values for permeability for virgin aggregate concrete or RCA. However, it says that RCA concrete typically has a higher porosity due to the existing mortar, implying a higher porosity for the entire concrete sample [27].

Once this test is conducted on hardened concrete, each state's testing facilities will retrieve density, absorption, and voids in the specific sample tested. These values give quantities that are useful for conversions between mass and volume of concrete. The permeability of recycled concrete aggregate is typically higher than the concrete made of virgin aggregate samples [28]. As concrete sample cracks, it loses the benefits of low permeability, and the durability of the concrete also reduces. Engineers from New Hampshire found similar results after testing permeability on their hardened concrete. They add that concrete durability was adversely affected when an increase in the amount of RCA was used. Researchers from Nebraska found high permeability in concrete mixes containing 30 to 70 percent RCA, with the remaining percentages being virgin aggregates [29].

## 2.7 Environmental Issues

In the US, the production of virgin aggregate was estimated at 2 billion tons per year in 2004. Furthermore, it was predicted that this amount would increase to 2.5 billion tons in 2020 [30]. However, concerns about the cost-effectiveness and unfavorable environmental impact of using quarried aggregate and the feasibility of continuing to dispose of matured infrastructure in landfills have created the option of using recycled concrete aggregate (RCA) as an economical and feasible alternative to conventional aggregate [30].

Concrete structures can be disposed of through concrete recycling. This practice is increasing due to greater awareness about the environment, better government laws, and possible economic benefits. The economic model for recycling includes three steps: company, area, and natural ecology system. Recycling concrete has both advantages and disadvantages [31]. To increase the cost-savings and to improve the viability of highway infrastructure, agencies have emphasized the need to use the resources of the aggregate carefully by enacting the recent federal legislation, including the Moving Ahead for Progress in the 21-st Century Act (MAP-21) and Transportation Equity Act for the 21$^{st}$ Century (TEA-21) [30]. The cost of recycled concrete aggregate varies with different considerations and factors such as production method, efficiencies, hauling, quality-control, and quality assurance [30].

# Chapter III

# Materials and Methods

## 3.1 Overview of the Experiments

In this study, three types of controlled RCA, Dolomite, Granite, and Limestone from New Jersey in the USA, and three types of RCA from Maryland, Colorado, and Nebraska were collected to determine the LA abrasion, specific gravity, absorption, unit weight, and residual mortar content. After testing all the RCA, concrete cylinders were made with those RCAs by following mixture proportions. Then those concrete cylinders were tested to determine surface resistivity, density, absorption of voids in concrete, and abrasion resistance. Based on the laboratory results, regression model of LA abrasion, electrical resistivity and voids in concrete, were proposed.

## 3.2 Materials

Type I Portland cement was used in all the concrete mixtures. Two types of coarse aggregates were used in this study. One is manufactured RCA, and the other one is commercial RCA. The fine aggregate was concrete sand. Air entraining admixture was also added to the mixture. The description of the materials is discussed in the following sections.

### *3.2.1 Portland Cement*

Type I Portland cement conforming to ASTM C150 was used in the concrete mixtures. The chemical oxide composition of the cement is presented in Table 1.

**Table 1**

*Chemical Composition of Portland Cement*

| Chemical component (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | Cao | MgO | $K_2O$ | $Na_2O$ | $SO_3$ | Other elements |
|---|---|---|---|---|---|---|---|---|---|
| CEM I | 19.32 | 5.77 | 2.38 | 61.55 | 2.63 | 0.97 | 0.33 | 4.56 | 2.49 |

## 3.3 Controlled Aggregates

Coarse RCA was manufactured by crushing three parent concretes, each with either Dolomite (designated as D), Granite (designated as G), and Limestone (designated as L) coarse aggregates. Those aggregates were called as "Controlled RCA".

The aggregates differ by their commonly known permeability, density, durability, and absorption characteristics. The parent concrete was crushed and graded at 1" and ¾" nominal maximum size to determine the RCA production effects of new concrete.

Dolomite (designated as D), Granite (designated as G), and Limestone (designated as L) were used to make parent concrete blocks and test cylinders with a water to cement ratio of 0.38 and 0.48. The physical properties of these aggregates, such as specific gravity, absorption, and LA abrasion are presented in Table 3.

Sika Air (AEA-14) as an air-entraining agent and Sikament 686 were used as a high range water reducer in manufacturing concrete specimens with natural aggregates. A high range water reducer is recommended especially for RCA to improve workability with lower water to cement ratio and to increase strength and durability.

**Table 2**

*The Sources of Parent Concrete Materials*

| Description | Source | Type/ Product Name |
|---|---|---|
| Coarse Aggregate | Stavola Lafayette<br>Tilcon- Pompton Lakes | Dolomite |
| Coarse Aggregate | Tilcon- Pompton Lakes | GraniteGneiss |
| Coarse Aggregate | Brean- Franklin | Limestone |
| Fine Aggregate | Phoenix Pinelands | Natural |
| Air Entrainment | Sika | Sika Air |
| Water Reducer | Sika | Sikament 686 |

**Table 3**

*Properties of Natural Aggregates*

| Aggregate type | Specific Gravity | Absorption, % | LA Abrasion Loss, % |
|---|---|---|---|
| Limestone | 2.79 | 0.3 | 40 |
| Dolomite | 2.81 | 0.8 | 21 |
| Granite | 2.78 | 0.5 | 25 |

The test cylinders and parent concrete blocks of Dolomite, Limestone, and Granite for water to cement ratios 0.38 and 0.48 were made by following the mix designs stated in Table 4. The target for the slump was 6" ± 2" measured according to ASTM C143-20. Sika Air was used as an air-entraining agent which improves durability, plasticity, and cohesiveness. The air content target was 6.5± 1.5 % as a typical range to produce concrete with higher resistance to freeze-thaw cycles.

**Table 4**

*Proportion of Mix Design, Slump, Air, Unit Weight, And Compressive Strength of the Parent Concrete*

| Mix No | Concrete designated | NA type | w/c | Aggregate (pcy) | Cement (pcy) | Sand (pcy) | Water (lb) | Air Sika (oz) | HRWR (oz) | Slump (in) | Air (%) | Unit Weight (pcf) | Compressive strength, (psi) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | L48 | Limestone | 0.48 | 1755 | 575 | 1310 | 276 | 0.5 | 4.5 | 6.5 | 6.8 | 142.2 | 6301 |
| M2 | L38 | Limestone | 0.38 | 1745 | 730 | 1180 | 276 | 0.5 | 4.5 | 4 | 5 | 149.4 | 9077 |
| M3 | D48 | Dolomite | 0.48 | 1760 | 575 | 1310 | 276 | 0.5 | 4.5 | 5.5 | 6 | 145.6 | 6991 |
| M4 | D38 | Dolomite | 0.38 | 1750 | 730 | 1180 | 276 | 0.45 | 4.5 | 5.5 | 5.4 | 146.8 | 8704 |
| M5 | G48 | Granite | 0.48 | 1750 | 575 | 1310 | 276 | 0.55 | 4.5 | 8 | 7.2 | 147.4 | 5209 |
| M6 | G38 | Granite | 0.38 | 1740 | 730 | 1180 | 276 | 0.45 | 4.5 | 4 | 4.5 | 148.2 | 9805 |

## 3.4 Commercial Recycled Concrete Aggregate

Three types of commercial RCA were collected in three different locations Maryland (MD), Colorado (CO), and Nebraska (NE) mentioned in Table 5. Coming from a manufacturer of commercial RCA, the age, mixture proportion, water to cement ratio, aggregate, and cement of the concrete from which the RCA was made was unknown. The commercial RCA were sieved in the laboratory to produce 1" and 3/4" nominal maximum size (NMAS) coarse recycled aggregates.

**Table 5**

*Source of RCA*

| Description | Source |
|---|---|
| Coarse Aggregate | The recycling center: Laney Recycling, Laurel, MD |
| Coarse Aggregate | Hawkins Construction Company, Omaha, NE |
| Coarse Aggregate | Allied Recycled Aggregates, Commerce City, CO |

### *3.4.1 Gradation of Both Controlled and Commercial Recycled Concrete Aggregate*

Figure 1 through 3, present the gradation of the RCA produced from the parent concrete mixes stated in Table 4 as well as the RCAs that were collected from the external sources. In Figure 1, D56 and in Figure 2, D 57 are the size numbers of all 1" NMAS RCAs. Some of them falls within the limit of D56 and some of them falls within the limit of D57. Similarly, In Figure 2, D6 and in Figure 4, D67 are the size numbers of all 3/4" NMAS RCAs. Some of them falls within the limit of D6 and some of them falls within the limit of D67. The limits of the size numbers were collected from ASTM C33 [32].

**Figure 1**

*Gradation of D57*

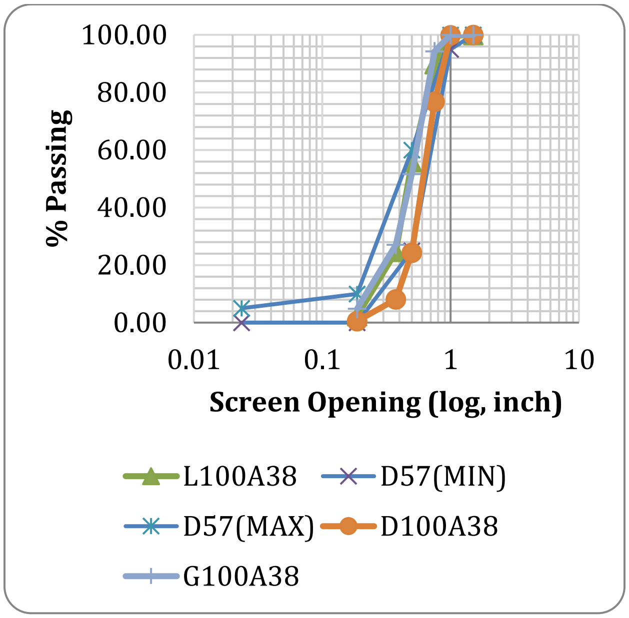


**Figure 2**

*Gradation of D56*

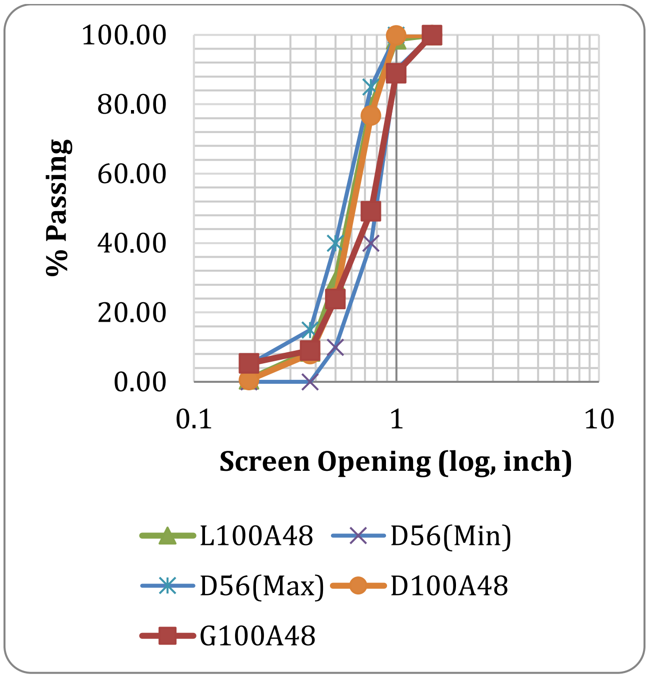


**Figure 3**

*Gradation of D6*

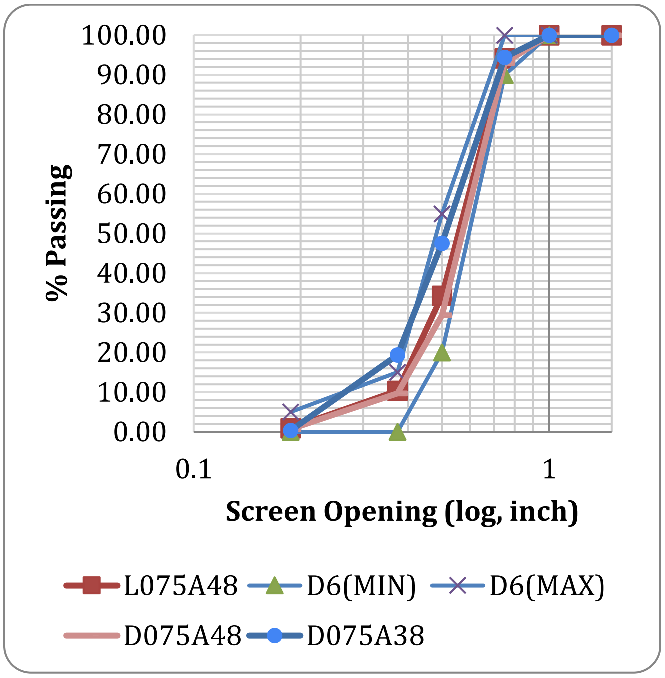
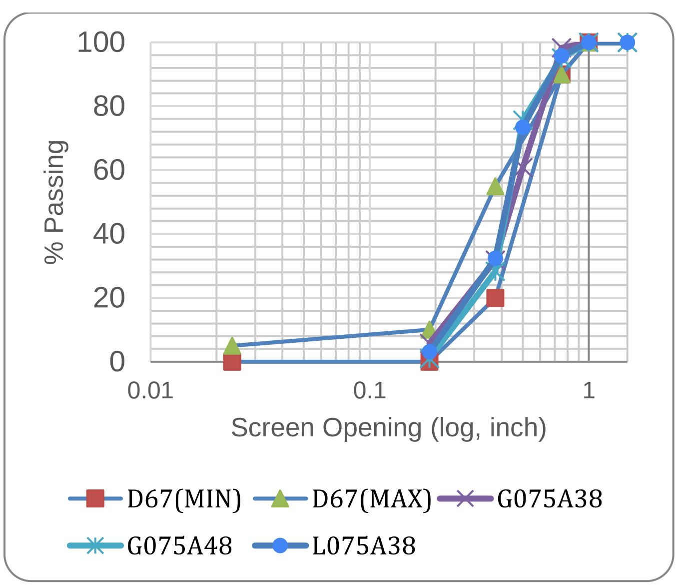



**Figure 4**

*Gradation of D67*

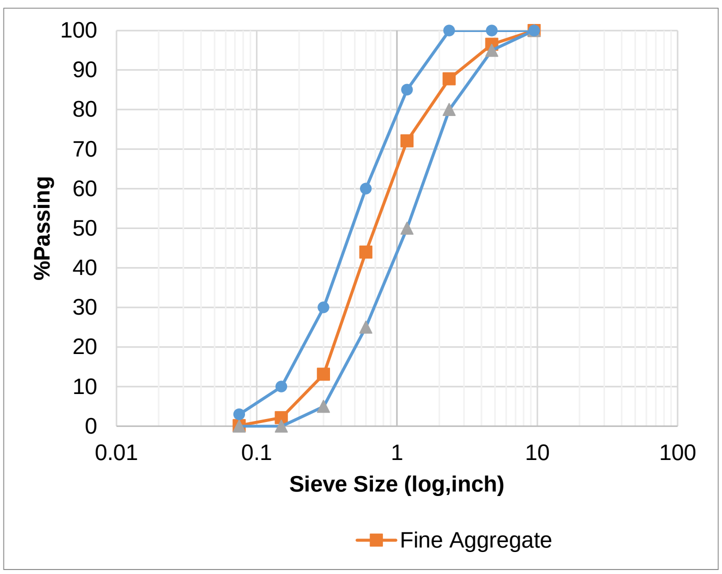


## 3.5 Fine Aggregates

Concrete sand was used as fine aggregates. It was used in the mix design to make new concrete that incorporated the various RCA used in the study. It was collected from Frank J. Fazzio & Sons Inc., located in New Jersey, USA. The specific gravity of the fine aggregate is 2.62, and the fineness modulus is 2.81. In Fig 5, the gradation of the fine aggregates was made according to the ASTM C33 specification limit.

**Figure 5**

*Gradation of Fine Aggregates*




## 3.6 Admixture (Chemical)

The chemical admixture, Sika Air (AEA-14) was used as an air-entraining agent. The target of the air content was 4% to 8%. The dosage was determined based on the small trial mixes.

**Table 6**

*Air Entraining Dosage Used in Concrete Made from the Commercial RCA*

| Aggregate type | Dosage (oz/cwt) |
|---|---|
| MD | 1 |
| CO | 0.6 |
| NE | 1 |

## 3.7 Mix Design of New Concrete

To produce the RCA, the parent concrete was cured for a minimum of 56 days prior to crushing. Two nominal maximum sizes, 1" and ¾" RCAs, were produced. A total of 24 different concrete mixes were produced from the controlled RCA, two from each parent mix listed in Table 4 after regrading to 1" and ¾" NMAS. These mix designs are shown in Table 7. Table 7 also presents the mix design of three commercial RCA for two water to cement ratios, 0.38 and 0.48. The mix designation naming convention is shown below the table.

**Table 7**

*Mix Design of New Concrete*

| Concrete | Cement pcy | Water pcy | RCA pcy | Sand pcy | Slump inch | Air % | Unit Weight pcf |
|---|---|---|---|---|---|---|---|
| C48-MD100 | 523 | 251 | 1454 | 1504 | 5.00 | 5.00 | 126.30 |
| C38-MD100 | 726 | 272 | 1401 | 1323 | 2.50 | 8.00 | 130.30 |
| C48-CO 075 | 590 | 283 | 1320 | 1456 | 5.00 | 7.00 | 140.68 |
| C38-CO 075 | 745 | 283 | 1320 | 1327 | 1.50 | 4.5 | 146.52 |
| C48-NE100 | 572 | 275 | 1503 | 1280 | 5.75 | 8.00 | 138.97 |
| C38NE100 | 723 | 275 | 1503 | 1154 | 3.25 | 4.25 | 145.17 |
| C48D100A48 | 527 | 275 | 1401 | 1476 | 8.50 | 9.00 | 137.69 |
| C38D100A48 | 723 | 275 | 1401 | 1351 | 2.00 | 4.75 | 149.66 |
| C48D100A38 | 527 | 274 | 1567 | 1258 | 2.25 | 5.75 | 147.27 |
| C38D100A38 | 723 | 275 | 1567 | 1133 | 1.75 | 4.25 | 151.16 |
| C48D075A48 | 590 | 283 | 1473 | 1321 | 5.25 | 8.25 | 139.18 |
| C38D075A48 | 752 | 283 | 1473 | 1192 | 6.00 | 7.75 | 133.20 |
| C48D075A38 | 590 | 283 | 1447 | 1391 | 5.75 | 7.00 | 145.17 |
| C38D075A38 | 745 | 283 | 1447 | 1262 | 1.50 | 5.25 | 145.53 |
| C48G100A48 | 590 | 283 | 1363 | 1393 | 4.50 | 8.00 | 141.70 |
| C38G100A48 | 723 | 275 | 1473 | 1213 | 2.25 | 5.25 | 141.43 |

| **Concrete** | **Cement** pcy | **Water** pcy | **RCA** pcy | **Sand** pcy | **Slump** inch | **Air** % | **Unit Weight** pcf |
|---|---|---|---|---|---|---|---|
| C48G100A38 | 572 | 275 | 1513 | 1343 | 2.50 | 5.75 | 145.26 |
| C38G100A38 | 723 | 275 | 1513 | 1218 | 1.50 | 4.00 | 149.24 |
| C48G075A48 | 590 | 283 | 1362 | 1394 | 4.50 | 8.00 | 141.70 |
| C38G075A48 | 745 | 283 | 1362 | 1265 | 2.25 | 6.00 | 144.42 |
| C48G075A38 | 590 | 283 | 1448 | 1388 | 6.50 | 7.75 | 143.07 |
| C38G075A38 | 745 | 283 | 1448 | 1258 | 3.25 | 6.00 | 142.33 |
| C48L100A48 | 572 | 275 | 1496 | 1314 | 6.50 | 7.75 | 142.03 |
| C38L100A48 | 723 | 275 | 1496 | 1118 | 3.00 | 5.50 | 145.17 |
| C48L100A38 | 572 | 275 | 1508 | 1325 | 4.75 | 7.25 | 142.57 |
| C38L100A38 | 723 | 275 | 1508 | 1199 | 6.50 | 6.25 | 144.93 |
| C48L075A38 | 590 | 283 | 1395 | 1410 | 5.00 | 7.75 | 143.28 |
| C38L075A38 | 745 | 283 | 1380 | 1315 | 2.00 | 4.75 | 151.01 |
| C48L075A48 | 590 | 283 | 1384 | 1399 | 5.75 | 8.00 | 140.38 |
| C38L075A48 | 745 | 283 | 1382 | 1285 | 3.00 | 7.00 | 145.59 |

*Example of Concrete with RCA Designation*

C48L075A48- indicates a 0.48 w/b concrete with 0.75" NMAS RCA made from parent concrete with limestone coarse aggregate and 0.48 w/b concrete.

## 3.8 Testing of Coarse RCA

The properties of RCAs were determined based on tests listed in Table 8. The properties defined were needed for concrete mixture design and assessing aggregate contribution to durability.

**Table 8**

*Test Names of RCA with the Designation*

| Test Name | Test Designation |
|---|---|
| Bulk Density (Unit Weight) | ASTM C 29 |
| Relative Density (Specific gravity) and Absorption | ASTM C 127 |
| Resistance of aggregates to abrasion | ASTM C131 |
| Residual Mortar | [33] |

**Table 9**

*Test Names of Concrete Made of RCA With the Designation*

| Tests Name | Test Designation |
|---|---|
| Resistance to Degradation | ASTM C 944 |
| Electrical Resistivity | AASHTO T 358 |
| Density, Absorption and Voids for Hardened Concrete | ASTM C 642 |

### *3.8.1 Bulk Density (Unit Weight)*

This experiment helps to monitor the aggregate consistency and is needed to develop any concrete mix design. In addition, the bulk density or the unit weight of aggregate can be determined in a compacted or loose condition, and voids between the aggregates can also be calculated.

To perform this test, ASTM C29/C29M was followed [34]. The aggregates need to be oven-dried for 24 hours and let cool down before starting the experiment to avoid all kinds of moisture. A measure shown in the Figure 6 as used in this experiment which has a volume of 0.5ft^3. A scale accurate to within 0.05kg and a tamping rod with a diameter of 16+/-2 mm was used. At first, the weight of the empty measuring cylinder was taken, and then one-third of the cylinder was filled with aggregates, and the surface was then leveled by using fingers. The layer of the total aggregate was rodded 25 times by the tamping rod. While rodding, the tamping rod cannot be hit to the bottom of the measure forcefully. Then again, two-thirds of the measuring cylinder was filled with the aggregate and leveled by finger. It was again rodded 25 times by the tamping rod. The tamping rod was not allowed to penetrate the first layer. Lastly, the measure was filled to overflowing and was again rodded 25 times. The surface of the aggregates was then leveled with fingers so that the larger aggregates filled the large voids in the surface below the top of the measuring cylinder.

**Figure 6**

*Aggregates in Compacted Condition*

### *3.8.2 Specific Gravity and Absorption*

In this experiment, the relative density (SSD), apparent relative density, absorption, and surface moisture of the aggregates were determined according to ASTM C127-15 [35]. Specific gravity or relative density is determined to calculate the volume of aggregates in different mix designs. Initially, 5 kg representative coarse aggregate was collected. Then, the weight of the specimens is recorded when it was oven-dried, surface saturated dried, immersed in water, and oven-dried. Based on the weight change of the coarse aggregate at these stages, specific gravity and water absorption were calculated.

**Figure 7**

*Aggregates in Submerged in Water in Wire Basket*


### *3.8.3 Resistance of Aggregates to Abrasion*

Resistance to abrasion of the recycled coarse aggregates was determined in the Los Angeles abrasion machine according to ASTM C131 [36]. The Humboldt abrasion testing machine model H-3860D was used to conduct the experiment. Representative oven-dried aggregate samples of 3500 g were selected and placed inside the LA machine with 11 steel spheres and rotated at a speed of 30 rpm for 500 revolutions. The materials were then discharged from the machine, and the finer portion was sieved on a 1.70 mm sieve [No. 12]. The percentage of loss was calculated based on the difference between the original mass and the final mass of the aggregates.

**Figure 8**

*Steel Spheres Rotating Inside the LA Abrasion Machine*

### *3.8.4 Residual Mortar*

Mortar attached to the virgin aggregate is one of the essential properties differentiating RCA from virgin aggregates. This mortar is responsible for the RCA's higher porosity, lower specific gravity, texture, etc.

The mortar content attached to the aggregates was determined according to the method described by Abbas [33]. Sodium sulfate solution was prepared by dissolving 260 g of $Na_2SO_4$ in one liter of water. Initially, oven-dried aggregates were fully immersed in the solution for 24 hours and then subjected to 10 cycles of freeze-thaw temperature ranging from -20º C to 80º C. Specimens were exposed to freezing temperature for 16 hours and thawing temperature for 8 hours. At the end of the freeze-thaw cycles, aggregates were washed with tap water and sieved by the #4 sieve to remove all the excess mortar. The aggregates are then oven-dried at 110+/-5 ºC for 24 h before their final weight is recorded. The residual mortar content is calculated based on the equation stated below.

$$\text{Residual Mortar Content, RMC \%} = ((W_{RCA} - W_{OVA})/W_{RCA}) \times 100$$

where $W_{RCA}$ is the initial oven-dried mass of the sample, $W_{OVA}$ is the final oven-dried mass of the original virgin aggregates after removing the residual mortar through the freeze-thaw cycling.

**Figure 9**

*The Residual Mortar Attached with RCA*

## 3.9 Durability Test on Hardened Concrete

### *3.9.1 Resistance to Degradation*

Resistance of the concrete specimens to abrasion was determined according ASTM C944 [37]. The test was performed to determine the concrete specimen's surface resistance to wear. The mass loss under the rotating cutter indicates the durability of the concrete surface and can be used to control the durability of the roadway surface. Concrete specimens with $\Phi$ 4 × 8 in$^2$ were manufactured and cured for 28 days. The cylinder specimens were then cut from top and bottom to obtain a $\Phi$ 4 × 2 in$^2$ cylinder from the middle. The new obtained small cylinders were then prepared by measuring weight. The specimen was then subjected to a rotating abrasive cutter at a speed of 200 revolutions per minute for two minutes. A constant load of 98 ±0.9 N (22 ±0.2 lbf) was applied during operation. Figure 10 shows the abrasion machine with specimens under a rotating cutter. At the end of the test, the sample was removed and the sample's surface cleaned by a brush before measuring the weight to determine the change in mass.

**Figure 10**

*Abrasion Machine with 98N (22lb) of Load and A Rotating Cutter*

### *3.9.2 Resistivity Test*

For this experiment, AASHTO Designation: T 358 was followed [38]. This method covers the determination of the electrical resistivity of water-saturated concrete to provide a rapid indication of its resistance to the penetration of chloride ions.

This test was done to calculate the surface resistivity of Φ 4" x8" concrete cylinders. For that, at first mix design needed to be developed to make those concrete cylinders.

This concrete was cured in the tank for 90 days shown in Figure 11. An electrical resipod was used to determine the electrical resistivity in kΩ-cm. Some factors affect the resistivity, such as water/cement ratio, pozzolans, admixtures, air-void system, aggregate type, and degree of consolidation. The resistivity was measured at 0, 90, 180-degree points of the circumference, which was marked on the top circular face after removal from the mold, and then the average of the three measurements was taken as the final data for each sample. The measurements were made at 7 days, 14 days, 28 days, and 90 days of the curing.

**Figure 11**

*Measuring Surface Resistivity by Resipod*

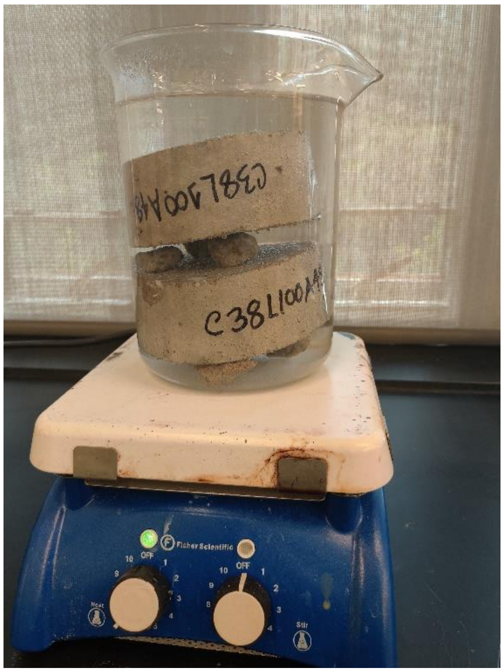

### *3.9.3 Standard Test for Density, absorption, and Voids for Hardened Concrete*

Followed by the ASTM standard C642, this test took part to determine the absorption (%), apparent density (pcf), bulk density (pcf), and voids (%) of hardened concrete [39]. The Φ 4" x 8" concrete was cut in Φ 4" x 2", and this test was cured for 28 days after mixing.

At first, the weight of the concrete core was measured using a scale. Then it was oven dried for 24h at 110+/-5 ºC and let it cool in dry air to a temperature of 20 to 25 ºC, and then the weight of that was determined. The same procedure was repeated until the difference between two consecutive mass values exceeded 0.5% of the lesser value. The last value has been designated as A. After final drying and cooling, the next step is to immerse the samples in water at around 21 ºC for not less than 48h. After that, the surface of the concrete samples was dried by using a towel. Mass of the surface dried sample has to be measured after every 24 h. That mass was designated by B. After that, the samples were placed into a heat-proof beaker and filled with tap water. It was then boiled on a heat plate for five hours. After finishing boiling, the sample was cooled naturally for no less than 14 h to a temperature of 20 to 25 ºC. Then the surface moisture was removed by a towel, and the saturated mass of those samples was taken, designated as C. The last step is to put the samples in a wire basket fully submerged in water and take the sample's mass in that position, which would be the apparent mass D.

**Figure 12**

*Boiling Concrete on A Heating Plate*



# Chapter IV

# Results and Discussion

## 4.1 Properties of Aggregates

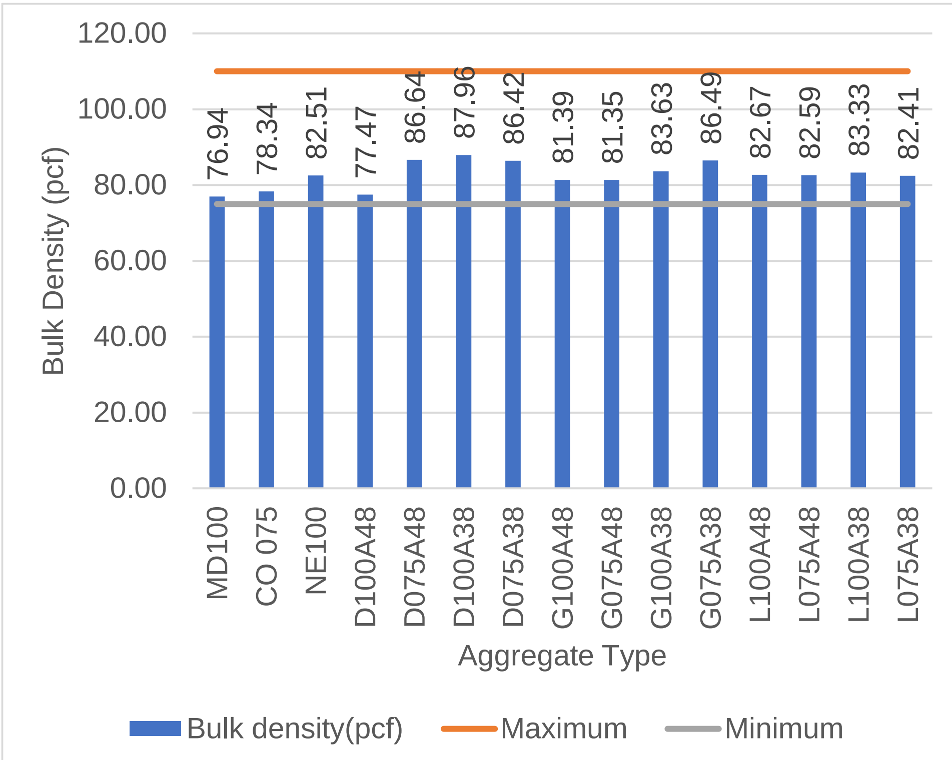
### *4.1.1 Bulk Density (Unit Weight)*

Bulk density of aggregates is defined as the aggregate mass required to fill the container of a unit volume after aggregates are batched based on the volume. The voids between the aggregates influence bulk density. The lower the voids, the higher the bulk density. Compaction will reduce the pore space between the aggregates. The density of the particles also depends on the size, shape, and texture of aggregates. Having smaller particles within large particles helps to reduce the voids after compaction, increasing the bulk density.

In this study, we determined the aggregate's bulk density in a compacted condition for selecting the mixture proportions of concrete. The bulk density of natural aggregates is 75 pcf to 110 pcf [40]. Figure 13 indicates the range of the bulk density of the RCA measured in this study is 76.94 pcf to 82.41 pcf. Among all the manufactured RCA, Dolomite-based RCA 1" NMAS with w/c 0.48 (D100A48) has the highest bulk density, with lower voids. In addition, Granite-based RCA ¾" NMAS w/c 0.38 (G100A38) has the lowest bulk density. MD100 (Maryland 1" NMAS) is the lowest commercial aggregates, and NE100 (Nebraska 1" NMAS) has the highest density. Therefore, we were able to determine that Dolomite-based RCA has a higher bulk density compared to others.

**Figure 13**

*Bar Graph of the Bulk density of RCA, pcf*



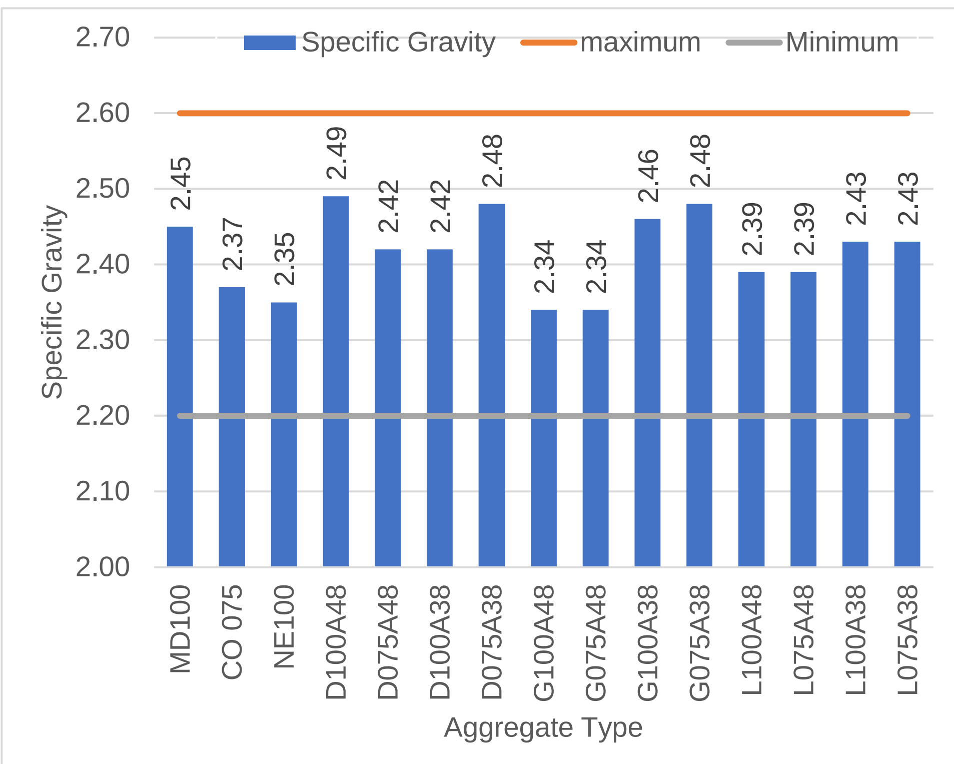

### *4.1.2 Specific Gravity*

Figure 14 represents the specific gravity of manufactured and commercial recycled concrete aggregates. The typical range of specific gravity of natural aggregate is 2.40 to 2.90, and for RCA, the range is 2.2 to 2.6 [40]. Figure 14 shows that RCA's specific gravity ranges from 2.34 to 2.49, significantly lower than natural aggregates' specific gravity because of the attached mortar. The specific gravity of natural limestone is 2.79 and reduces to 2.39 when recycled from concrete with a w/c of 0.48. A similar reduction occurred for other aggregates with both w/c ratios. This reduction of specific gravity for RCA is comparable to the literature [2].

Similarly, decreasing the water to cement ratio increases the specific gravity for all aggregate types. For example, the specific gravity of limestone 1" NMAS with w/c ratio of 0.48 is 2.39, and it increased to 2.43 for w/c of 0.38 due to decreased porosity in concrete with a lower water to cement ratio.

**Figure 14**

*Bar Graph of Specific Gravity of RCA*

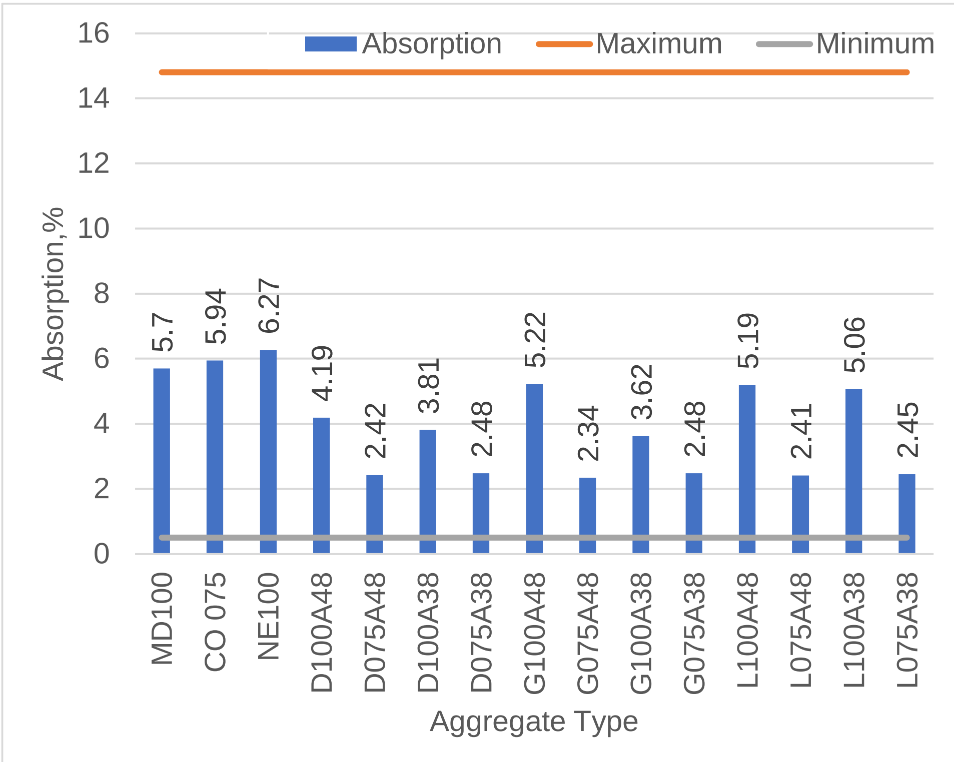


### *4.1.3 Absorption of Aggregates*

Figure 15 shows the absorption of RCA ranging from 2.48% to 6.27 %, including the manufactured and commercial, which shows a significant increase compared to absorption of natural aggregates. The absorption capacity of natural aggregates is 0.2 to 4% and for RCA it ranges from 0.5% to 14.8% [40]. The results in Figure 15 fall within this range. RCA has a higher absorption capacity due to the adhered mortar present in RCA, which exhibits higher porosity than the natural aggregates. Results also show that absorption capacity of RCA is related to the w/c ratio of the parent concrete. For example, Dolomite 1" with w/c of 0.38 offers water absorption of 3.81% and increases to 4.19% when w/c of 0.48 is used. Due to having rigid mortar, the absorption capacity of RCA is 10 to 20 times more than NA [41]. The adhered mortar to the RCA is accountable for the increase. The size and shape of the aggregate also influence the absorption rate. Therefore, in Figure 15, it is shown that absorption of aggregate increases with the decrease of the nominal maximum size of aggregates.

**Figure 15**

*Bar Graph of Absorption Rate of RCA*




### *4.1.4 Residual Mortar*

The quantity of mortar attached to the natural aggregate in RCA is referred to as residual mortar content. The air voids existing in residual mortar affect the density, porosity, and strength of the concrete. Having air voids in the mortar adds extra weight to the aggregate, which causes lower specific gravity and higher absorption.

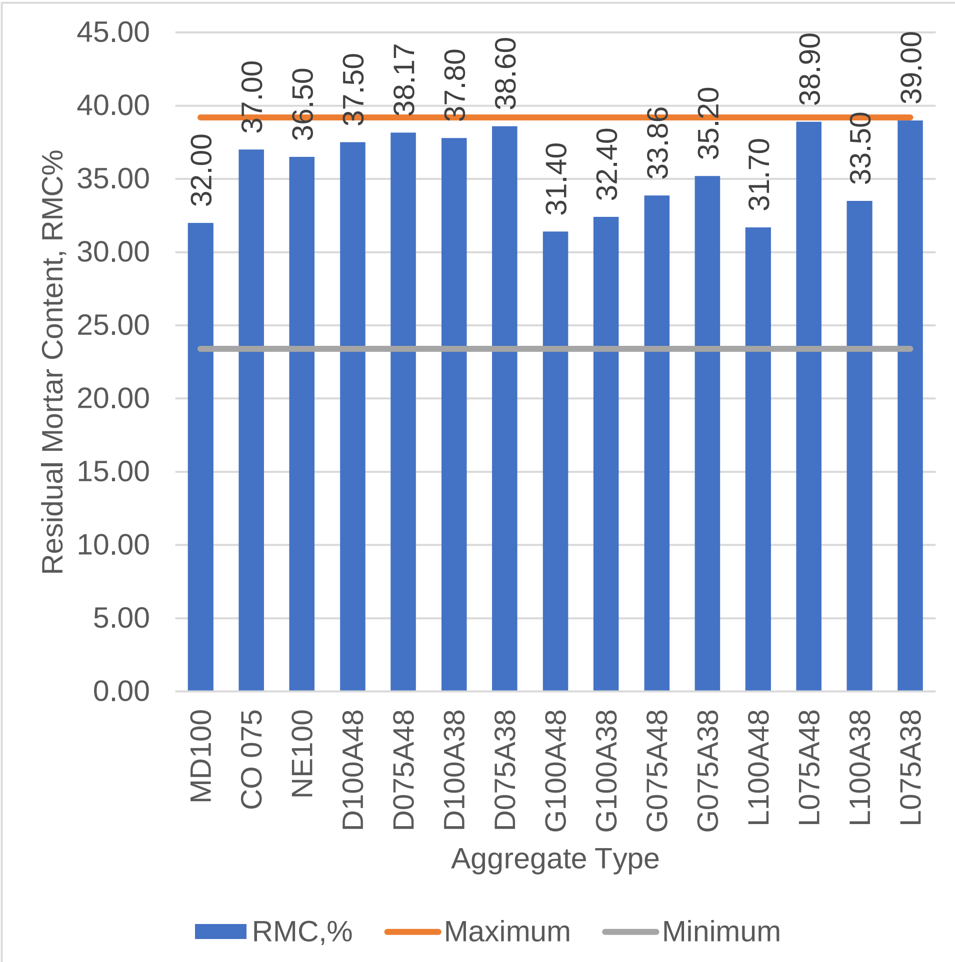
RCA's typical range of residual mortar content is 23.4% to 39.2%, with an average of 31.6% [42]. The residual mortar content measured in this study ranges from 31.4 % to

39%, with a mean value of 35.2%, including manufactured and commercial aggregates. Therefore, all the data presented in Figure 16 fall within the typical range.

It is observed that the aggregate manufactured from concrete having a lower water to cement ratio has a higher residual mortar content. Because RCA from concrete having a lower water to cement ratio is denser and more rigid than the aggregates that have a higher water to cement ratio. The mortar from concrete with a lower w/c is stronger and therefore does not break from the aggregate during crushing. Therefore, the residual mortar content of RCA produced from concrete with a lower water to cement ratio is higher than the others. For example, Dolomite-based RCA having 1" NMAS with w/c of 0.38 has higher residual mortar content than the same aggregate with w/c of 0.48. The results also show that Granite-based RCA having 1" NMAS with w/c of 0.48 has the lowest RMC%, and Limestone-based RCA having ¾" NMAS with w/c of 0.38 has the highest RMC%.

**Figure 16**

*Bar Graph of Residual Mortar Content of RCA, %*



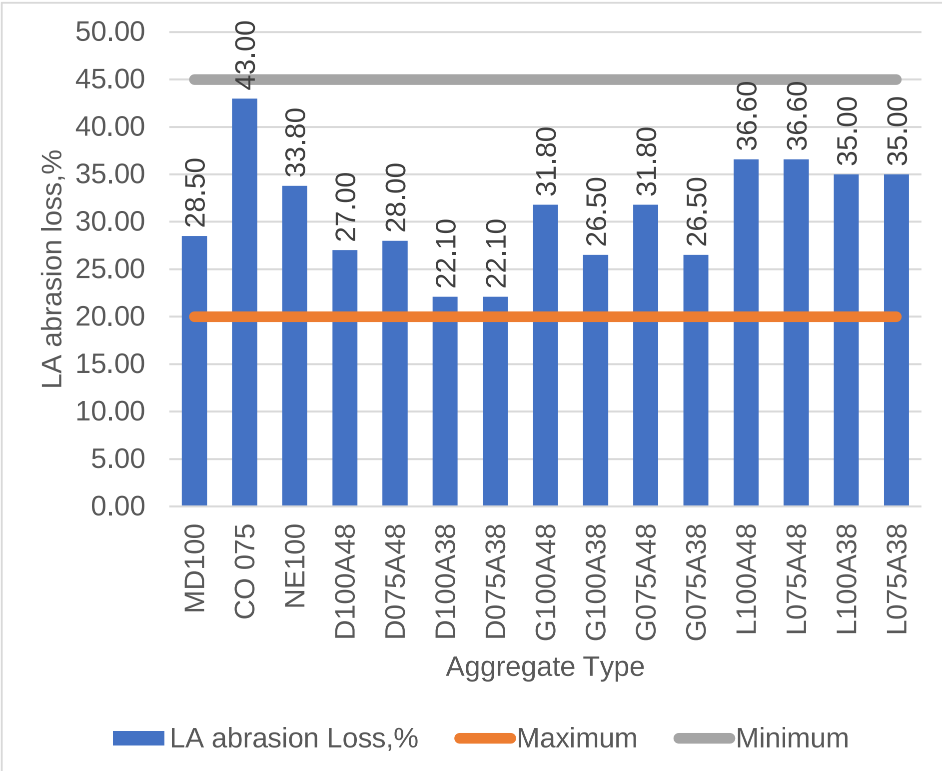

### *4.1.5 LA Abrasion*

LA abrasion tests were performed on RCA aggregates, and the results are presented in Figure 17. The higher percentage loss value indicates a lower resistance to abrasion or weaker aggregates, and therefore, a lower value is generally desirable for concrete with higher abrasion resistance. In Figure 17, Limestone-based RCA shows the most increased abrasion related to dolomite and granite, which agrees with others.

Dolomite and granite as natural aggregates have low LA abrasion values compared to when they are obtained from RCA. For example, natural granite in shows LA abrasion of 25.0%. It is mentioned in Table 3. The corresponding value for RCA with granite aggregate and water to cement ratio of 0.38 is 26.5 %. The LA abrasion value for the corresponding RCA increases to 31.8% when a water to cement ratio of 0.48 is used. This is because the mortar attached to the granite is weaker and, therefore, provides higher LA abrasion than the virgin aggregates. Increasing the water to cement ratio also lowers the compressive strength of the concrete and hence, further increases the LA abrasion loss. The range of LA abrasion loss of RCA, reported in literature, is 20% to 45%, and the findings in Figure 17 falls within the range.

**Figure 17**

*Bar Graph of LA Abrasion of RCA, %*




## 4.2 Performance of the Durability Test on Hardened Concrete

### *4.2.1 Surface Electrical Resistivity*

This test was performed on the concrete cylinders made by RCA. The test was performed after 7 days, 14days, 28days, and 90days of the concrete mixing. They were cured in a moist tank.

Surface resistivity is the resistance to leakage current along the surface of the concrete. Concrete that has higher permeability has lower chloride ion penetration resistance. On the other hand, concrete with a higher water to cement ratio has more pores, absorbing more water. Therefore, it will have less chloride ion penetration resistance. The findings in Figure 18 show that concrete with lower water to cement ratio has higher electrical resistivity, which means it has high chloride ion penetration resistance than concrete with a higher water to cement ratio. According to the range of electrical resistivity in Table 10, the results of electrical resistivity at the age of 7 days, 14day and 28 days show high chloride ion penetration. When the age of the concrete reaches 90 days, the concrete has moderate chloride ion penetration.

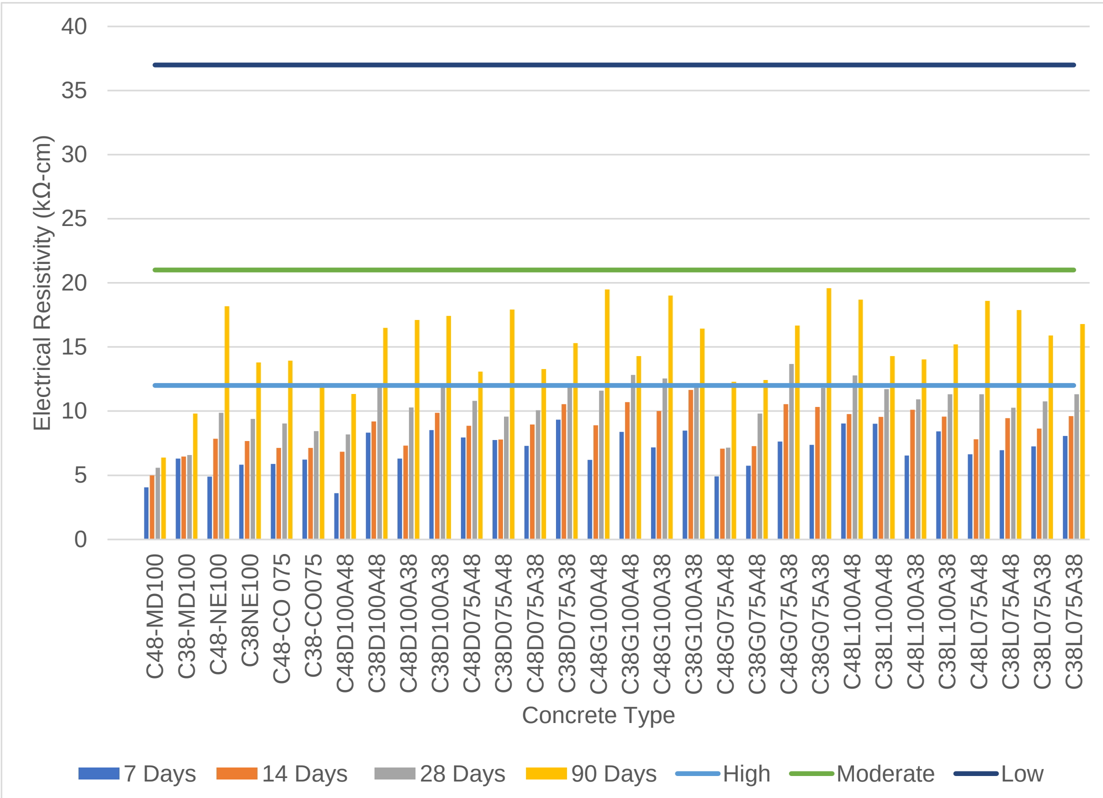
**Table 10**

*Range of Electrical Resistivity [38]*

| Chloride Ion Penetration | Electrical Resistivity (kΩ-cm) |
|---|---|
| High | <12 |
| Moderate | 12-21 |
| Low | 21-37 |
| Very Low | 37-254 |
| Negligible | >254 |

**Figure 18**

*Bar Graph of Surface Resistivity of Concrete, kΩ-cm*




### *4.2.2 Resistance to Degradation of Concrete*

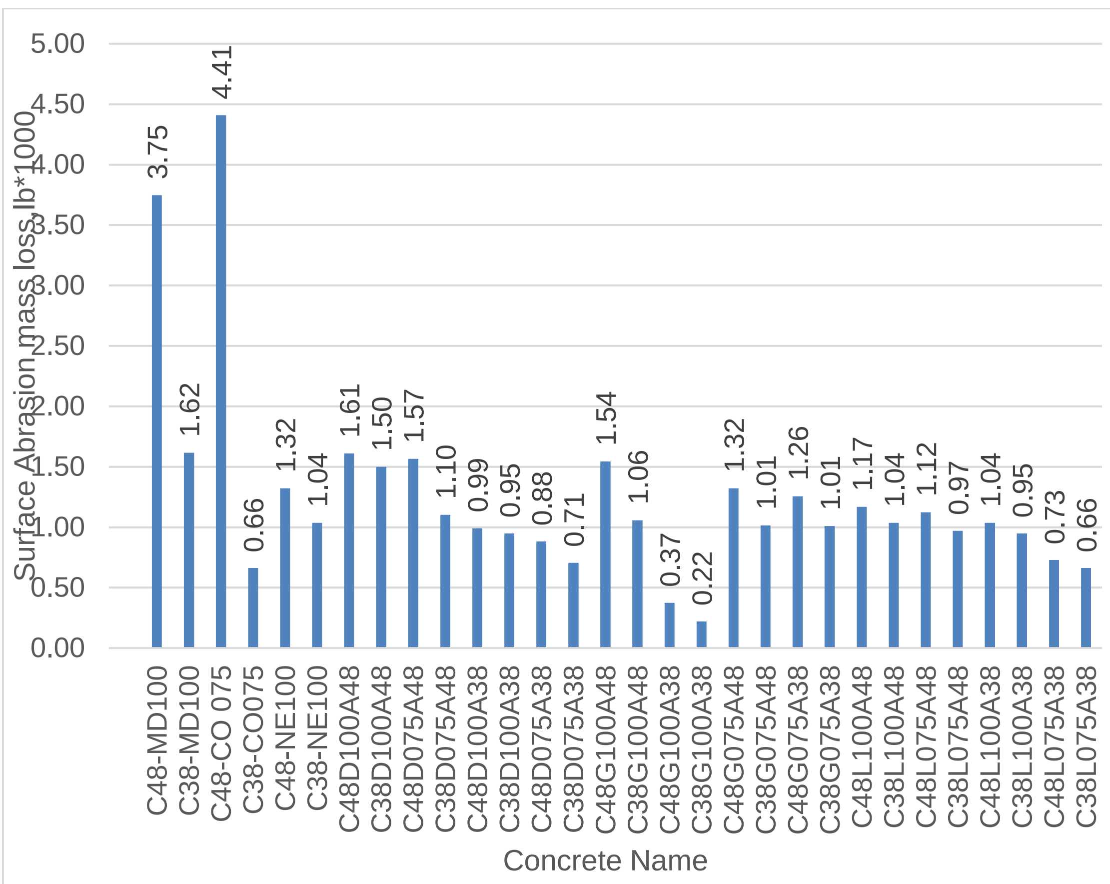
This test method covers a procedure for determining the resistance of either concrete or mortar to abrasion. This has been successfully used in the quality control of highway and bridge concrete subject to traffic. This experiment was performed on concrete made of coarse RCA. The concrete was cured for 28 days before performing the test.

The concrete that has lower w/c ratio is denser and stronger. Therefore, the surface abrasion mass loss is less for concrete with lower w/c ratio. For example, in

Figure 19, the concrete made of Dolomite-based RCA with 0.48 w/c ratio has higher abrasion mass loss than the concrete made of Dolomite-based RCA with 0.38 w/c ratio. Figure 19 also shows that the abrasion mass loss Maryland 1" w/c ratio 0.48 and Colorado 3/4" w/c ratio 0.48 has very high abrasion mass loss due having very low strength.

**Figure 19**

*Bar Graph of Surface Abrasion Mass Loss of Concrete, lb*1000*



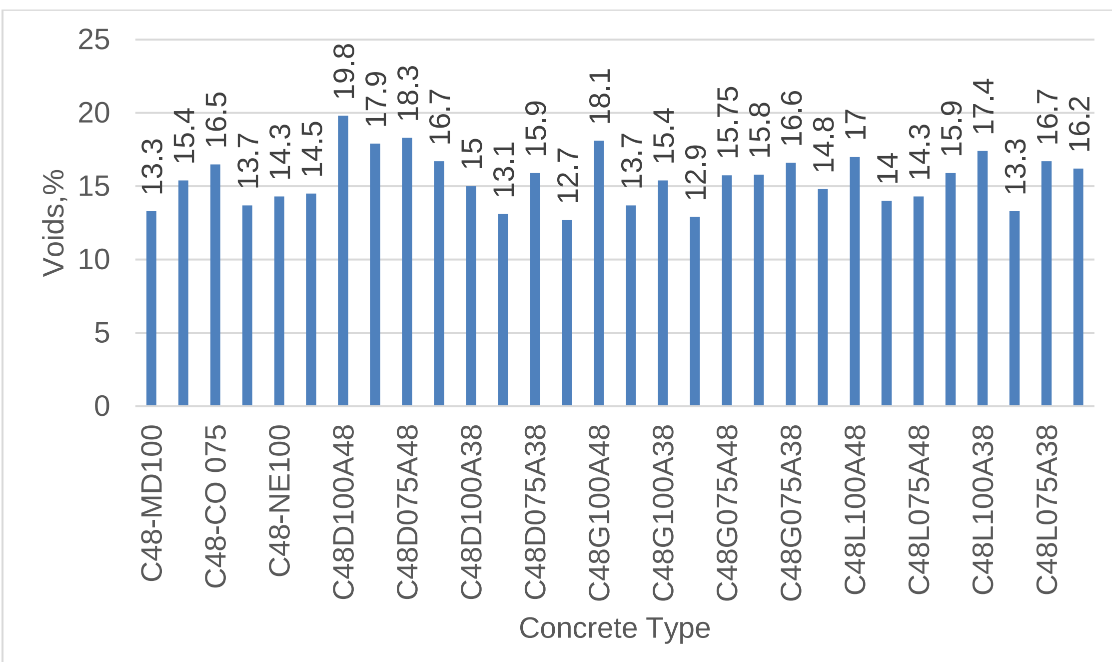
### *4.2.3 Density, Absorption, and Voids in Hardened Concrete*

This test was performed on concrete made of coarse RCA. The concrete was cured for 28 days before performing the test.

The concrete having lower water to cement have less voids because they are dense. Therefore, they absorb less water. On the contrary, the concrete having higher water to cement absorb more water due to having more voids. For example, in Figure 20, the concrete made of Dolomite-based RCA with 0.48 w/c ratio has higher voids than the concrete made of Dolomite-based RCA with 0.38 w/c ratio.

**Figure 20**

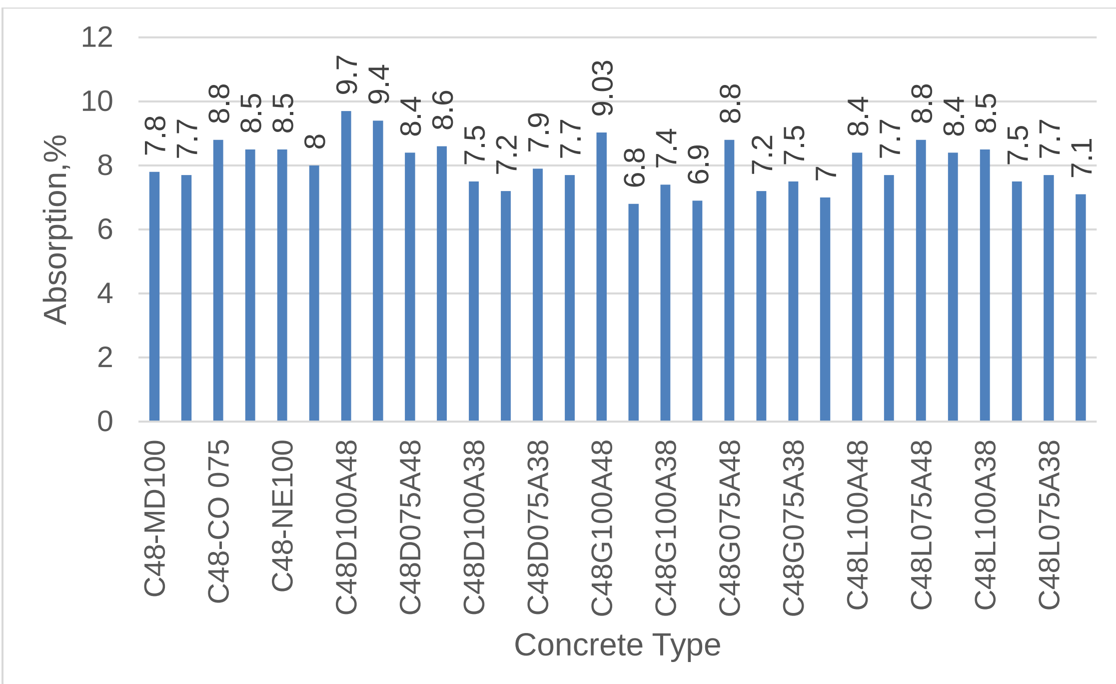
*Bar Graph of Voids in Concrete, %*



The concrete which has higher voids will have higher absorption. For example, In Figure 21, the concrete made of Dolomite-based RCA with 0.48 w/c ratio has higher absorption due to having more voids than the concrete made of Dolomite-based RCA with 0.38 w/c ratio.

**Figure 21**

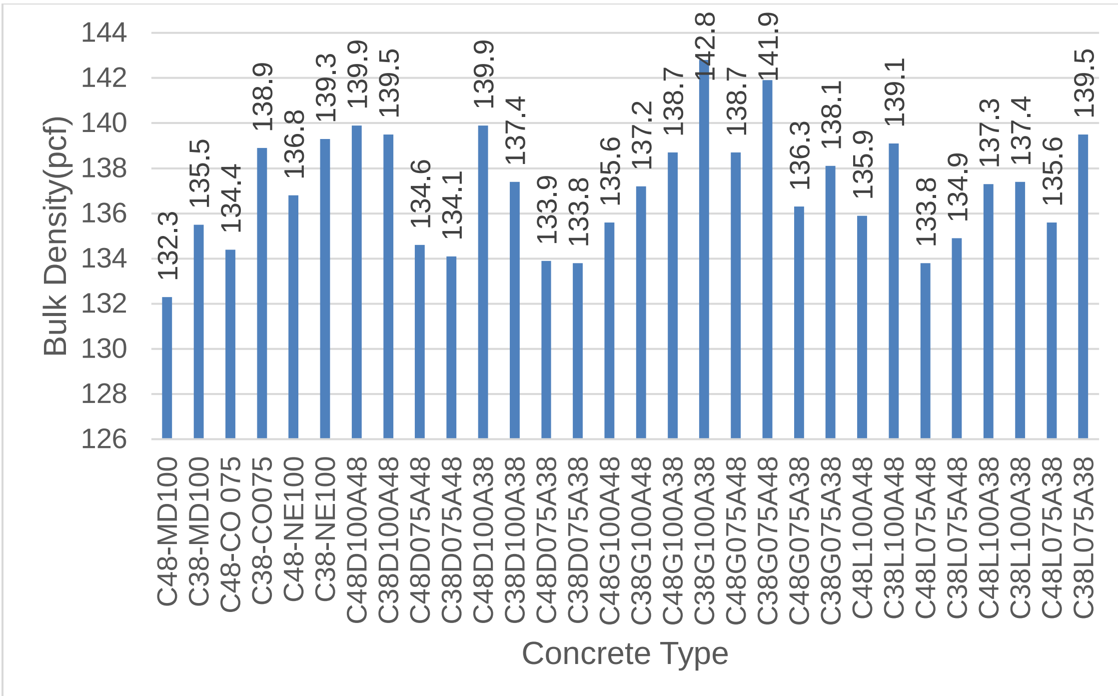
*Bar Graph of Absorption in Concrete, %*




The density of concrete should be higher for the concrete which has lower w/c ratio because those concrete are denser than the concrete has higher w/c ratio. For example, in Figure 22, the concrete made of Granite-based RCA with 0.48 w/c ratio has lower density than the concrete made of Granite-based RCA with 0.38 w/c ratio.

**Figure 22**

*Bar Graph of Bulk Density of Concrete, pcf*




## 4.3 Correlations Between RCA Properties

### *4.3.1 Relationship of LA Abrasion Loss to Other Properties*

The measured values from the LA abrasion testing of RCA depend on several properties such as strength and surface abrasion resistance of concrete. Therefore, the LA abrasion of natural aggregates was statistically analyzed to develop an equation that can correlate the LA abrasion of RCA with other properties. The certainty of the analysis depends on the coefficient of determination (R2) for each regression. The stepwise regression model was used.

$R^2$ represents the goodness of fit of a model. It represents the proportion of the variance for a dependent variable explained by the independent variables in a regression model. Here, LA abrasion of RCA is a dependent variable, and strength and surface abrasion of concrete and LA abrasion of natural aggregates are independent variables. The $R^2$ of 1 indicates the regression predicts perfectly fit the data. In Equation 1, the regression analysis was formed using the LA abrasion of RCA, LA abrasion of natural aggregate, strength, and surface abrasion to get a good prediction model with $R^2 = 0.998$ is close to 1, and all data are statistically significant since Prob>|t| is less than 0.05. Therefore, the data and the equation are acceptable.

$$LA_{RCA} = 69.5412 + 7.8968\text{x}10^{-7} \times (f_c)^2 - 0.0001 \times f_c \times LA_{n.agg} + 0.0096 \times f_c \times SA + 1.0604 \times LA_{n.agg} - 55.7223 \times SA - 0.0134 \times f_c \quad (1)$$

$LA_{RCA}$ – Los Angeles abrasion, %

$f_c$ – the strength of Parent Concrete, psi

$SA$ – surface abrasion of Parent Concrete, lb*1000

$LA_{n.agg}$ – Los Angeles abrasion of natural aggregate in parent concrete, %

If the data of L.A abrasion of natural aggregate and mixture proportion is not available; Equation 2 can be used. They are also statistically significant, and $R^2$ reduces to 0.908.

$$LA_{RCA} = 84.47684 + 1.28039\text{x } 10^{-6} * (f_c)^2 + 34.29797 *SA - 0.01933* f_c \quad (2)$$

$LA_{RCA}$ – Los Angeles abrasion, %

$f_c$ – strength, psi

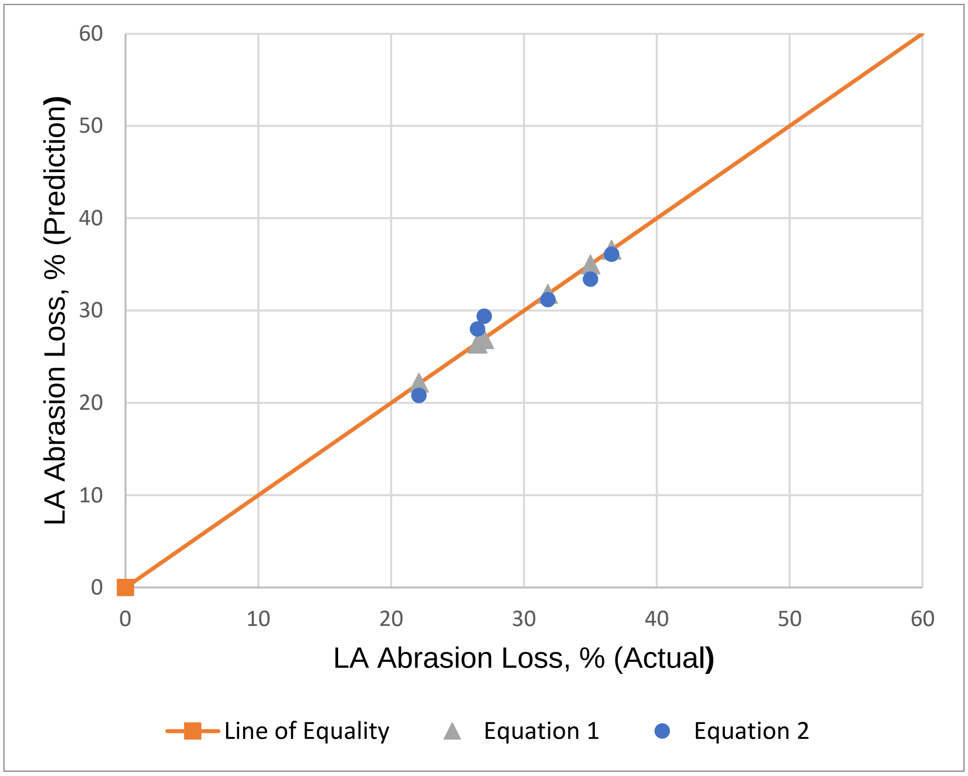
$SA$ – surface abrasion of Parent Concrete, lb*1000

For example, the experimental value of LA abrasion of RCA for Limestone- based RCA is 36.6%. By applying equation 1(a), the prediction of LA abrasion of RCA for the same aggregate is 36.6 with 99.8% certainty, and from equation 1(b), the prediction for the same aggregate is 36.1 with 90.8% certainty.

Figure 23 shows the comparison between the prediction value found from the equations and the experimental values of LA abrasion mass loss.

**Figure 23**

*Prediction Value Vs Actual Value of LA Abrasion Mass Loss, %*




### *4.3.2 Statistical Model for Surface Resistivity of Concrete*

This analysis aims to predict the electrical resistivity of the concrete only by knowing the properties of the RCA. Instead of measuring the electrical resistivity of the concrete sample manually, it can be predicted by using the model equation.

Here, electrical resistivity is a dependent variable, and absorption of RCA, the volume of new mortar, residual mortar content of RCA, and volume of RCA are independent variables. Though R2 of 1 indicates the regression predicts perfectly fit the data, the value of $R^2$ coefficient more than 0.50 is acceptable.

The analysis was grouped by two sizes, 1" and 3/4" nominal maximum aggregate size (NMAS). Two model equations were analyzed from each group.

In Equation 3, the regression analysis was formed by using electrical resistivity, absorption of RCA, the volume of new mortar, the volume of RCA, residual mortar content of RCA, and water to cement ratio of the concrete made of RCA. The equation was grouped by RCA 1" NMAS to get an excellent prediction model with $R^2 = 0.862$, more than 0.5. From that model equation, it has been found that when the residual mortar content increases, the concrete's electrical resistivity will decrease. Indicating that if the independent variables are known, there is 86.2% certainty about the electrical resistivity and all variables are statistically significant due to having Prob>|t| less than 0.05. Therefore, the data and the equation are acceptable.

$$Resistivity_{RCA} = -395.14 - 34.63*Absorption_{RCA} - 9.49*RMC + 2.66*Volume_{RCA} + 916.72*Volume_{mortar} + 795.03*w/c + 1.07*RMC*Absorption_{RCA} + 11.12*Volume_{RCA}*RMC - 1251.75*Volume_{mortar}*w/c \quad (3)$$

$Resistivity_{RCA}$ – Electrical Resistivity, kΩ-cm

$Absorption_{RCA}$ – Absorption of RCA, %

$RMC$ – Residual Mortar Content of RCA, %

$Volume_{mortar}$ – Volume of new mortar, pcy

$Volume_{RCA}$ – Volume of RCA, pcy

$w/c$ – Water to cement ratio of concrete made of RCA

In Equation 4, the regression analysis was formed by using electrical resistivity, absorption of RCA, the volume of RCA, residual mortar content of RCA. Here, the equation was grouped by RCA 3/4" NMAS. The model was built with 76.9% certainty about what the electrical resistivity will be. Since the R Squared value is more than 50%, the model is acceptable.

$$Resistivity_{RCA} = -6.91 - 51.87 * Absorption_{RCA} + 1.07 * RMC + 780.26 * Volume_{RCA} - 21.93 * Volume_{RCA} * RMC + 1.34 * RMC * Absorption_{RCA} \quad (4)$$

$Resistivity_{RCA}$ – Electrical Resistivity, kΩ-cm

$Absorption_{RCA}$ – Absorption of RCA, %

$RMC$ – Residual Mortar Content of RCA, %

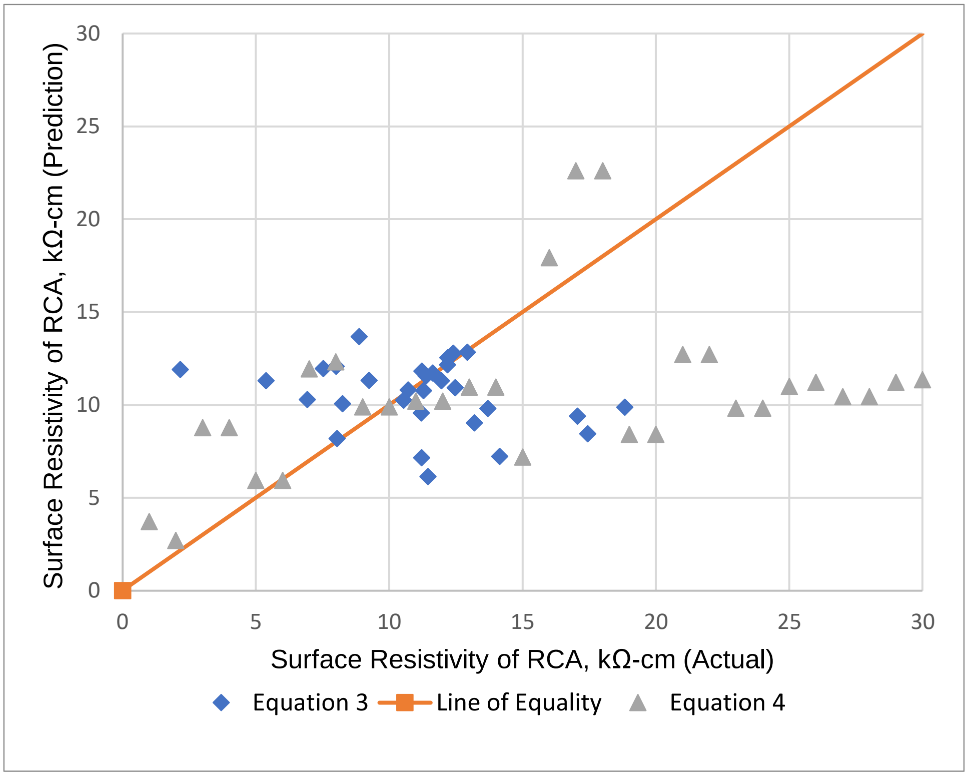
$Volume_{RCA}$ – Volume of RCA, pcy

To verify this equation, the experimental results of the concrete made of commercial RCA and the prediction of the same concrete-based RCA were compared. For example, the experiment resistivity result of the concrete made of commercial RCA C48-CO075 is 9.03. By applying Equation 3, the prediction of the resistivity of the same concrete is 8.88 with 86.2% certainty, and from Equation 4, the prediction of the resistivity of the same concrete is 13.44 with 76.9% certainty.

Figure 24 shows the comparison between the prediction value found from the equations and the experimental values of surface resistivity of RCA (kΩ-cm).

**Figure 24**

*Prediction Value Vs Actual Value of Surface Resistivity of Concrete, kΩ-cm*



#### *4.3.3 Relationship of Voids to Other Properties*

According to the stated model equation, voids in concrete depend on the absorption of RCA, residual mortar content of RCA, the volume of RCA, and the water to cement ratio of the concrete are independent variables. The analysis was grouped by two sizes, 1" and 3/4" nominal maximum aggregate size (NMAS). Two model equations were analyzed from each group.

In Equation 5, the regression analysis was formed by using Voids in concrete, absorption of RCA, residual mortar content of RCA, the volume of RCA, and water to cement ratio of concrete made of RCA. From that model equation, it has been found that when the water to cement ratio decreases, the concrete's electrical resistivity will increase. The equation was grouped by RCA 1" NMAS to get an excellent prediction model with $R^2$ = 0.747, more than 0.5. This means that there is 74.7% certainty about the electrical resistivity if the independent variables are known. All variables are statistically significant. Therefore, the data and the equation are acceptable.

$$\text{Voids}_{\text{concrete}}=-4.22-58.39*\mathit{Absorption}_{RCA}-0.31*\mathit{RMC}-908.69*\mathit{Volume}_{RCA}+18.19*w/c+162.91*\mathit{Volume}_{RCA}*\mathit{Absorption}_{RCA} \quad (5)$$

Here,

$\text{Voids}_{\text{concrete}}$= Voids in Concrete made of RCA, %

$\mathit{Absorption}_{RCA}$– Absorption of RCA, %

*RMC*– Residual Mortar Content of RCA, %

$\mathit{Volume}_{RCA}$ – Volume of RCA, pcy

*w/c*- Water to cement ratio of concrete made of RCA

In Equation 6, the regression analysis was formed by using Voids in concrete, absorption of RCA, residual mortar content of RCA, the volume of RCA, and water to cement ratio of concrete made of RCA. From that model equation, it has been found that when the water to cement ratio decreases, the concrete's electrical resistivity will increase. Therefore, the equation was grouped by RCA ¾ " NMAS to get a good prediction model with $R^2$ = 0.872, more than 0.5. This means that if the independent variables are known, there is 87.2% certainty about the voids in concrete. Therefore, the data and the equation are acceptable.

$$\text{Voids in concrete} = -1881.41+151.32*\mathit{Absorption}_{RCA}+34.38*\mathit{RMC}+5542.97*\mathit{Volume}_{RCA}-15.77*w/c-100.46*\mathit{Volume}_{RCA}*\mathit{RMC}-437.89*\text{v(rca)}*\mathit{Absorption}_{RCA} \quad (6)$$

$\mathit{Voids}_{concrete}$= Voids in Concrete made of RCA, %

$\mathit{Absorption}_{RCA}$– Absorption of RCA, %

*RMC*– Residual Mortar Content of RCA, %

$\mathit{Volume}_{RCA}$ – Volume of RCA, pcy

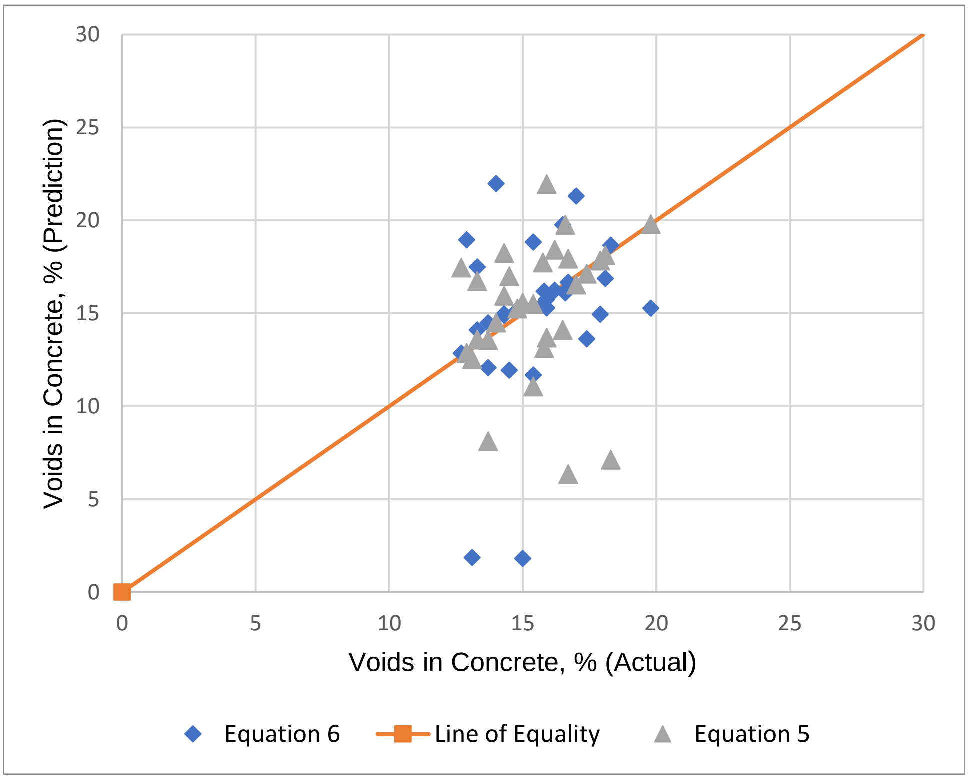
*w/c*- Water to cement ratio of concrete made of RCA

The experimental value of voids of C48-MD100 is 13.30. From Equation 5, the result of the percentage of the voids of the same concrete is 16.99%, with 74.7% certainty. Similarly, from Equation 6, the prediction of voids for the same concrete is

14.63% with 87.2%. Figure25 shows the comparison between the prediction value found from the equations and the experimental values of voids of hardened concrete, %

**Figure 25**

*Prediction Value Vs Actual Value of Voids in Hardened Concrete, %*



# Chapter V

# Conclusions and Recommendations

## 5.1 Summary and Conclusions

This study used three types of aggregates, dolomite, granite, and limestone, to make concrete. Concrete was manufactured with each aggregate type with water to cement ratios of 0.48 and 0.38. Concrete is then crushed and graded to obtain two nominal recycled concrete aggregates, 1" and ¾". In contrast, test cylinder specimens were tested to determine commercial and manufactured concrete's electrical resistivity and abrasion resistance.

The RCAs were tested for bulk density, specific gravity, resistance to degradation to abrasion, and residual mortar. Then the RCA was used in concrete mixing. The concrete samples were cured for 28days and tested for resistance to degradation, electrical resistivity, and voids in concrete.

- The bulk density of dolomite-based RCA is the highest among all the manufactured RCA, and NE100 (Nebraska 1" NMAS) has the highest bulk density among all the commercial RCA.
- The lower water to cement ratio of parent concrete tends to have a higher specific gravity RCA. For example, dolomite-based RCA of ¾" NMAS with water to cement ratio 0.38 has a specific gravity of 2.48, and dolomite-based RCA of ¾" NMAS with water to cement ratio of 0.48 has a specific gravity of 2.42.

- RCA with a smaller NMAS tends to have a lower absorption. For example, dolomite-based RCA with ¾" NMAS has lower absorption than dolomite-based RCA with 1" NMAS.

- Aggregate having lower water to cement ratio has higher RMC. For example, dolomite-based RCA having 1" NMAS with w/c of 0.38 has higher residual mortar content than the same aggregate with w/c of 0.48.

- The mortar attached to the granite is weaker and provides higher LA abrasion than the virgin aggregates. For example, granite as natural aggregates have lower LA compared to when they are obtained from RCA, which is 25%. The corresponding value for RCA with granite aggregate and water to cement ratio of 0.38 is 26.5 %. The LA abrasion value for the corresponding RCA increases to 31.8% when a water to cement ratio of 0.48 is used.

- A regression model for LA abrasion of RCA incorporating parent concrete strength, parent concrete surface abrasion, and natural aggregates LA abrasion as variables was developed. The results showed that LA abrasion of RCA increases when the parent concrete's surface abrasion and natural aggregate LA abrasion increases, but will decrease when the parent concrete's strength increases.

- A regression model for the surface resistivity of RCA incorporating absorption of RCA, volume of RCA, volume of mortar, w/c of concrete, residual mortar content as variables was developed. The results showed that the surface resistivity of concrete with RCA increases when the absorption of RCA and, w/c of concrete decreases. Moreover, as volume of mortar decreases, the resistivity of concrete increases.

- A regression model for voids in concrete incorporating the absorption of RCA, residual mortar content, volume of RCA, as variables was developed. The results showed that voids in concrete increases when the absorption of RCA, the residual mortar content and the volume of RCA increases.

### 5.1.1 Recommendations for Future Work

- A wider range of water to cement ratios can be studied. Parent concrete with a higher water to cement ratio can be used to represent RCA with even lower strengths. Lower water to cement ratio can also be used to create higher strength new concrete with RCA. Lower water to cement ratio may have fewer pores, giving increased strength to concrete and increasing the durability of the concrete.
- Study the effect of supplementary cementitious materials in concrete with a wide range of RCA. Concrete mixed in the present study uses Type I Portland cement. Supplementary cementitious materials will contribute to improving the durability of concrete with RCA.

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# Appendix

## Additional Tabulated Data

**Table A1**

*Properties of RCA*

| RCA | Specific Gravity | Bulk Density, pcf | Absorption, % | LA Abrasion Loss, % | Residual Mortar Content, % |
|---|---|---|---|---|---|
| MD100 | 2.45 | 76.94 | 5.7 | 28.50 | 32.00 |
| CO 075 | 2.37 | 78.34 | 5.94 | 43.00 | 37.00 |
| NE100 | 2.35 | 82.51 | 6.27 | 33.80 | 36.50 |
| D100A48 | 2.49 | 77.47 | 4.19 | 27.00 | 37.50 |
| D075A48 | 2.42 | 86.64 | 2.42 | 28.00 | 38.17 |
| D100A38 | 2.42 | 87.96 | 3.81 | 22.10 | 37.80 |
| D075A38 | 2.48 | 86.42 | 2.48 | 22.10 | 38.60 |
| G100A48 | 2.34 | 81.39 | 5.22 | 31.80 | 31.40 |
| G100A38 | 2.34 | 81.35 | 2.34 | 26.50 | 32.40 |
| G075A48 | 2.46 | 83.63 | 3.62 | 31.80 | 33.86 |
| G075A38 | 2.48 | 86.49 | 2.48 | 26.50 | 35.20 |
| L100A48 | 2.39 | 82.67 | 5.19 | 36.60 | 31.70 |
| L075A48 | 2.39 | 82.59 | 2.41 | 36.60 | 38.90 |
| L100A38 | 2.43 | 83.33 | 5.06 | 35.00 | 33.50 |
| L075A38 | 2.43 | 82.41 | 2.45 | 35.00 | 39.00 |

**Table A2**

*Properties of Concrete Made of RCA*

| Concrete | W/C of New Concrete | Volume of RCA, pcy | Vol Mortar in Concrete, pcy | Electrical Resistivity (kΩ-cm) | Voids, % | Absorption of concrete, % | Surface abrasion, lb |
|---|---|---|---|---|---|---|---|
| C48-MD100 | 0.48 | 0.352 | 0.648 | 6.14 | 13.3 | 7.8 | 0.00375 |
| C38-MD100 | 0.38 | 0.339 | 0.661 | 7.23 | 15.4 | 7.7 | 0.00162 |
| C48-CO 075 | 0.48 | 0.331 | 0.669 | 9.03 | 16.5 | 8.8 | 0.00441 |
| C38-CO075 | 0.38 | 0.331 | 0.669 | 8.44 | 13.7 | 8.5 | 0.00066 |
| C48-NE100 | 0.48 | 0.379 | 0.621 | 9.87 | 14.3 | 8.5 | 0.00132 |
| C38-NE100 | 0.38 | 0.379 | 0.621 | 9.39 | 14.5 | 8 | 0.00104 |
| C48D100A48 | 0.48 | 0.335 | 0.665 | 8.19 | 19.8 | 9.7 | 0.00161 |
| C38D100A48 | 0.38 | 0.335 | 0.665 | 12.08 | 17.9 | 9.4 | 0.00150 |
| C48D075A48 | 0.48 | 0.361 | 0.639 | 10.81 | 18.3 | 8.4 | 0.00157 |
| C38D075A48 | 0.38 | 0.361 | 0.639 | 9.57 | 16.7 | 8.6 | 0.00110 |
| C48D100A38 | 0.48 | 0.384 | 0.616 | 10.28 | 15 | 7.5 | 0.00099 |
| C38D100A38 | 0.38 | 0.384 | 0.616 | 11.95 | 13.1 | 7.2 | 0.00095 |
| C48D075A38 | 0.48 | 0.346 | 0.654 | 10.07 | 15.9 | 7.9 | 0.00088 |
| C38D075A38 | 0.38 | 0.346 | 0.654 | 11.9 | 12.7 | 7.7 | 0.00071 |
| C48G100A48 | 0.48 | 0.345 | 0.655 | 11.56 | 18.1 | 9.03 | 0.00154 |
| C38G100A48 | 0.38 | 0.366 | 0.634 | 12.83 | 13.7 | 6.8 | 0.00106 |
| C48G100A38 | 0.48 | 0.365 | 0.635 | 12.54 | 15.4 | 7.4 | 0.00037 |
| C38G100A38 | 0.38 | 0.365 | 0.635 | 12.17 | 12.9 | 6.9 | 0.00022 |
| C48G075A48 | 0.48 | 0.345 | 0.655 | 7.15 | 15.75 | 8.8 | 0.00132 |
| C38G075A48 | 0.38 | 0.345 | 0.655 | 9.81 | 15.8 | 7.2 | 0.00101 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| C48G075A38 | 0.38 | 0.346 | 0.654 | 13.68 | 16.6 | 7.5 | 0.00126 |
| C38G075A38 | 0.38 | 0.346 | 0.654 | 11.81 | 14.8 | 7 | 0.00101 |
| C48L100A48 | 0.48 | 0.371 | 0.629 | 12.78 | 17 | 8.4 | 0.00117 |
| C38L100A48 | 0.38 | 0.371 | 0.629 | 11.71 | 14 | 7.7 | 0.00104 |
| C48L075A48 | 0.48 | 0.344 | 0.656 | 10.26 | 14.3 | 8.8 | 0.00112 |
| C38L075A48 | 0.38 | 0.340 | 0.660 | 10.76 | 15.9 | 8.4 | 0.00097 |
| C48L100A38 | 0.48 | 0.369 | 0.631 | 10.92 | 17.4 | 8.5 | 0.00104 |
| C38L100A38 | 0.38 | 0.369 | 0.631 | 11.31 | 13.3 | 7.5 | 0.00095 |
| C48L075A38 | 0.48 | 0.341 | 0.659 | 11.32 | 16.7 | 7.7 | 0.00073 |
| C38L075A38 | 0.38 | 0.334 | 0.666 | 11.31 | 16.2 | 7.1 | 0.00066 |

**Table A3**

*Properties of Parent Concrete*

| Parent Concrete | Compressive Strength (psi) | Surface Abrasion,lb |
|---|---|---|
| D100A48 | 6991 | 0.00051 |
| D100A38 | 8704 | 0.00022 |
| G100A48 | 5209 | 0.00037 |
| G100A38 | 9805 | 0.00029 |
| L100A48 | 6301 | 0.00066 |
| L100A38 | 9077 | 0.00055 |

**Table A4**

*Parameter Estimates of Equation 1*

| Term | Estimate | Prob>\|t\| | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Intercept | 13.019495 | <.0001* | 10.91691 | 15.122079 |
| Surface abrasion, lbx1000 | 18.015642 | <.0001* | 14.133166 | 21.898119 |
| LA abrasion of Natural aggregate,% | 0.292268 | <.0001* | 0.2284078 | 0.3561283 |
| Strength (psi) | -7.828e-5 | 0.6415 | -0.000419 | 0.000262 |
| (LA abrasion of Natural aggregate,%-28.6667)*(Strength (psi)-7681.03) | -0.000126 | 0.0408* | -0.000247 | -5.684e-6 |
| (Strength (psi)-7681.03)*(Strength (psi)-7681.03) | 7.8968e-7 | <.0001* | 7.0277e-7 | 8.7659e-7 |
| (Surface abrasion, lbx1000-0.43333)*(Strength (psi)-7681.03) | 0.0096092 | 0.0077* | 0.0027431 | 0.0164753 |

**Table A4**

*Parameter Estimates of Equation 2*

| Term | Estimate | Prob>\|t\| | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Intercept | 8.9361571 | 0.0006* | 4.1641552 | 13.708159 |
| Strength (psi) | 0.0003385 | 0.0921 | -5.861e-5 | 0.0007357 |
| Surface abrasion, lbx1000 | 34.297968 | <.0001* | 29.969698 | 38.626237 |
| (Strength (psi)-7681.03)*(Strength (psi)-7681.03) | 1.2804e-6 | <.0001* | 9.6728e-7 | 1.5935e-6 |

**Table A5**

*Parameter Estimates of Equation 3*

| Term | Estimate | Prob>\|t\| | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Intercept | -359.7695 | 0.0004* | -540.4479 | -179.0912 |
| Absorption of RCA, % | 2.8868921 | <.0001* | 2.1737997 | 3.5999846 |
| RMC of RCA | -0.586574 | <.0001* | -0.716747 | -0.456401 |
| Volume of RCA, pcy | 392.05917 | 0.0001* | 211.69335 | 572.42498 |
| Volume of New Mortar | 378.47422 | 0.0003* | 193.62313 | 563.32532 |
| New concrete W/C | -12.44919 | <.0001* | -17.76503 | -7.133341 |
| (Absorption of RCA, %-4.62083)*(RMC of RCA-35.0117) | 1.0715118 | <.0001* | 0.8311751 | 1.3118486 |
| (RMC of RCA-35.0117)*(Volume of RCA, pcy-0.35567) | 11.122049 | 0.0026* | 4.2433109 | 18.000787 |
| (Volume of New Mortar-0.64508)*(New concrete W/C-0.43) | -1251.745 | <.0001* | -1743.887 | -759.6043 |

**Table A6**

*Parameter Estimates of Equation 4*

| Term | Estimate | Prob>\|t\| | Lower 95% | Upper 95% |
|---|---|---|---|---|
| Intercept | 59.11372 | <.0001* | 40.431618 | 77.795821 |
| Absorption of RCA, % | -3.143658 | <.0001* | -4.150511 | -2.136804 |
| RMC of RCA | -0.751952 | <.0001* | -1.052025 | -0.451879 |
| Volume of RCA, pcy | -16.43131 | 0.1377 | -38.43351 | 5.5708804 |
| (Absorption of RCA, %-4.4425)*(RMC of RCA-36.3267) | 1.3413877 | <.0001* | 0.955196 | 1.7275794 |
| (RMC of RCA-36.3267)*(Volume of RCA, pcy-0.35458) | -21.9314 | 0.0003* | -32.95878 | -10.90403 |

**Table A7**

*Parameter Estimates of Equation 5*

| **Term** | **Estimate** | **Prob>\|t\|** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|---|
| Intercept | 220.55406 | 0.0005* | 105.10171 | 336.00642 |
| Absorption of RCA, % | -1.078971 | <.0001* | -1.440982 | -0.716961 |
| RMC of RCA | -0.218757 | <.0001* | -0.274407 | -0.163106 |
| Volume of RCA, pcy | -301.6758 | <.0001* | -422.3249 | -181.0267 |
| New concrete W/C | 36.264845 | <.0001* | 32.409062 | 40.120628 |
| (RMC of RCA-35.0117) *(Volume of RCA, pcy-0.35567) | -5.562362 | 0.0265* | -10.42339 | -0.701338 |
| (Absorption of RCA, %-4.62083) *(Volume of RCA, pcy-0.35567) | 200.06425 | <.0001* | 168.74276 | 231.38574 |
| Volume of New Mortar | -156.1003 | 0.0088* | -269.569 | -42.63163 |
| (New concrete W/C-0.43) *(Volume of New Mortar-0.64508) | 983.27151 | <.0001* | 643.77949 | 1322.7635 |

**Table A8**

*Parameter Estimates of Equation 6*

| **Term** | **Estimate** | **Prob>\|t\|** | **Lower 95%** | **Upper 95%** |
|---|---|---|---|---|
| Intercept | 159.22508 | <.0001* | 116.63343 | 201.81673 |
| Absorption of RCA, % | -7.229849 | <.0001* | -9.303914 | -5.155784 |
| RMC of RCA | -2.218993 | <.0001* | -2.863628 | -1.574358 |
| Volume of RCA, pcy | -103.3742 | <.0001* | -135.2199 | -71.52858 |
| New concrete W/C | 9.4667559 | <.0001* | 6.3661502 | 12.567362 |
| (RMC of RCA-36.3267)*(Volume of RCA, pcy-0.35458) | -170.7748 | <.0001* | -213.6757 | -127.874 |
| (Absorption of RCA, %-4.4425)*(Volume of RCA, pcy-0.35458) | -684.1436 | <.0001* | -840.4951 | -527.792 |
| (Absorption of RCA, %-4.4425)*(New concrete W/C-0.43) | -21.71444 | <.0001* | -26.46887 | -16.96001 |