RECYCLED CONCRETE AGGREGATE: INFLUENCE OF AGGREGATE PRE-SATURATION AND CURING CONDITIONS ON THE HARDENED PROPERTIES OF CONCRETE

by

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AUTHOR`S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

Recycled concrete aggregate (RCA) is a construction material, which is being used in the Canadian construction industry more frequently than it was in the past. The environmental benefits associated with RCA use, such as reduced landfilling and natural aggregate (NA) quarrying, have been identified by industry and government agencies. This has resulted in some incentives to use RCA in construction applications. Some properties of RCA are variable and as a result the material is often used as a structural fill, which is a low risk application. The use of RCA in this application is beneficial from an overall sustainability perspective but may not represent the most efficient use of the material. Efficient use of a material means getting the most benefit possible out of that material in a given application. The initial step in efficient material use is evaluating how a material affects its potential applications. In the case of RCA, this includes its use in concrete as a coarse aggregate.

RCA is made up of both aggregate and cement mortar from its original application. Its make-up results in absorption capacities, which are higher than NA. Its high absorption capacity indicates that RCA can retain a relatively large proportion of water. Internal curing of concrete is the practice of intentionally entraining reservoirs of water within concrete. This water is drawn into the cement at a beneficial point in the cement hydration process. This water allows for a more complete hydration reaction, less desiccation, a less permeable concrete pore system, and less susceptibility to the negative effects of poor curing. The potential for RCA to act as an internal curing agent was evaluated in this research.

Two RCA types were studied in the course of this research, one RCA of high-quality and one low-quality. These were compared to one NA type, which served as experimental control. Neither RCA type was found to desorb significant amounts of entrained water at relative humidity levels between 85% and 93%. This behaviour indicates that they would not behave as a traditional internal curing agent.

Within concrete, the initial saturation levels of these RCAs were 0%, 60% and 100% of their full absorption capacity. The mixtures ranged from 30% RCA (by volume of coarse aggregate) to 100% RCA. These mixtures were subjected to two curing regimes, MTO-specified curing conditions and moist curing, in order to gauge the internal curing potential of the RCA.

Fully saturated RCA mixtures were found to retain water throughout the course of testing. They were also found to increase the rate of compressive strength gain at early ages in comparison to similarly cured NA mixtures. Full saturation was found to have a negative effect on the thermal expansion behaviour of the concrete at 28 days concrete age. Permeable porosity of concrete was measured as an indicator of more thorough hydration in RCA concrete, but any potential benefits were masked by the increase in permeable porosity associated with permeable RCA.

When compared with NA control mixtures and RCA mixtures cured under ideal conditions, it was found that saturated RCA mixtures provided compressive strength benefits. Low-quality RCA, which lost entrained water earlier in the testing period than high-quality RCA, benefitted in terms of early age compressive strength gains under specified curing conditions. High-quality RCA, which retained a relatively higher proportion of its entrained water throughout the early testing period, improved later age compressive strength under spec-curing conditions.

Mixtures with 30% RCA (by volume of coarse aggregate) were generally found to not significantly affect the tensile strength, elastic modulus, and permeable porosity of the concrete. Tensile strength and elastic modulus were found to be consistently lower in RCA concretes, while permeable porosity was consistently higher. However, the magnitudes of these changes were not large enough to be statistically significant based on the testing regime employed. Compressive strength was significantly improved at 28 days when the 30% RCA was fully saturated. 30% RCA mixtures significantly reduced the thermal expansion of concrete at 28 days, which could provide particular benefit to concrete pavement applications.

Overall, RCA saturation in new concrete had both positive and negative effects on the properties of concrete, which should both be considered in the context of the application for which RCA concrete is being considered. Specifically, concrete applications with the potential for poor curing and the need for reduced thermal expansion could benefit through the inclusion of coarse RCA. For example, these benefits could manifest in reduced thermal cracking at slab joints and reduced thermal stresses due to temperature gradients in pavements.

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This thesis is dedicated to my family,

whose support and love have made this a possibility.

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CHAPTER 1
INTRODUCTION

The use of recycled concrete aggregate (RCA) as a building material is gaining momentum within Canada's construction industry. RCA use in road construction projects in the province of Ontario more than doubled between 1991 and 2006, and continues to grow (MNR, 2010). While Canada is a large and resource-rich country, the population distribution makes it such that the availability of aggregate in high density areas is becoming limited. This results in longer distances between the aggregate supply and the location of the construction project, which increase the transportation costs in terms of both monetary and environmental costs (MNR, 2010). Additionally, areas of high population density produce a large amount of waste, which is discarded into landfills. Demolition wastes have also traditionally been landfilled, which further increases the load on these facilities. The use of RCA diverts some of this waste stream away from landfills and into new construction. Since the use of RCA helps to alleviate both of these important environmental issues, it is becoming a more desirable building material.

RCA is a construction material produced by demolishing and crushing previously cast concrete. The products of this crushing can then be used again as a granular fill-type material or as a graded replacement of aggregate in the production of new concrete.

RCA is commonly divided into two primary components based on particle size, fine RCA and coarse RCA. The research outlined herein considers only the coarse fraction of two RCA sources, which is defined as being composed of particles that would be retained on a 4.75 mm sieve.

Internal curing is the practice of intentionally casting concrete with reservoirs of water entrained within the concrete mixture. These internal reservoirs become effective during the hydration process of concrete after a portion of the mixing water is consumed in the chemical hydration reaction. This creates what is essentially a moisture gradient, which draws the water from the reservoirs into the concrete paste matrix. Figure 1.1, which is adapted from Bentz and Weiss (2011), illustrates the basic process of internal curing with entrained water reservoirs. The presence of this extra water allows for a more complete hydration reaction of the concrete, and is particularly useful in two situations.

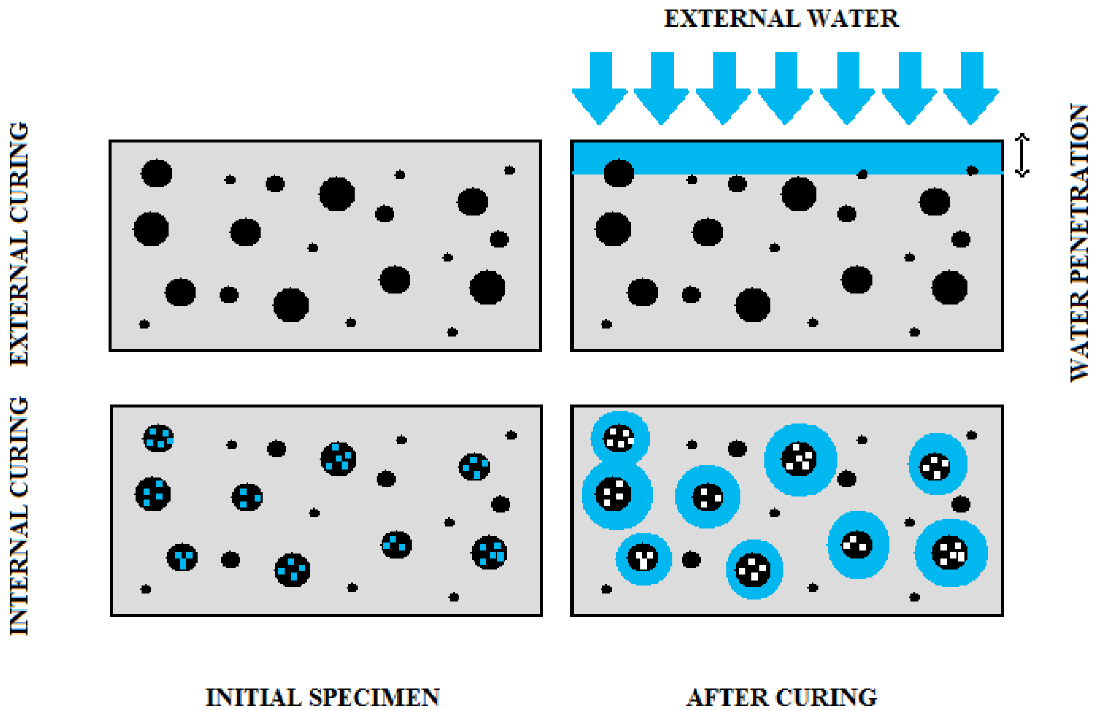


Figure 1.1: Internal curing compared to external curing (after Bentz & Weiss, 2011)

Firstly, the internally entrained water helps to alleviate the negative effects of concrete drying by replacing any evaporated water prior to the desiccation of the concrete and the onset of shrinkage cracks. In this case, the internal curing helps to alleviate the effects of non-ideal curing practices (Henkensiefken et al., 2009). The second related situation is in the case of high strength (low water/cement ratio) concrete. This type of concrete contains a high cement content, which often becomes so impermeable that the concrete's pore system can no longer transport external curing water to the interior of the concrete. When the concrete's permeable porosity drops, the entrained internal curing water is drawn out and consumed in the hydration process, allowing for more complete cement hydration to be achieved.

Internal curing is typically provided by fine materials. This is because of two main factors. Firstly, aggregates that have high enough absorption to provide sufficient internal curing water are inherently weak due to the presence of voids. Therefore, replacement of strong coarse aggregate with lightweight materials can significantly reduce the overall strength of the material. Secondly, in order for internal curing to be effective, it should provide water to the entire cement paste matrix. Since water can disperse only about 2-3 mm in dense concrete, this requires dispersal throughout the entire concrete mixture with small enough spacing to overlap effective zones. This is achieved through the use of fine internal curing reservoirs (Bentz et al., 2005).

Internal curing in concrete provides several benefits, which include:

- reducing plastic, autogenous, and drying shrinkage (and associated cracking)
- increasing hydration in cement-rich mixtures
- improving late age compressive strength
- reducing the transport properties of concretes by reducing the permeable porosity with additional hydration products, including calcium silicate hydrate

Consequently, many of these benefits improve durability in cement-rich concrete mixtures. The interfacial transition zone (ITZ) of the internal curing reservoirs improves as compared to the natural aggregate due to higher availability of water (Bentz & Weiss, 2011).

Figure 1.1 illustrates an example of poor dispersion of internal curing reservoirs, wherein the hydrated zones do not overlap. A larger proportion of coarse aggregate is required to achieve a similar particle dispersion and spacing. Normally it is poor practice to replace large amounts of coarse aggregate with a weaker material and thus this is generally not considered. The addition of RCA however, is largely driven by external factors such as including a given amount of recycled material to gain environmental credits. This could therefore result in large proportions of absorptive RCA material being present in concrete. If there is benefit to be gained by using that coarse aggregate in a way that would have internal curing-like effects then this could serve to help maximize the utility of RCA, which is normally deemed to be a “lower quality” material.

1.1 Aggregate Demands

Between 2000 and 2009, construction projects in Ontario used approximately 179 million tonnes of aggregate per year. This translates into approximately 14 tonnes of aggregate per year for every resident of Ontario. The province’s population is projected to grow by approximately 33%

over the next twenty years and this increase would result in a similar increase in demand for aggregate. Between 2020 and 2029, Ontario's average annual aggregate demand is projected to hit approximately 191 million tonnes. These values incorporate all aggregate uses, which includes low to high qualities for various applications (MNR, 2010).

Currently the Greater Toronto Area (GTA) accounts for about one third of the province's total aggregate demand and this high demand results in a significant aggregate concern. Approximately 95% of the aggregate used in Ontario is produced by private pits and quarries; however the highest demand is in an area where the population density makes new quarries and gravel pits unfeasible. This results in the need to transport significant amounts of aggregate into the GTA for construction. Aggregate is a heavy material and its transportation is associated with increased costs, high emissions, and significant infrastructure deterioration of the routes used to transport the material (MNR, 2010).

Figure 1.2, which is adapted from the State of the Aggregate Resource study commissioned by the provincial Ministry of Natural Resources (MNR) in 2010, illustrates the total reserve base for aggregate within Southern Ontario and compares it to the high quality reserves that are available for concrete and asphalt production and are within 75 km of the GTA. The term "high quality" refers to aggregate that meets the Ontario Provincial Standards and Specifications (OPSS) for use in concrete and asphalt applications. The production of concrete and asphalt grade stone from quarries or pits results in by-products. These by-products generally account for about one third of the initial material. Therefore, approximately two thirds of the products of this process are usable in the production of concrete and asphalt and are considered to be available reserves. The 75 km distance represents a distance beyond which the transportation of aggregate would become infeasible due to the high transportation costs, as determined by the MNR. The data are based on the estimated capacities and productions of 97 licenced aggregate quarries within southern Ontario (MNR, 2010).

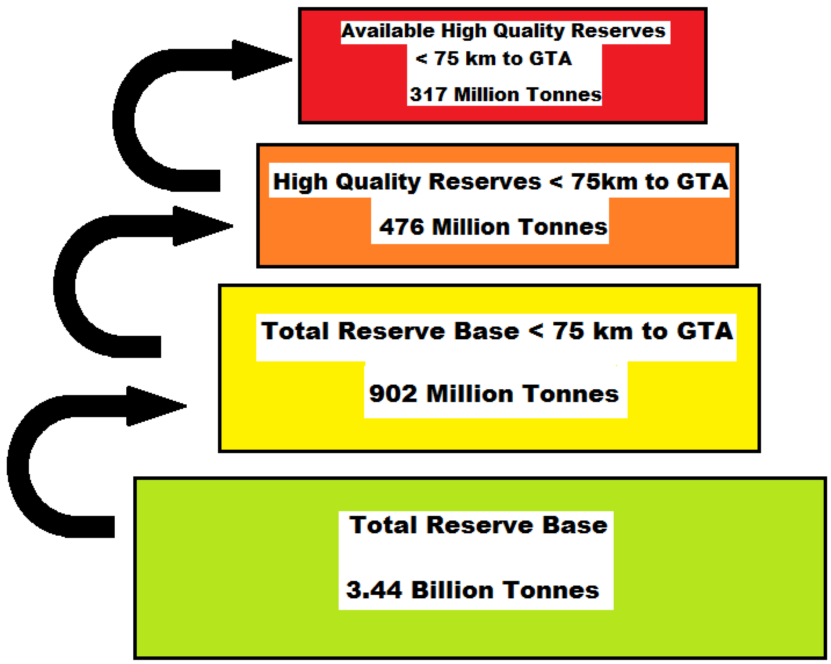


Figure 1.2: Natural aggregate reserves within 75 km of the Greater Toronto Area (MNR, 2010)

As shown in Figure 1.2, despite the large reserve base in Ontario, the aggregate that is available for use in the largest market represents less than 10% of this total reserve. With Ontario's estimated annual aggregate use projected to reach 191 million tonnes within the next 15 years, it is clear that this reserve must be supplemented with another aggregate source. This is the main reason why the use of RCA as a replacement for natural aggregate (NA) in concrete and other applications is being studied.

1.2 Concrete Production

The cement and concrete industry is estimated to have contributed approximately $3.2 billion to Canada's GDP in 2008. It is also estimated that about 28.1 million cubic metres of concrete are produced annually in Canada (CAC, 2010). Since aggregate makes up a significant volumetric proportion of most concrete, with an estimated average of 60-80%, it can be estimated that this corresponds with approximately 19.7 million cubic metres of aggregate. With an estimated average aggregate density of 1.7 tonnes per cubic metre, this corresponds to about 35 million tonnes of aggregate used annually in the production of concrete in Canada (Lafarge North

America, 2013). This represents a substantial portion of the total aggregate used in Canada, and highlights the importance of aggregate availability to the concrete industry.

1.3 Research Objectives

Currently, there are various “acceptable” ways of dealing with absorbed water in recycled aggregate. The RCA can be soaked to ensure it reaches saturated condition during mixing, “misted” or “sprinkled” to ensure that the material has some entrained moisture, or it can be used with its in-situ moisture content (which is obviously variable and dependant on various environmental conditions).

The objective of this proposed research is to determine the effects of RCA saturation levels on mechanical properties of concrete produced using the RCA. The concrete properties researched in this work include: transport properties (water absorption and total porosity), fresh properties (slump, air content, fresh density) and hardened properties (compressive and tensile strength, modulus of elasticity, and the linear coefficient of thermal expansion).

The nature and extent of the effects of varying the pre-soaking protocols and different saturation levels of the aggregate are examined. The effects are studied with consideration for any internal curing-like benefits. While the use of recycled aggregate purely as an internal curing agent may not be feasible, internal curing-like benefits may be achieved by incorporating RCA into concrete. Part of the aggregate-specific testing will focus on the properties of the material that are relevant to internal curing. The methodology for this research is illustrated in Figure 1.3, which shows the general flow of the research activities.

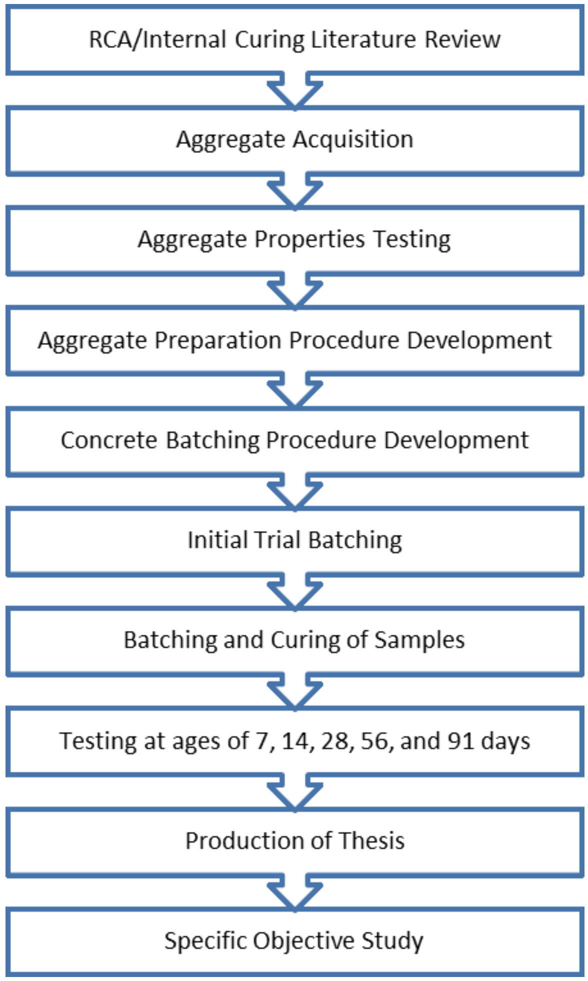


Figure 1.3: Program methodology

1.3.1 Experimental Matrix

Overall, two different sources of recycled aggregate (RCA1 and RCA2) and one natural aggregate (NA) are employed across variations in aggregate saturation, aggregate replacement level, and curing method. These variations are presented in Table 1-1, which indicates the different concrete mixtures that were studied as part of this research. Each variable category is described in detail in the following sections.

Table 1-1: Experimental Matrix

Aggregate Type	Curing Regime	Coarse Aggregate Saturation	RCA Replacement	Mixture Designation
NA	Moist Curing	100%	0% (control)	NA M 100-0
NA	Specified Curing	100%	0% (control)	NA S 100-0
NA	Specified Curing	0%	0% (control)	NA S 0-0
RCA1	Moist Curing	100%	100%	RCA1 M 100-100
RCA1	Specified Curing	100%	100%	RCA1 S 100-100
RCA1	Specified Curing	60%	100%	RCA1 S 60-100
RCA1	Specified Curing	0%	100%	RCA1 S 0-100
RCA1	Specified Curing	100%	30%	RCA1 S 100-30
RCA1	Specified Curing	60%	30%	RCA1 S 60-30
RCA1	Specified Curing	0%	30%	RCA1 S 0-30
RCA2	Moist Curing	100%	100%	RCA2 M 100-100
RCA2	Specified Curing	100%	100%	RCA2 S 100-100
RCA2	Specified Curing	60%	100%	RCA2 S 60-100
RCA2	Specified Curing	0%	100%	RCA2 S 0-100
RCA2	Specified Curing	100%	30%	RCA2 S 100-30
RCA2	Specified Curing	60%	30%	RCA2 S 60-30
RCA2	Specified Curing	0%	30%	RCA2 S 0-30

1.3.1.1 Aggregate Type

The two recycled aggregate sources that were selected for this research are referred to herein as RCA1 and RCA2. They were also used in a previous study at the University of Waterloo (UW) whereby the current research is an extension (Butler, 2012).

RCA1 was produced through the crushing of non-structural concrete from the Region of Waterloo. The concrete came from demolished transportation structures including curbs, gutters, and sidewalks. In most cases, this concrete was made available through roadway expansion and not due to failures. It should also be noted that given its age, the available material was very good in both quality and consistency.

RCA2 was produced by crushing concrete that was returned to the ready-mix producer still in a fresh state. The concrete could have been returned for various reasons including improper mix performance or age issues, but was most commonly “left-over” concrete, which remained in the ready mix truck at the conclusion of a concrete pour. This material is typically washed from the concrete trucks into piles on the ground, which would be crushed when a sufficient amount had accumulated. No attempt at proper curing or consolidation was made for this mix.

Both RCA sources were graded to satisfy the MTO requirements for concrete coarse aggregate, outlined in OPSS 1002 (OPSS, 2013). The results of previously performed aggregate tests are summarized later in Table 2-1.

1.3.1.2 Aggregate Saturation

Many previous RCA studies do not explicitly state the method of aggregate preparation in terms of saturation. Others use RCA in its “as received” moisture condition in an attempt to reproduce actual common concrete practices (Martinez-Lage et al., 2012). However, this condition results in a source of variation within an already widely variable material study.

Previous research has studied the effects of pre-saturation of coarse recycled aggregate in concrete production. This research indicated that 100% saturation of aggregate may have a detrimental effect, but that a smaller saturation percentage (specifically 90%) was ideal. This research focused only on one recycled aggregate type, but varied aggregate replacement amounts on a volumetric basis similar to the replacement basis used in the current research (Ferreira et al., 2011).

Within the current research, the saturation levels of the coarse aggregate were varied to represent three distinct preparation regimes. These saturation levels were 0% or oven dry, 60%, and 100% or fully saturated.

These saturation levels represent aggregate condition at the beginning of mixing. Upon addition into the concrete mixture, it is understood that the water in the mixture begins to migrate according to the specific moisture gradient, which exists in each situation.

The 100% saturation condition was achieved through 24 hours of submerged soaking, followed by one minute of material drainage to remove excess soaking water. Previous research pertaining to these materials found that 24 hours of submerged soaking would ensure that both the RCA and NA would achieve 100% saturation. The 100% saturated test case is intended to allow for the study of the materials with the maximum amount of water entrained in the coarse aggregate.

The 60% saturation condition was achieved by soaking for a prescribed time, which varied based on the absorption rate of the coarse aggregate type. This condition replicates a brief pre-soak procedure, which could be employed in industry without requiring a full day of saturated soaking. This condition provides some entrained moisture, but not the full capacity of the aggregate.

The 0% saturation condition involved oven dried aggregate. In order to account for the surface adhered fine material that was lost during the 60% and 100% soaking procedures, the coarse aggregate for use in the 0% saturated condition was exposed to a similar soaking procedure prior to being oven dried. The material was dried at 110 ± 5°C, in accordance with ASTM C127-12, which is a test method pertaining to the testing of coarse aggregate. This condition was considered in order to effectively contrast other saturation conditions. While negligible pre-saturation may occur in industry, it is unlikely that material would be completely dried prior to concrete batching however this depends partly on seasonal environmental conditions.

1.3.1.3 Aggregate Replacement Level

Previous research at the University of Waterloo has indicated that replacing natural aggregate with RCA had little observable effect on compressive or flexural strength up to a 30% threshold (Smith, 2009). This conclusion was based on the results of testing mixtures including only one source of RCA. In order to gauge whether similar results are found when varying qualities of RCA are used, a 30% aggregate replacement mixture is included within the research.

As discussed in later in Section 3.2.1, the 30% aggregate replacement is performed on a volumetric basis, which uses the natural aggregate as a reference point. For each RCA source, the 30% replacement amount is calculated based on the dry density of the RCA.

1.3.1.4 Curing Conditions

Two different curing regimes were considered for the concrete samples. The first included sample storage at 100% relative humidity (RH) at 24°C up until the time of testing. This was designated as Moist Curing. The second curing regime included was in accordance with MTO OPSS 350 as well as a modified CSA A23.2-3C. This included 7 days moist burlap curing covered by a vapour barrier. After the seven days, the samples were exposed to drying in the conditions present within the lab, which were approximately 50% ± 10% RH and a temperature of 21 ± 2°C. The temperature within the lab was similar to the moist curing room and was maintained at a relatively constant level. This second curing regime was designated as Specified Curing (spec-curing).

The beneficial effects of internally entrained water were hypothesized to be more apparent in situations where external curing water is not as readily available, such as in the case of Specified Curing. This also would more closely resemble field conditions in most applications. Comparisons between the two curing conditions were made in order to gauge the relative effects of the availability of external curing water on the concrete.

1.4 Project Significance

The use of RCA in the Canadian construction industry provides many potential technical, economic, and environmental benefits. While crushed concrete has existed almost as long as concrete itself, its use as a construction material in Canada is still a relatively new process. New processes in the construction industry are often implemented slowly and with considerable caution. This is partly related to conservative government policies. The size and scope of construction projects can correlate to significant risk in the use of "unproven" materials and this can dissuade contractors and governing agencies from using these materials.

In the case of RCA, the material is often used as a granular fill material as this represents a relatively low-impact application. While this is an important beginning, highly sustainable practices require that a material be used effectively in order to provide the most value. "Effective use" is a subjective term, which depends on the required performance on a specific application. In order to determine RCA's most effective use, its performance under various conditions must be studied from a thorough engineering perspective.

Since internal curing often involves the entrainment of a porous aggregate into concrete, the potential for coarse RCA to be used as this aggregate could provide a source of value to the material. This value could affect what is widely considered to be the most effective use of the material. Regardless of the outcome, it is important to establish the value of RCA in order to use it most effectively.

This research is significant because it provides insight into the performance of RCA concretes under various curing conditions, replacement levels, and saturations for two dissimilar types of RCA. The performance is measured based on widely used and specified concrete material properties as well as some properties that are relevant to durability.

1.5 Thesis Arrangement

Chapter 2 provides background information pertinent to internal curing, recycled concrete aggregates, and the experimental tests undertaken as part of this research. Chapter 3 describes the experimental program used for this research. Chapter 4 presents the general results and discussion of the study, while Chapter 5 presents analysis of the results pertaining to three specific objectives. These objectives include studying the effects of: initial RCA saturation levels, variable concrete curing conditions, and acceptable RCA replacement levels. Chapter 6 presents the conclusions and recommendations for further work.

CHAPTER 2

LITERATURE REVIEW

2.1 Recycled Concrete Aggregate (RCA)

The use of RCA in Ontario is gaining acceptance as more performance information is becoming available and political pressure to use less natural aggregate is increasing. Organizations such as Aggregate Recycling Ontario, which advocate for the use of RCA have begun to affect some change in the practices of municipalities throughout Ontario. Recently Bill 56 has been proposed to the Legislative Assembly of Ontario. The bill aims to prohibit the practice of limiting public sector construction projects to virgin materials. Previous practice has allowed for bids proposing the use of recycled material to be rejected based on this fact. The bill has been carried through the first and second readings in the house and has been referred to the standing committee on Finance and Economic Affairs (Legislative Assembly of Ontario, 2013).

The most common practices for RCA use in Ontario involve placement of RCA as a fill type material. This includes use as granular base and sub-base for pavements, trench backfill material, engineered fill, stabilization of soft subgrades, fill under concrete slab-on-grade, and pavement shoulder construction (Aggregate Recycling Ontario, 2011).

In 2007, it was estimated that approximately 13 million tonnes of RCA was used in Ontario. This corresponds to about 7% of the total aggregate used in that year. Most of this RCA was used in the construction of roadways as outlined previously (MNR, 2010). There is currently no widespread use of RCA in the production of concrete in Ontario.

RCA is a material that has a large potential supply which currently outstrips its demand. This potential supply consists of every existing concrete structure that will eventually be demolished. One of the prominent issues associated with this large supply however is that each concrete structure is composed of different materials. These differences depend on factors such as structural requirements, available materials, the year in which the concrete was produced, and many others. This wide variation in concrete composition results in a similar variation in the RCA, which is produced when the concrete is crushed. The wide variation in RCA results in some materials with intrinsic properties that lend themselves well to the production of high quality concrete and other materials, which could be detrimental to the performance of any concrete. Between these two extreme RCA types exists a wide spectrum of RCAs that perform variably in concrete.

While some of the RCAs on this spectrum may not be feasible for use in concrete, they are often found to be acceptable for use as granular material in fill or base applications.

The inherent variability of RCA causes concern amongst concrete producers and specifiers in Canada, which often results in avoiding the use of RCA completely or to limiting its use to lean concrete or other similar low-demand applications. Several studies have indicated that the use of RCA in concrete can result in a loss of compressive strength and durability characteristics, including those by Maruyama and Sato (2005), Fonseca, de Brito, and Evangelista (2011), and Olorunsogo and Padayachee (2002). Given the findings of this previous research, limiting the use of RCA is often considered as a reasonable way to limit the risk associated with the material.

Some RCAs have been found to have properties that are not detrimental to concrete production or performance when incorporated. In these cases, the practice of avoiding the use of RCA results in the loss of significant potential value, in terms of available construction materials.

Previous research performed at the University of Waterloo produced an RCA classification framework that served to classify different RCAs according to their best potential use or application. These applications ranged from use in reinforced structural concrete to use only as a fill material. The framework was developed such that classification depended largely on aggregate tests. This allows for classification to be performed without knowledge of RCA's source concrete, since this information is often unknown for a given RCA. The framework developed is an excellent step towards the development of a widely source-inclusive tool that could be used industry-wide to achieve much more effective use of existing and future RCAs (Butler et al., 2013a).

According to the classification framework developed through previous research at the University of Waterloo, RCA1 was classified as Class A1 (or Class A2), and RCA2 was classified as C. This implies that RCA1 is "high quality" material and would be suitable for use in structural and non-structural concrete applications. Conversely, RCA2 would be considered "low-grade" material and would be suitable only for use in structural and non-structural fill applications (Butler et al., 2013a).

Table 2-1: Aggregate Test Results of RCA1 and RCA2 (Butler et al., 2013a)

Recycled Aggregate Type	Aggregate Crushing Value	Relative Density	% Adhered Mortar	Absorption Capacity	Abrasion Loss (Micro Deval)	Classification
RCA1	23.1	2.37	20.40%	4.66%	15.10%	**A1 (or A2)**
RCA2	28.5	2.23	36.10%	7.81%	25.00%	**C**

Note: Class A1 (or Class A2): suitable for use in structural and non-structural concrete applications
Class C: suitable only for use in structural and non-structural fill applications

The two aggregate types clearly represent two extremes of the RCA quality spectrum. They have both been included in this research to gauge any relative internal curing effects and benefits between a low-grade material, with high absorption capacity and a high-quality material, with lower absorption capacity.

Despite the previously mentioned variability of RCA, one property that appears to be consistent is an absorption capacity, which is larger than most natural aggregates used for production of concrete. For reference, the Cement Association of Canada states that the typical absorption capacity range for coarse concrete aggregate is 0.2% to 4%, and 0.2% - 2.0% for fine concrete aggregate (Kosmatka et al., 2011). Table 2-2 summarizes some absorption capacities found in previous selected RCA research.

The absorption capacity can potentially be utilized in order to achieve some internal curing benefits in a given RCA concrete. These benefits may improve the characteristics of an acceptable mix, or potentially counteract some of the negative qualities associated with the use of some RCAs in concrete.

Table 2-2: Absorption Capacities of Various RCA Sources

Researcher(s)	Source	Absorption Capacity	Aggregate Size Fraction
L. Butler, S. Tighe, J. West	Crushed Sidewalk/Curbs/Gutters	4.7%	coarse
	Building Demolition	6.2%	coarse
	Crushed Returned Concrete	7.8%	coarse
H. Kim, D. Bentz	6.9 MPa Concrete	16.0%	fine
	20.7 MPa Concrete	12.4%	fine
	34.5 MPa Concrete	12.0%	fine
L. Ferreira, J. de Brito, M. Barra	Building Demolition	5.8%	coarse
A.K. Padmini, K. Ramamurthy, M.S. Mathews	35MPa Concrete	2.2-4.6%	coarse
	50MPa Concrete	2.5-4.8%	coarse
	60MPa Concrete	2.8-5.0%	coarse
C.S. Poon, Z.H. Shui, L. Lam, H. Fok, S.C. Kou	Building Demolition	6.3-7.6%	coarse
K. Obla, H. Kim, C. Lobo	Various Sources	4.3-5.9%	coarse
C.S. Poon, Z.H. Shui, L. Lam	Crushed Normal Strength Concrete	7.9-8.8%	coarse
	Crushed High Performance Concrete	6.5-6.8%	coarse

2.2 Internal Curing

Internal curing provides several benefits in various concrete mixture types. Some of these benefits include reducing plastic, autogenous, and drying shrinkage (and associated cracking), providing increased hydration in rich mixtures, improving late age compressive strength, and reducing the transport properties of concretes. Many of these benefits improve durability in rich concrete mixtures. The quality of the ITZ of the internal curing reservoirs is found to improve as compared to the natural aggregate due to higher availability of water (Bentz & Weiss, 2011).

Internal curing is often employed through the use of lightweight aggregate (LWA). The three main requirements for an internal curing agent in descending order of importance include: favourable desorption at approximately 93% RH, particle spacing within the mix of less than 2-3 mm, and absorptive capacity large enough to provide sufficient water. Fine LWAs provide all three of these requirements. LWAs have a relatively large void content, which makes them ideal materials for absorbing water. The amount of the LWA included in internally cured concrete is generally proportioned in order to provide enough extra water for full hydration of binder-rich mixtures. The size of the fine LWA is generally small enough such that it is dispersed throughout the cement matrix. The methodology is based upon the theory of protected paste volume (Bentz & Snyder, 1999). Many LWAs also exhibit favourable desorption characteristics, which make them a prime candidate for internal curing (Bentz & Weiss, 2011). The desorption characteristics are discussed further in Section 2.2.5.

In the literature, some studies have examined the effectiveness of fine RCA as an internal curing agent. It was observed that as the sole internal curing agent, it resulted in significant strength loss and negligible benefit in terms of autogenous shrinkage reduction. However, mixtures of RCA and LWA produced results similar to poor LWA internal curing (Kim & Bentz, 2008). To the author's knowledge, there have been no studies concerning use of coarse RCA to achieve internal curing-like benefits.

2.2.1 Physical Classification

Physical qualitative classification of recycled aggregate represents a difficult task due to the inherent variability of the material in terms of original aggregate type and shape, cement matrix, and production or preparation technique. However, since this research considers RCA for the production of new concrete, the classification herein conforms to an accepted physical classification system. The following tables present the aggregate classification system outlined in British Standard 812. This standard classifies aggregate based on the particle shape as well as the surface texture of the aggregate (Neville, 1997).

RCA is almost universally produced by crushing of existing concrete. This should often result in Angular/Rough characteristics initially. The strength of the adhered mortar can be somewhat gauged by the RCA's resistance to attrition over time.

Table 2-3: Particle Shape Classification of BS 812: Part 1: 1975 (Neville, 1997)

Classification	*Description*	*Examples*
Rounded	Fully water-worn or completely shaped by attrition	River or seashore gravel; desert, seashore, and windblown sand
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges	Other gravels; land or dug flint
Flaky	Material of which the thickness is small relative to the other two dimensions	Laminated rock
Angular	Possessing well-defined edges formed at the intersection of roughly planar faces	Crushed rocks of all types; talus; crushed slag
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions	-
Flaky and Elongated	Material having the length considerably larger than the width, and the width considerably larger than the thickness	-

Table 2-4: Surface Texture of Aggregates (BS 812: Part 1: 1975 from Neville, 1997)

Group	*Surface Texture*	*Characteristics*	*Examples*
1	Glassy	Conchoidal fracture	Black flint, vitreous slag
2	Smooth	Water-worn, or smooth due to fracture of laminated or fine-grained rock	Gravels, chert, slate, marble, some rhyolites
3	Granular	Fracture showing more or less uniform rounded grains	Sandstone, oolite
4	Rough	Rough fracture of fine- or medium-grained rock containing no easily visible crystalline constituents	Basalt, felsite, porphyry, limestone
5	Crystalline	Containing easily visible crystalline constituents	Granite, gabbro, gneiss
6	Honeycombed	Visible pores and cavities	Brick, pumice, foamed slag, clinker, expanded clay

2.2.2 Adhered Mortar Content

Adhered mortar content is an aggregate property unique to recycled aggregates. The term refers to the amount of original cement matrix, which constitutes the particles of RCA. The content is expressed as a percent (by mass) of the overall RCA's oven-dry mass.

In order to determine a given aggregate's adhered mortar content, an acceptable method for separating the original aggregate from the mortar is required. Various methods for removing the adhered mortar have been examined, however previous research found that a method employing thermally induced stresses provided an effective means to do this (Butler et al., 2013a). This thermal method was adopted in the current research.

2.2.3 Density, Absorption, and Surface Adhered Moisture

Several densities are considered when testing coarse aggregate. The term Bulk Relative Density refers to the ratio of the mass of aggregate (in either oven dry or saturated surface-dry condition) to the mass of an equal volume of distilled water at the same temperature. The volume of aggregate includes any voids within the aggregate particles but does not include the voids between particles. Apparent Relative Density refers to the ratio of the mass of a given volume of aggregate to the mass of an equal volume of distilled water at a given temperature. The given volume of aggregate includes only the impermeable portions of the aggregate particles.

These densities of the different aggregate sources used in this research are important aggregate characteristics, both from a quality perspective and during concrete mixture proportioning. As noted in previous studies, there appears to be some correlation between the density of an RCA source and the performance of that aggregate in concrete (Butler et al., 2013b). In terms of mixture proportioning, aggregate density is important because this is the characteristic that determines the replacement amount of RCA when using volumetric proportioning. This proportioning method replaces a given amount of natural aggregate with an equal volume of RCA. The only feasible method of quantifying aggregate is by mass, and therefore the density (Mass/Volume) is important because it relates these two characteristics.

The term absorption refers to the amount of water that can be drawn into the pore structure of an aggregate (but does not include water adhering to the aggregate's surface) expressed as a percentage of the aggregate's dry mass. The absorption capacity of aggregate sources is of great importance to this research. This characteristic determines the amount of water that can potentially be entrained in a given aggregate source. Absorption is also an important consideration when proportioning a concrete mixture. In order to design all of the mixtures to have a comparable water-cement ratio, it is necessary to determine approximately how much water will be entrained within the aggregate. The aggregate's absorption capacity determines this value.

2.2.4 Absorption Rate of Coarse Aggregate

The absorption rate refers to how quickly a sample of aggregate absorbs water. This is important when considering RCA as it can be used to determine the soaking time required for an RCA type to reach a targeted level of saturation.

The instantaneous absorption rate of RCA has been found to decrease as the saturation level increases. A study regarding the presaturation of recycled aggregate found that their particular RCA source absorbed 89.2% of its capacity in the first five minutes of soaking but after 30 minutes the RCA had only reached approximately 95% capacity (Ferreira et al., 2011).

Similar findings were made by Butler et al. (2013b) when determining the soaking time required to fully saturate the RCA being studied. During this study it was observed that the times required to saturate RCA1 and RCA2, which are used in the current research, were 4 and 8 hours, respectively. Based on these findings, 24 hour saturation was used for 100% saturated mixtures (Butler et al., 2013b).

For the purpose of this research, absorption rate is considered as an average secant value, which is used to determine the soaking time required to achieve a given saturation level. This is further discussed in Section 3.1.5.

2.2.5 Desorption of Coarse Aggregate

The desorption of a material refers to the manner in which this material releases entrained water into the surrounding environment. In the case of this research, it refers to the amount of entrained moisture within an aggregate, which is released in an environment with a controlled RH.

The feasibility of a material as an internal curing agent is often considered in reference to the material's desorption characteristics. Previous research, specifically focused on fine lightweight aggregate, found that a significant proportion of the moisture contained within the aggregate should be released at a high RH (approximately 93%) in order to provide the most benefit to the hydration process (Castro et al., 2011). While this previous research and most internal curing applications focus on fine materials for both surface area and dispersion benefits, this threshold RH is considered to be relevant when considering the desorption of a coarse material.

Bentz and Snyder (1999) presented an equation to be used for the proportioning of concrete mixes with internal curing. This equation was later modified and expanded upon by Bentz et al. (2005). Their equation was produced specifically for Light Weight Aggregate (LWA) and calculates the required mass of dry LWA to provide a given internal curing performance. The LWA mass calculated is to be used as a replacement amount for normal aggregate in a concrete mixture. The theory behind this equation, Equation 2.1 presented below, is to provide sufficient water during the hydration process such that desiccation does not occur. This is particularly important in high performance concretes where the density and impermeability of the concrete paste does not allow for the penetration of external curing water into the interior of a concrete structure.

$$M_{LWA} = \frac{C_f \times CS \times \alpha_{max}}{S \times \emptyset_{LWA}} \quad \textbf{(2.1)}$$

Where M_{LWA} = dry mass of LWA required per unit volume of concrete (kg/m^3)

C_f = cement factor – from concrete mix design (kg of cement / m^3 concrete)

CS = chemical shrinkage of cement (g (water) / g (cement))

α_{max} = maximum expected degree of hydration

S = degree of saturation of aggregate (0-1)

ϕ_{LWA} = absorption of LWA (kg (water) / kg (dry LWA))

Equation 2.1 can be a useful tool for determining the feasibility of using RCA as an internal curing agent by determining the relevant RCA properties. Using a given mix design for an RCA concrete, an M_{RCA} can be calculated in place of an M_{LWA}. This value can be used to determine whether the mixture designs provide the requisite amount of internal curing capacity within the RCA. For use with RCA, this equation requires some preliminary assumptions to be made.

Attempting to provide internal curing via the coarse fraction of a concrete mixture's aggregate could potentially result in limiting the effectiveness of internal curing by reducing the volume of paste within the zone of influence of each internal curing particle (by reducing the ratio of the internal curing particles' surface area to volume). This proportioning equation does not incorporate this issue and focuses solely on the mass of aggregate required for internal curing.

The chemical shrinkage (CS) of cement varies widely based on several factors. Portland cement typically has a value of 0.07 mL water/g cement, but fly ash and slag can be on the order of 3 times greater than this value. Proportionate values of CS can be found for mixes containing these admixtures with known CS values, or ASTM C1608 can be used to find the CS value for any paste of interest. The temperature of the mixture also has an effect on this value. For the purposes of this research, CS= 0.07 mL/g is used.

The maximum expected degree of hydration (α_{max}) is dependent on the water/cement ratio (w/c) of the concrete mixture. When this ratio is below a threshold value of 0.36 in a Portland cement mixture, full hydration is no longer feasible based on engineering experience (Neville, 1997). In these cases, α_{max} can be approximated by $\frac{w/c}{0.36}$, otherwise α_{max} can be taken as 1 to indicate that full hydration can occur.

The degree of saturation of the aggregate is between 0 and 1 to indicate what level of the absorption capacity the aggregate is providing, with 0 being dry and 1 indicating full saturation.

The sorption capacity of the aggregate (ϕ_{LWA} or ϕ_{RCA}) is not a measure of the aggregate's ability to absorb water in wet conditions, but rather the aggregate's ability to desorb water in an 85-95% RH environment. This RH level approximates the conditions within curing concrete when water provided from internal curing agents have been found to have the greatest effect (Bentz & Weiss, 2011). If the water within an aggregate cannot be readily drawn out at these humidity levels then the additional water will not serve to benefit the concrete's hydration.

There are different methods available for measuring the sorption properties of materials. While no method has been standardized for the characterization of internal curing agents, different methods have been used to provide results. ASTM C1498 outlines a procedure for producing the sorption isotherms for different building materials using saturated salt solutions to produce environments of known RH. Several previous studies relating to internal curing have used this methodology to test material or calibrate equipment (Bentz et al., 2005, and Radlinska et al., 2008). The drawbacks of this method include the fact that RH environments are limited to those produced by readily available saturated salt solutions. The execution of the test is uncomplicated and requires only constant temperatures and air tight containers to produce RH environments.

Dynamic vapour desorption is another method that has been employed to produce the desorption isotherm of material (Castro et al., 2011). This method involves passing an air stream over the material within a known RH environment created by an RH chamber. The material is kept on a high resolution balance and mass changes are observed. When constant mass is achieved, the RH level is dropped by 1% to the next level and maintained until constant mass is achieved again. This process is continued from a starting point of 98% RH to a point of 80% RH. This process is applicable up to 98% RH and provides results quickly.

A pressure plate method suggested by Johansson (2010) has been used by researchers to determine desorption behaviour at RH levels greater than 98% (Pour-Ghaz et al., 2010). The method used provides precise results over a small RH range and requires the use of specialized equipment.

For the purpose of this research, the desorption isotherms for the materials being used could be developed based on Section 7.4 of American Society for Testing and Materials (ASTM) Standard C1498 (ASTM, 2010). This method would provide a broader perspective of the desorption behaviour of the materials, which could provide insight into the feasibility of the materials in terms of internal curing benefits.

2.2.6 Aggregate Crushing Value

Aggregate Crushing Value (ACV) is an aggregate strength test based on British Standard 812-110 (British Standards Institution, 1990). There is no equivalent test currently presented by the Canadian Standards Agency (CSA) or the American Society for Testing and Materials (ASTM), but previous research has indicated that this aggregate property has a correlation to the tensile strength of concrete produced with that aggregate. The average secant modulus of elasticity of bulk aggregate determined during the ACV test was also found to correlate well with the elastic modulus of concrete produced with the aggregate. While modulus of rupture is outside of the scope of this research, ACV was also found to be a strong indicator for this property of concretes with strengths of 40 MPa or less (Butler et al., 2013b).

According to BS 882:1992, aggregates of various crushing values can be classified in terms of their possible application (excerpt from Rahman et al., 2009):

- ACV < 25% Aggregates can be used in the production of concrete in heavy duty floors
- 25% < ACV < 45% Aggregates can be used in concrete for wearing surfaces
- ACV > 45% Aggregates can be used in concrete for other purposes.

It has been noted that the ACV test can become insensitive to the variations in strength of weaker aggregates (ACV>25%). This is due to the compaction of fines, which are produced at relatively low loads. The weaker materials crush and compact at low loads and then are better suited to resist higher loads due to the confining nature of the test (Neville, 1997).

2.3 Concrete Batching Procedure

Many different batching procedures have been employed during the production of concrete for a number of different reasons. These reasons can include the weather, mixer type, admixture or supplementary cementing materials use, and distance between batching plant and placement location. In the case of RCAs, specialized batching procedures have been used to account for the high absorption of the material. These procedures are also considered in order to improve the mechanical performance of the hardened concrete by controlling how the extra water, that high absorption RCA necessitates, is initially added to the concrete mixture. Figure 2.1 illustrates three batching procedures, which have been used to produce RCA concrete.

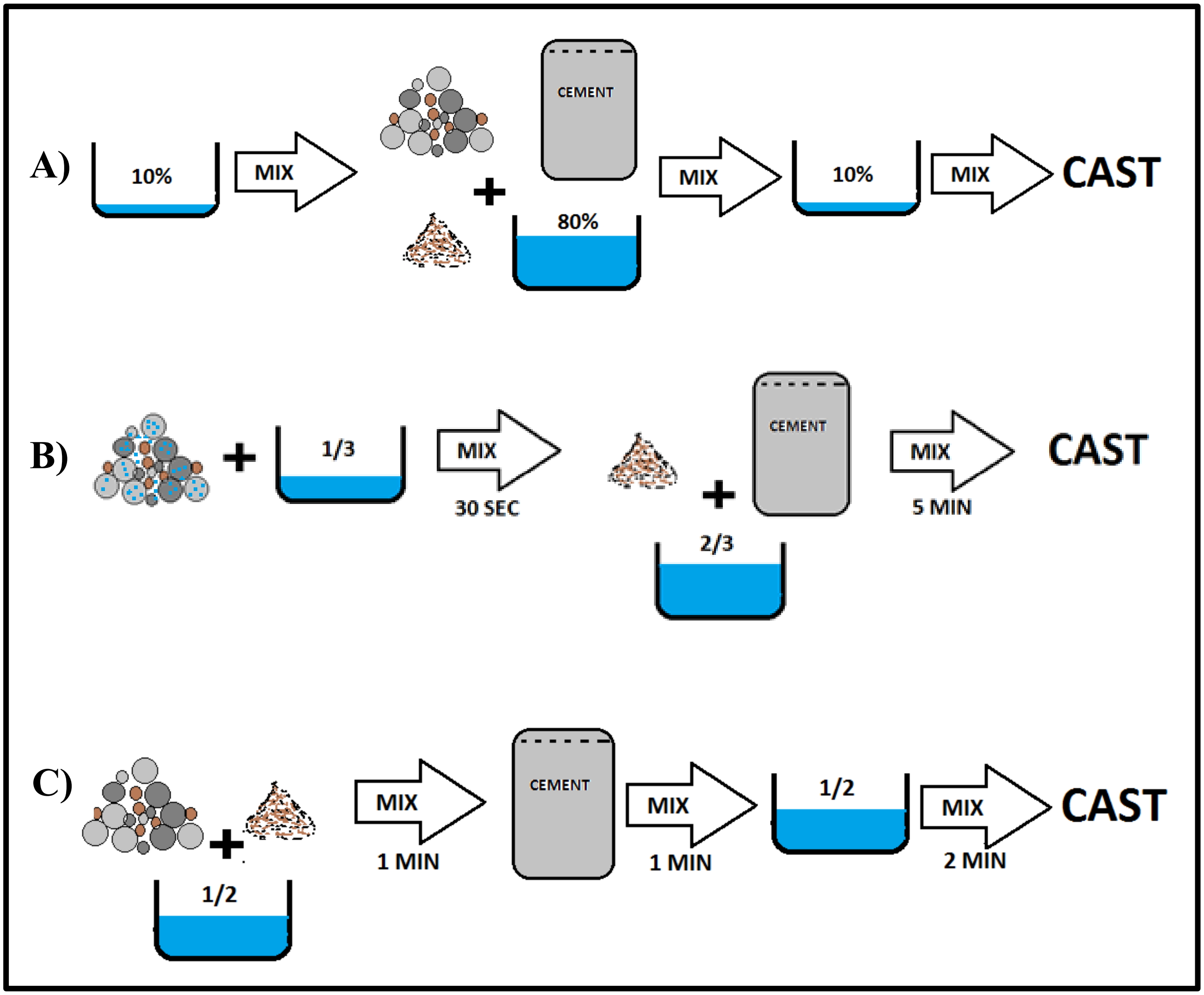


Figure 2.1: Summary of batching procedures: A) CAC design guide, B) Butler, C) Two Stage Mixing

Ferreira et al. (2011) investigated the effects of pre-saturation of RCA on concrete properties using RCA produced during a building demolition. The study considered RCA that had attained approximately 90% of its absorption capacity prior to mixing, according to a timed immersion based on previous absorption evolution tests. This was considered as the ideal moisture content to prevent absorption of mix water and prevent aggregate bleeding into the cement matrix (Ferreira et al., 2011).

Procedure A) pertains to the production of regular concrete using natural aggregate and no admixtures. It is described in the CAC guide for the design and control of concrete mixtures

(Kosmatka et al., 2011). It involves priming the drum with 10% of the mixing water, then adding all solid materials with 80% of the mixing water simultaneously, and then adding the final 10% of the water during the final mixing prior to casting. Procedure B) pertains to the use of presaturated RCA and was the procedure used by Butler et al. in their RCA research at the University of Waterloo (Butler et al., 2013b). It involves mixing of previously saturated coarse RCA with one third of the mixing water, then mixing the fine aggregate and cement with the remaining two thirds of the mixing water, mixing the whole mixture for five additional minutes (with two intermediate minutes of rest) prior to casting. Procedure C) was developed by Tam et al. for use with coarse RCA. They determined that mixing the aggregate with half of the mixing water prior to the addition of cement and the remainder of the mixing water served to prime the absorptive coarse aggregate with water that they theorized would form a slurry on the surface and improve the interfacial zones between aggregate and cement paste. They observed that this improved the early and later compressive strengths of RCA concrete when compared to concrete batched using a normal mixing approach similar to Procedure A) (Tam et al., 2005).

2.4 Fresh Properties

2.4.1 Coarse Aggregate Saturation

The absorption capacity of coarse RCA, which is generally higher than that of natural aggregate, results in the need for consideration during the design and batching of concrete mixtures. The Cement Association of Canada's (CAC) concrete proportioning guide indicates that RCA should be wetted prior to concrete batching or that stockpiles should be kept moist (Kosmatka et al., 2011). No specific guidance is given as to the ideal level of saturation for batching.

The current research study uses the saturation of the aggregate as a variable, and as such requires that the level of saturation be tested prior to concrete batching. The purpose of this test is to assist with estimating the water content of the aggregate and thereby the concrete at the time of mixing. Migration of water between the aggregate and cement paste is known to occur, which affects the effective water cement ratio of the concrete, but initial conditions are what are controlled and measured in this experiment.

In their study of the presaturation of RCA materials, Ferreira et al. (2011) considered materials which had attained approximately 90% of its absorption capacity prior to mixing, according to a timed immersion based on previous absorption evolution tests. No testing was performed to confirm the assumed moisture content of the RCA as the rate of absorption past 90% saturation was sufficiently low to assume this value.

Tam et al. (2005) investigated the effects of different concrete mixing procedures on the microstructure of concrete produced with RCA. The absorption capacity of the coarse RCA was observed to be 1.65–2.63% with moisture contents determined to be 0.33 - 0.49%. While one mixing procedure involved mixing RCA with water prior to the addition of cementitious materials, the level of aggregate saturation was never measured.

The amount of water adhered to the surface of RCA prior to or during mixing is largely ignored for one of two reasons; the saturation is part of the mixing procedure and therefore any adhered water is part of the designed mix water or saturated RCA is brought to or below SSD condition by hand or air drying respectively. Both methods have inherent potential problems related either to the required equipment or impracticality of the method for full-scale application.

While some studies consider the aggregate moisture states at the time of mixing, many rely on an as-received moisture analyses or assume that aggregate are at 0% or 100% saturation.

2.4.2 Slump

The slump of fresh concrete, as measured through the use of an Abrams cone, is a measure of the consistency and workability of the concrete. In general, the consistency of a fresh concrete describes its ability to flow, while workability relates more closely to the placement and finishing of a concrete and how well these procedures can be performed without losing homogeneity of the mixture.

The slump of a concrete is dependent on several factors including water content, air-entrainment, aggregate size, shape, grading, and texture, as well as the presence of any admixtures.

In the case of concrete containing coarse RCA, the water content can be affected by the relatively high absorption potential of the material and subsequently affected by the efforts made to address this characteristic. RCA can draw water from the mixture if it is less than saturated prior to mixing. Normally, moisture corrections are applied in concrete batching to compensate for the absorptivity of aggregate by including extra mixing water in the mixture. If RCA is saturated it can become a source of extra water during the mixing procedure, either through moisture adhered to the surface of the RCA or water that is easily lost from the RCA. Either situation can impact the initial workability of the mixture up until moisture equilibrium in the aggregate is reached.

RCA is also 100% crushed and therefore has a shape and texture that can reduce the slump as compared to concrete produced with some rounded aggregate.

In their study on the effects of moisture states of RCA on the slump of concrete, Poon et al. kept the total water content of mixtures constant by increasing the amount of mixing water added as the entrained moisture in the RCA was reduced. The mixtures with oven-dry RCA and high compensating amounts of mixing water had high initial slump but also high early slump losses as well. Mixtures with saturated, surface dry RCA and relatively low amount of mixing water had lower initial slump values, but the early slump losses were much less severe. Median situations involving air dried RCA and some compensating extra mixing water fell between these two cases in terms of initial slump and early slump losses (Poon et al., 2004).

Other studies include the use of plasticizers to mediate the changes workability associated with varying saturation levels in RCA concretes (Barra de Oliveira & Vazquez, 1996).

Air entrainment, size, grading, and admixtures will all be kept constant and should not have a large bearing on the slump results found in the current research study.

2.4.3 Air Content

Air content of a concrete is an important physical characteristic of concrete. It refers to the amount of air entrapped or entrained within a given concrete batch. Entrapped air generally refers to small voids that are left in concrete during its placement. Poor placement practices can result in higher levels of entrapped air that can have a negative effect on the compressive strength of the concrete. Entrained air refers to small "bubbles" that are placed in concrete to provide freeze-thaw deterioration resistance.

It has been found that the addition of RCA into concretes can increase the air content by about 0.6% and cause wider variability within the results, even in non-air entrained concretes (ACI, 2004). This constitutes a form of entrapped air that is not due to placement techniques but material properties. This is somewhat intuitive as the porosity, angularity, and surface texture of RCA all serve to entrain air and the material itself is variable.

The RCA concrete in this study is non-air entrained, but air content is measured to assess the variability of air content within the mixtures. The CSA A23.2-4C pressure method of measuring air content was used despite the caveat placed in the standard regarding the unsuitability of the procedure for concretes produced with "low-density or other porous aggregate". This method is widely used across the industry and is therefore highly applicable. The results of this test should not be used directly for the determination of freeze-thaw resistance because the measured air is not evenly dispersed throughout the mixture. However, the results can be used in a relative sense to gauge the effect of coarse RCA on entrapped air content.

2.4.4 Fresh Density

Generally the density of coarse RCA is lower than that of natural aggregate. As such, it intuitively follows that RCA concrete produced through volumetric replacement of natural aggregate will have a lower density. This assumption is confirmed throughout the majority of the studies into RCA.

This characteristic of fresh concrete will be used to compare the initial densities of all mixtures with the final hardened densities for each mixture type.

2.5 Hardened Properties

2.5.1 Density

In comparison with natural concrete aggregate, RCA typically has a lower density due to its porous nature, which is due to the adhered mortar. Because of the RCA's lower density, the density of concrete produced using the RCA is typically found to be decreased as well.

When natural aggregate is 100% replaced with RCA, studies have found an associated drop in hardened density of approximately 6% to 10% (Zaharieva et al., 2003, Tam & Tam, 2008, Poon et al., 2004, Ferreira et al., 2011, and Martinez-Lage et al., 2012). While this drop in density is not unsubstantial, it typically does not classify the resulting concrete as low-density or semi-low-density concrete, the threshold for which is approximately 1850 kg/m^3 and 2150 kg/m^3, respectively (CSA, 2009). While reduced density is not a negative quality in concrete, it is often due to increased voids, which can result in strength and permeability issues.

The density of each concrete state is measured as part of this study. Any related strength losses or increased permeability are also addressed within this study.

2.5.2 Compressive Strength

Compressive strength is an important material property of concrete and is often related to the quality of the concrete. Compressive strength is commonly used in material specification as it can be easily tested and other properties of concrete can be correlated to the compressive strength. As such, most RCA studies have included the effects of RCA addition on the compressive strength of concrete.

Concrete is essentially a two-phase material that consists of aggregate and mortar. The compressive strength of concrete depends on the inherent strength of these two phases as well as that of the zone between the two, often referred to as the Interfacial Transition Zone (ITZ). In low strength concretes (below 40 MPa), the aggregate is typically stronger than the paste and does not control the compressive strength. In high strength concretes, the paste's strength can exceed that of the aggregate and at that point the aggregate strength can govern. When the ITZ is weak it can form a failure plane that can reduce the overall strength of the concrete in either case. In all situations, aggregate can initiate and arrest the propagation of cracks in the paste (ASTM, 2006).

Generally, the addition of coarse RCA coincides with a reduction in compressive strength, though some RCAs have been observed to cause an increase. The severity of this reduction has been observed to depend on a large number of variables, which include mix design strength, natural aggregate replacement level, RCA saturation, RCA source material, concrete mixing procedure, curing conditions, and several other factors. Each of these variables can affect the two phases of concrete and the ITZ in a number of different ways. With such a high number of variables, it is difficult to present any results without several qualifying statements. Across this scope of variables, concretes produced using RCA have exhibited compressive strengths ranging from approximately 60%-160% of the control concrete's compressive strength.

Generally, the ITZ in RCA concrete is considered to be the weak point of the material. This is often attributed to weak pre-existing mortar on the RCA and localized water/cement ratio fluctuations due to the absorptive nature of the aggregate.

RCA is inherently angular because it is produced through crushing. It is thought that this could provide some benefit in terms of compressive strength, however mainly in low w/c content concretes (Neville, 1997). It has also been hypothesized that the superficial pores on the surface of RCA could allow for penetration of new hydration products, which could result in a "nailing effect" that could benefit the ITZ of RCA concrete.

This further supports the need for an accepted framework for classifying RCA as discussed by Butler (Butler et al., 2013a). Determining and standardizing the best practices for RCA use in concrete is an important step for widespread acceptance of such a framework.

2.5.3 Splitting Tensile Strength

Splitting tensile strength testing is a straight-forward method for determining concrete strength in tension. It is performed by applying a distributed load along the edges of a cylinder that are diametrically opposite of one another. This produces a near-uniform tensile stress along three quarters of the vertical plane bounded on the top and bottom by the uniform compression loads. The magnitude of this stress can be calculated based on the applied load and the specimen geometry. The stress that causes splitting of the specimen is considered the ultimate tensile stress.

During the concrete hydration process, microcracks form in the ITZ between the aggregate and mortar due to mechanical property differences between the two materials. In addition, strains due to shrinkage or thermal stresses result in microcracks. These microcracks are believed to be the points where stress concentrations develop under loading, which eventually lead to material failure. Because of this, Splitting Tensile Strength depends largely on the ITZ, which has been theorized to be weak in RCA concretes.

Several studies have investigated the effects of RCA on splitting tensile strength and results indicate that for a 100% RCA concrete, splitting tensile strengths are approximately 65%-70% as compared to those of non-RCA reference concretes (Maruyama & Sato, 2005), (Padmini et al., 2009), (Fonseca et al., 2011). Studies that aimed to improve the ITZ through specialized mixing techniques (Tam & Tam, 2008) have had success in improving the splitting tensile strength of concrete, but only at lower aggregate replacement amounts. These mixing techniques are designed to precondition the RCA and are discussed in Section 2.3.

2.5.4 Static Modulus of Elasticity

Elastic properties of materials are used by engineers in order to gauge the strain response in a material at a given stress level. Although concrete's stress-strain behaviour is non-linear and non-elastic, it is typically assumed that concrete behaves linearly under low, service loading (ASTM, 2006). This portion of linearity is described by the Modulus of Elasticity, which approximately represents the slope of linear portion on concrete's stress-strain plot. The modulus is calculated based on a secant between two stress levels, typically the stress producing a longitudinal strain of $50x10^{-6}$ mm/mm and the stress corresponding to 40% of the ultimate load.

When the stress-strain relationships for aggregate and cement paste are examined, it can be seen that both behave approximately linearly. Cement paste exhibits low stiffness as compared to aggregate, and concrete exhibits a stiffness between the two. As the stress levels applied to the concrete increase, the progressive microcracking at the ITZ between concrete's two phases results in lowering the local cross-sectional area of concrete that resists the applied load. This subsequently increases the local stress above the nominal stess level applied to the sample. This effective stress increase causes the non-linear behaviour of concrete under loading. As microcracks develop, local stress concentrations develop that are higher than the nominal stress on the material. This results in increased strain in the non-linear portions of the concrete stress-strain relationship. Concrete produced using natural aggregate is assumed to have an elastic modulus between 21 – 42 GPa (ASTM, 2006).

The ITZ of RCA concrete is typically assumed to be of poorer quality than in natural aggregate concrete and therefore the strains in the RCA concrete develop at lower stresses resulting in a lower elastic modulus. The stiffness of RCA itself is also typically lower than natural aggregate.

Previous studies have found that 100% replacement of natural aggregate with RCA in concrete results in an elastic modulus reduction of approximately 70-80%. While it is acknowledged that ITZ quality plays a role in elastic modulus, it is unclear whether methods used to improve the ITZ including varying presaturation levels (Poon et al., 2004 and Ferreira et al., 2011) or mixing procedures (Tam & Tam, 2008) cause large effects in the static modulus of RCA concrete. Curing conditions have been found to have some small effect on the relative decrease in elastic modulus of concrete, but largely due to a decrease in the modulus of the control concrete's elastic modulus (Fonseca et al., 2011).

Partial replacement of aggregate appears to reduce the elastic modulus proportionately, such that any replacement amount corresponds to some reduction in elastic modulus (Tam & Tam, 2008, Ferreira et al., 2011, and Fonseca et al., 2011).

2.5.5 Linear Coefficient of Thermal Expansion

The Coefficient of Thermal Expansion (CTE) is a material property that quantifies the expected change in a linear dimension per unit length caused by changes in the material's temperature, with units of (10^{-6} mm/mm)/°C. Results are generally presented in units of ($x10^{-6}$/°C). In concrete, CTE is the net effect of two processes. These processes include the typical expansion of solids and the expansion related to the movement of water in the capillaries and gel pores of the concrete.

The CTE of concrete is an important characteristic in design of concrete structures. This is especially true when considering a structure that will be subjected to a wide range of temperatures throughout the design life. One such type of structure is found in rigid pavements in northern climates. The large temperature range to which a Canadian concrete pavement is exposed can cause significant thermally-induced length changes. These can result in induced stresses where these length changes are externally restrained. Since these stresses can result in premature pavement failures, the response of concrete to thermal loading is an important consideration.

Concrete is a composite material and its constituent materials have different thermal properties. The thermal behaviour of the solid component of concrete is governed overall by the proportions within the mixture.

Since aggregate generally comprises the largest proportion of concrete, the thermal properties of the aggregate significantly influence the behaviour of the concrete. Natural aggregate typically has CTE values, which range from approximately 4 x 10^{-6}/°C for limestone to 12 x 10^{-6}/°C for quartzite (Neville, 1997). CTE testing of aggregate is generally performed on rock cores and this testing method is not available for RCAs unless cores were taken of the previous concrete structure. Similar to concrete, the CTE values of RCA will greatly depend on the aggregate type used. Since RCAs generally have a higher absorption capacity than natural aggregates, they theoretically should be more prone to the water-related effects of temperature changes.

A smaller proportion of concrete volume is made up of cement paste, which generally has a higher CTE (typically 9 – 22 x10^{-6}/°C) (ASTM, 2006). It is also the area where most of the water is situated within concrete and is therefore more susceptible to the swelling pressures associated with water. The swelling is due to the decrease in capillary meniscus tension with an increase in temperature (Neville, 1997). Capillary meniscus tension is the surficial force exerted by the surface of water on the concrete structure that surrounds it. As temperatures increase, this force is reduced, resulting in overall swelling. This also allows for the flow of water from capillaries into the smaller gel pores, which also causes swelling.

Previous studies have found that several variables can have significant effects on the CTE of a given concrete. The moisture condition of a concrete can greatly influence the thermal behaviour of the cement paste and therefore the concrete. When the concrete is dry, there are no capillary menisci so moisture transport and its associated swelling are not possible and the CTE value is at a minimum. Similarly, when the concrete is fully saturated, no menisci are present and the effects of temperature change (above the point of water freezing) are not present. Testing for CTE at either of these two extremes yields what is sometimes considered the "true" CTE of the material. However, these conditions do not closely reflect actual conditions of most concrete applications. The CTE values of cement paste that are observed at intermediate levels of saturation are found to be considerably higher, with a maximum at RH values of approximately 70% (Neville, 1997).

The temperature range considered also has an effect on the CTE that is measured. At higher temperatures the CTE of concrete remains constant and linear values can be considered, however near the freezing point of water, the CTE has been observed to change. This change is dependent on the moisture condition of the cement being tested. In previous research when cooling a 100% RH cement, the paste experienced a substantial decrease in CTE between approximately 10°C and -5°C, the CTE then went up to level higher than the original value at approximately -15°C. A 90% RH cement was observed to experience a much less pronounced decrease in CTE below 10°C, which continued below -20°C (Wittmann & Lukas, 1974).

The age of concrete also affects the CTE of cement pastes. The effect was found to be a reduction in the "peak" CTE value and also the RH level that would produce this peak. These affects were attributed to an increase in the amount of crystalline material in the hardened paste (Neville, 1997).

Previous studies regarding the CTE of concretes produced using RCA have produced variable results. In a study concerning RCA replacement amounts, Bekoe found that there was no clear difference in terms of CTE in mixtures regardless of RCA replacement amount and water/cement ratio (Bekoe, 2009).

As part of the research by Smith and Tighe, the CTE of concrete was shown to decrease as the replacement amount of RCA increased. This research included the study of cores taken from pavement test sections that were approximately 1 year of age. They found that 50% replacement of coarse aggregate with RCA resulted in a CTE value of approximately 4 x 10^{-6}/°C, as compared to a control mixture value of approximately 7.2 x 10^{-6}/°C (Smith & Tighe, 2009).

Butler found that the CTE of concretes produced using natural aggregate and three different RCA types were not significantly different in either direct replacement or strength based replacement mixture types. CTE was found to vary based on the density of the aggregate of each mixture (Butler, 2012).

The large effects of these variables, combined with the different conditions expected for different concrete applications have resulted in no standard test method for CTE being developed.

The focus of the current research study is to develop a practical use of RCA as a construction material. The method of testing CTE was developed to test in conditions similar to what may be reasonably expected in the field. This involved the following considerations:

- Samples would be tested according to a modified version of ASTM C531 similar to previous research performed at the University of Waterloo to allow for some comparison of results
- Samples were to be allowed to equilibrate for 24 hours in the concrete lab, which was considered to have an RH of 50% ± 10% and a temperature of 21 ± 2°C
- Testing would consider the length changes occurring between temperatures of approximately 20°C and -15°C
- Values obtained would be considered as an average CTE

2.5.6 Permeable Porosity of Concrete

One of the major concerns with the use of RCA concrete is the impact it can have on the durability characteristics of the concrete. There are many factors within concrete that affect durability and therefore effects on durability can be measured in many different ways. One such durability factor is the permeable porosity of concrete.

The porosity of a concrete refers to the amount of voids within a concrete. This is composed of capillary pores, gel pores, entrained and entrapped air, and spaces in the ITZ of concrete. The porosity of a concrete has effects on the strength and to a certain extent, the permeability of that concrete. The permeability of a concrete refers to the flow through a porous medium. The permeable porosity refers to that portion of the pore structure that contributes to the flow of liquid through concrete. Typically this includes the larger capillary pores, which are not discontinuous, and therefore provide a pathway for the passage of liquids. While porous aggregate introduces more pores into the concrete, these pores are generally contained and do not have a large impact on the permeability of a concrete. Within this test, pores that are either not saturated or not dried are considered impermeable. The cement microstructure is considered to have the greatest influence on this value (Neville, 1997).

The permeable porosity of a concrete affects the transport properties and therefore the durability of that concrete. The transport of chlorides, oxygen, carbon dioxide, and moisture can cause corrosion in reinforcement. The presence of water within concrete can also have negative effects in terms of freeze-thaw durability (Neville, 1997). When compared to the other accepted standards for measuring the permeable porosity of concrete the vacuum saturation technique was found to be the most effective and was therefore applied within the current research (Safiuddin & Hearn, 2005).

Similar tests have been performed on RCA concretes with the aim to determine the transport properties of RCA concrete. These tests include water absorption (Evangelista & de Brito, 2005), surface and air permeability (Zaharieva et al., 2003), capillary ascension (Ferreira et al., 2011), and depth of water penetration testing (Martinez-Lage et al., 2011 and Zega & Di Maio, 2011). The inclusion of RCA in concrete has appeared to increase the transport properties in most cases with higher absorption and permeability results. The penetration results however, indicate that the water penetration depth of RCA concrete is the same or less than the control mixtures. This could indicate that porous RCA is acting as internal reservoirs that increase absorption without affecting the penetration depth. This could cause freeze thaw issues at the surface of concrete structures.

2.6 Sustainability and Biodiversity

Several goals are outlined in the Province of Ontario's 2011 Biodiversity Strategy, one of which is the sustainable use of biological assets (Ontario Biodiversity Council, 2011). This research is relevant to this strategy for a number of reasons.

The biodiversity benefits of RCA use are two-fold. Firstly, it results in a decrease in demand for natural aggregate, the production of which requires quarrying that can be detrimental to local ecosystems. While RCA use will never fully replace the need for natural aggregates, the reduction in demand is an incremental benefit. Secondly, the diversion of waste concrete from landfills reduces the demands on these institutions. This ultimately could reduce their required footprint and thereby the impact on the local ecosystems.

This research also utilizes Portland Limestone cement (Type GU-L). This material is similar to type GU cement in performance but has 10% less clinker component, which is replaced by limestone. GU-L type cement has a corresponding reduction in the greenhouse gas emissions that are associated with clinker production. Reduction of greenhouse gas emissions can result in reduced impacts on the ecosystems surrounding the clinkering plant.

2.7 Summary of Findings

The most common practices for RCA use in Ontario involve placement of RCA as a fill type material. This is a good use for RCA, but may not effectively use the full value of the material. Gauging the full value of RCA is an on-going process to which this research aims to contribute. The contributions will be towards the following gaps that have been identified in the literature review.

Coarse RCA has not been thoroughly considered as a potential internal curing agent. This is because of several factors, which include: non-ideal desorption, incomplete dispersion, and the potential for overall strength reduction. Each of these factors is a legitimate concern however if some internal curing-like benefits can be gained through proper preparation of RCA, then this could contribute to knowledge of the full value of RCA as a construction material.

A potential benefit of including saturated RCA in concrete is the possibility to provide a buffer against the negative effects of specified concrete curing, primarily in terms of compressive strength development. This benefit could further enhance the value of certain RCA as concrete aggregate.

Research into the ideal procedure for RCA concrete batching has produced one procedure that seems to improve the compressive strength development of RCA concrete. Batching procedures are variable and depend on a number of factors. In this research, the need for known coarse aggregate saturation levels requires a modified batching procedure. The observed effects of this batching procedure could help to identify the potential issues associated with this particular modification.

Some research has been conducted regarding the low-temperature thermal expansion of RCA concretes, with promising results. Since the moisture state within the concrete can have significant effects on its thermal properties, further study is required to determine whether these results can be observed in various RCA replacement levels and saturation states.

All of these contributions have the potential to help further refine the existing RCA classification framework, which could further promote the effective use of RCA in concrete.

CHAPTER 3

RESEARCH METHODOLOGY

The overall research methodology is illustrated below in Figure 3.1. This chapter will provide in-depth discussion of the individual components that make up the study.

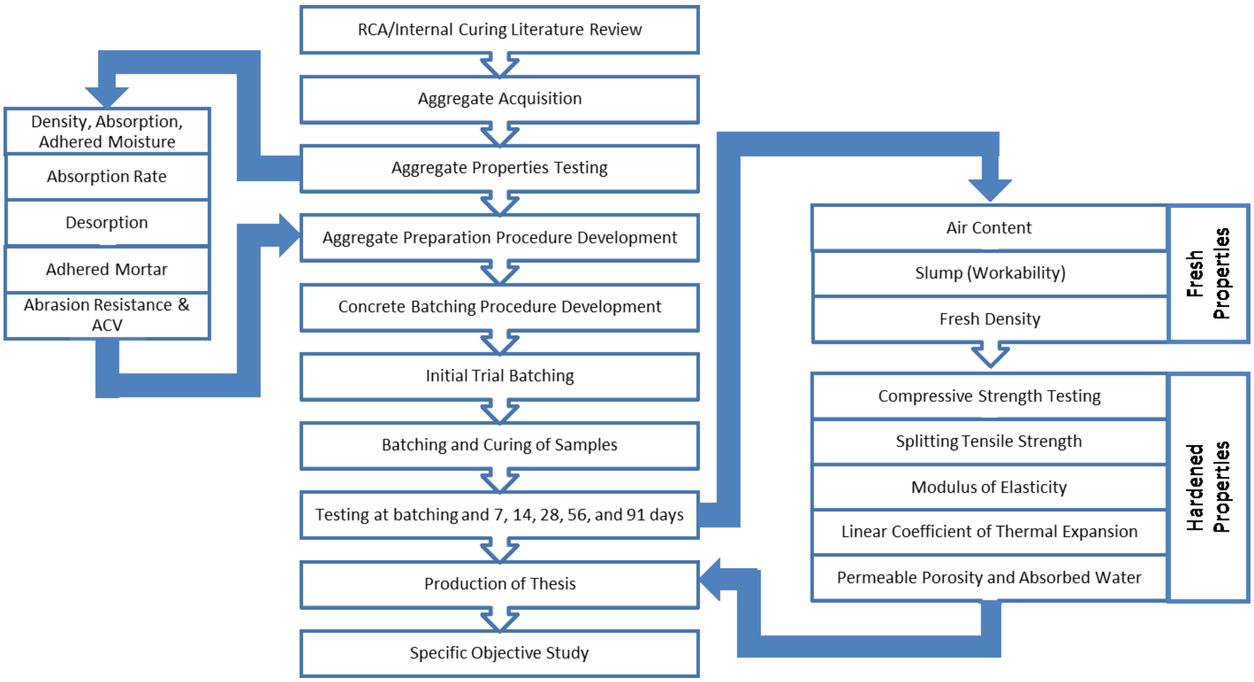


Figure 3.1: Research methodology

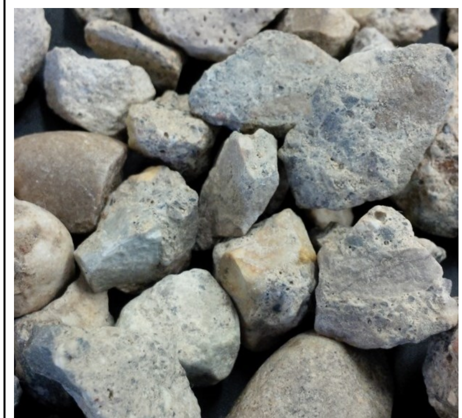
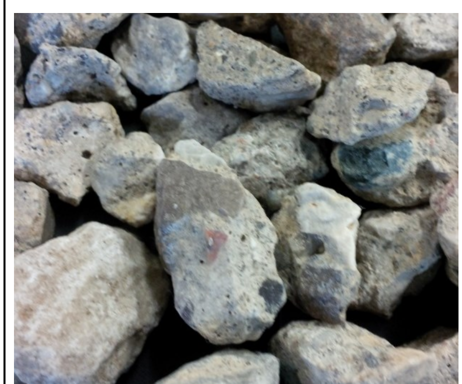
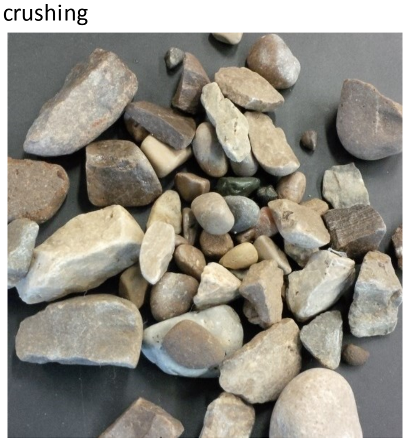
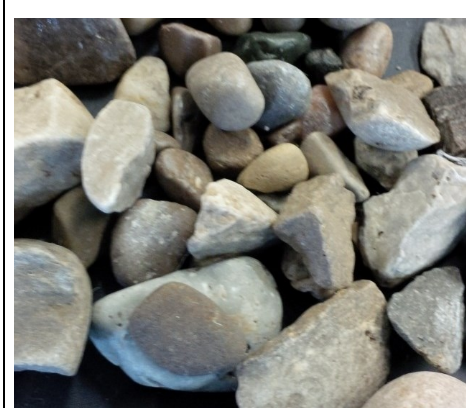
The research methodology is split into four distinct groups, which are: Aggregate Tests, Concrete Production, Concrete Fresh Properties, and Concrete Hardened Properties.

3.1 Aggregate

3.1.1 Physical Classification

Table 3-1 outlines the classification of the three aggregate types used in this research. Each aggregate type is classified in accordance with Table 2-3 and Table 2-4 in terms of particle shape and surface texture. Photographs illustrating the characteristics described are also included within Table 3-1.

Table 3-1: Aggregate Physical Classification

Aggregate Type	*Particle shape classification*	*Surface texture of aggregate*
RCA1	Irregular/Angular- partly shaped by attrition, partly shaped by crushing 	Rough- Fracture surfaces largely intact 
RCA2	Irregular/Rounded- Rounded edges formed through attrition 	Granular- Fracture showing rounded grains, surface adhered fines due to brittle adhered concrete 
Natural Aggregate	Irregular/Angular- partly shaped by river attrition, partly shaped by crushing 	Smooth/Rough- some faces water-worn, others fracture planes from crushing 

3.1.2 Grading

All three sources were graded for use in the production of concrete. For the purpose of this research, the particle size distributions for each aggregate type are considered in reference to the gradation requirements for coarse aggregate (nominal maximum size 19mm) for structural concrete, sidewalks, curbs, and gutters as outlined in the Ministry of Transportation Ontario's (MTO) LS-602.

Samples were obtained from stockpiles for both RCA sources and the natural aggregate source. The materials were oven dried at 110°±5°C then graded in accordance with LS-602 (MTO, 2001) using a mechanical shaker. The stack of sieves included the following nominal opening sizes: 26.5mm, 19.0mm, 16.5mm, 13.2mm, 9.5mm, and 4.75mm. The material retained on each sieve was weighed in order to determine cumulative percent passing of each sieve size, which is illustrated in the particle size distribution.

The particle size distributions are illustrated in Figure 3.2. The bold lines indicate the acceptance envelope defined by LS-602 (MTO, 2001).

As shown, all three aggregate sources fall within this envelope and are therefore acceptable for use in terms of particle size distribution. It can be seen that RCA2 approaches the lower bound of the acceptance envelope at the nominal diameter of 9.5 mm. This indicates that in comparison to the other two aggregate types, a larger proportion of RCA2 is has nominal diameter between 9.5 mm and 13.2 mm. While proper sampling techniques were employed whenever possible, this distribution may be affected by some material segregation caused by stockpiling, which was necessary for the RCA2 storage.

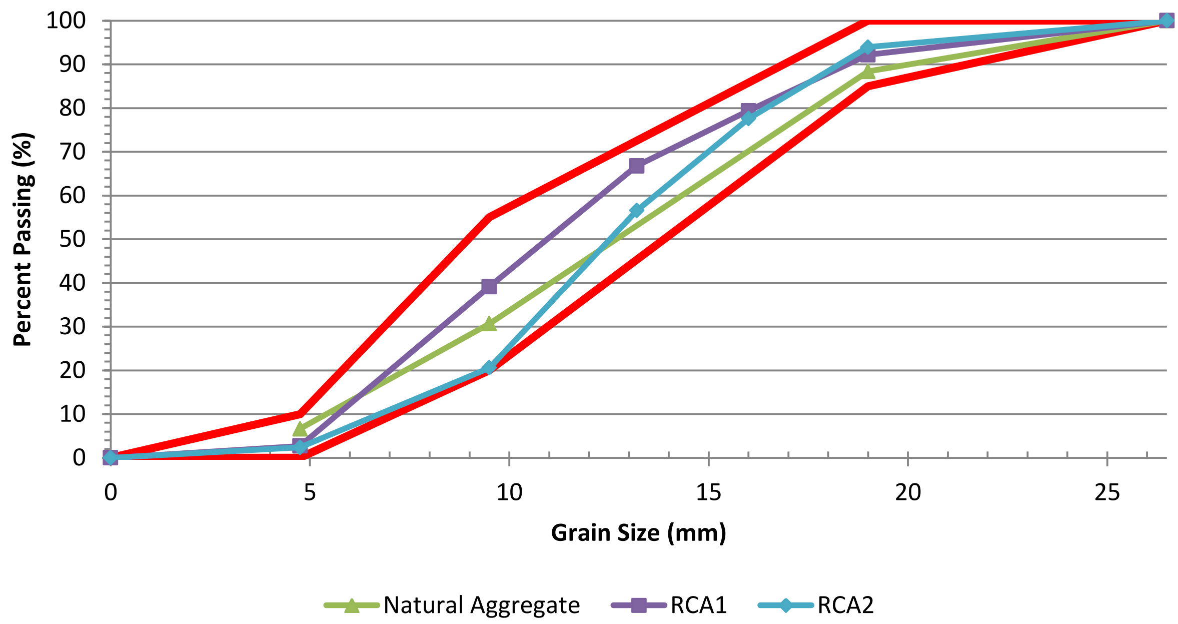


Figure 3.2: Particle size distributions for aggregate sources

3.1.3 Adhered Mortar Content

Adhered mortar content is an aggregate property unique to recycled aggregates. The term refers to the proportion of RCA, which is made up of the original concrete's cement matrix. The content is expressed as a percent of the original aggregate's oven-dry mass.

In order to determine a given aggregate's adhered mortar content, an acceptable method for separating the original aggregate from the mortar is required. Various methods for removing the adhered mortar have been examined. Butler found that a method employing thermally induced stresses provided an effective means of measuring adhered mortar (Butler et al., 2013a). This thermal method was adopted in the current research.

Figure 3.3: Muffle furnace employed in the adhered mortar test procedure

The methodology for this testing procedure involves the following steps:

1. Oven-dry aggregate samples were split into two size fractions, Coarse (retained on the 16mm and 19mm sieves) and Fine (retained on the 4.75mm and 9.5mm sieves).
2. Samples of each size fraction with an approximate mass of 250g were obtained.
3. These samples were submerged in water for 24 hours to ensure 100% saturation of the mortar and original aggregate.
4. The samples were then placed in a muffle furnace (shown in Figure 3.3) for two hours at a temperature of 500°C.
5. After two hours had elapsed, the sampled were quickly submerged into cold water, which served to induce thermal stresses with the aggregate.
6. At this point the mortar was removed by hand, or broken off with a rubber mallet then aggregate and removed mortar were dried at 110°±5°C.

7. Once dried, the material passing the 4.75mm sieve or pieces of mortar larger than this were removed and the remaining aggregate was weighed.
8. The amount of material lost was considered to be adhered mortar and these values resulted in a value for adhered mortar content, according to Equation 3.1.

$$\%Adhered\ Mortar = \frac{Mass\ of\ RCA - Mass\ of\ RCA\ after\ mortar\ removal}{Mass\ of\ RCA} \times 100\% \quad \textbf{(3.1)}$$

9. The overall adhered mortar was produced using a weighted average derived from the gradations for each material.

3.1.4 Density, Absorption, and Surface Adhered Moisture

3.1.4.1 Coarse Aggregate

Density and absorption testing of all coarse aggregate was performed in accordance with CSA A23.2-12A (CSA, 2009). Washed samples of each aggregate type were dried in ovens maintained at 110°±5°C until they reached a constant mass. The samples were then cooled and placed in room temperature water for 24 hours to achieve 100% absorption. The aggregate in each mixture was dried prior to soaking and thus the in-situ moisture of aggregate was disregarded.

The materials were then submerged in water for the determination of mass in water. Subsequently the material was removed and brought to a Saturated Surface-Dry (SSD) condition. This mass was also recorded prior to drying the material to gain an oven dry mass. Using these values, the Bulk Relative Density (SSD and oven dry), Apparent Relative Density, and Absorption were calculated using Equations 3.2, 3.3, 3.4, and 3.5, respectively.

Adhered surface moisture refers to the moisture that remains on the outside of aggregate particles after soaking. This moisture does not include that contained within the permeable pores of the aggregate particles. Adhered surface moisture testing was performed on all of the coarse aggregate samples in order to provide values for use in moisture corrections during concrete mixture proportioning. Since moisture adhering to the surface of the aggregate particles is available to mix with cement during concrete batching, the calculated amount of moisture adhering to the aggregate particles is subtracted from the mixing water proportioned for the concrete mixture.

$$BRD\ (oven\ dry)_{CA} = \frac{M_{oven-dry}}{M_{SSD} - M_{Water}} \quad \textbf{(3.2)}$$

$$BRD\ (SSD)_{CA} = \frac{M_{SSD}}{M_{SSD} - M_{Water}} \quad \textbf{(3.3)}$$

$$Apparent\ Relative\ Density_{CA} = \frac{M_{oven-dry}}{M_{oven-dry} - M_{Water}} \quad \textbf{(3.4)}$$

$$Absorption_{CA} = \frac{M_{SSD} - M_{oven-dry}}{M_{oven-dry}} \times 100\% \quad \textbf{(3.5)}$$

Where: BRD_{CA} = *Bulk Relative Density of coarse aggregate (relative to water density)*

$M_{oven-dry} = mass\ of\ oven\ dry\ specimen\ in\ air\ (g)$

$M_{SSD} =$ *mass of saturated surface-dry specimen in air* (g)

$M_{Water} = mass\ of\ saturated\ specimen\ in\ water\ (g)$

The soaking/draining procedure used in this research required a specialized method for determining the adhered surface moisture of the aggregates considered. The sieves used to drain soaking water away from the aggregate were effective however the large amount of aggregate confined within the centre of the sieve retained a proportionally higher amount of adhered water than the smaller samples recommended for use in CSA A23.2-11A. Figure 3.4 illustrates the sieve used for the draining of soaking water away from aggregate samples.

Each sieve consisted of a 19L bucket with a regular series of holes drilled in its side and bottom. The regular pattern of the holes made production of the sieve reproducible. Each drilled hole had a diameter of 4mm. This was chosen so that the smallest aggregate particles (4.75mm) would be retained throughout the sieving process.

Figure 3.4: Sieve used in aggregate preparation

Aggregate samples were prepared according to the procedure used for concrete batching and then tested. Three stratified samples were taken from each aggregate sample: one from each of the top, middle, and bottom of the sieve. The mass of these samples was recorded directly out of the sieve, once more after being brought to SSD condition, and then one final time after drying at 110°±5°C until they reached a constant mass. This process was repeated for each aggregate type as part of the absorption rate testing, described in Section 3.1.5. Adhered moisture was calculated using Equation 3.6. The results of the testing described in this section are summarized in Section 4.1.2.

$$Adhered\ Moisture, \% = \frac{M_{soaked} - M_{SSD}}{M_{oven-dry}} \times 100\% \qquad \textbf{(3.6)}$$

Where $M_{soaked} = mass\ of\ soaked\ aggregate\ sample, g$

$M_{SSD} = mass\ of\ saturated\ surface\text{-}dry\ sample, g$

$M_{oven\ dry} = mass\ of\ oven\text{-}dry\ aggregate\ sample, g$

3.1.4.2 Fine Aggregate

The bulk relative density for oven-dry and SSD samples as well as the absorption were also found for the fine aggregate used in concrete batching. This procedure was done in accordance with CSA A23.2-6A. To do this, first a sample of fine aggregate was dried to a constant mass at 110°±5°C, and subsequently soaked for 24 hours. After soaking, the vessel was decanted and the sample was then spread on a non-absorbent surface. The material was stirred as air was passed over it until it approached a free flowing condition. At this point, the material was repeatedly tamped into a cone shaped mold until upon removal of the mold the material did not retain the shape of the mold. At this point, the material was considered to be at SSD condition. A pyncometer was filled to a specified reference level with water and its mass plus the mass of the water was recorded as $M_{pync+water}$. Approximately 500g of SSD sand (M_{SSD}) was then added to the empty pyncometer with approximately 90% of the pyncometer's water capacity. This was agitated to remove trapped air and then filled to the reference level. The total mass was then recorded as $M_{pync+water+sand}$. The fine aggregate was then removed and dried at 110°±5°C until it reached a constant mass, recorded as $M_{oven\ dry}$. Using these values, the Bulk Relative Density (oven dry and SSD), Apparent Relative Density, and Absorption were calculated using Equations 3.7, 3.8, 3.9, and 3.10, respectively.

$$BRD\ (oven\ dry)_{FA} = \frac{M_{oven\ dry}}{M_{pync+water} + M_{SSD} - M_{pync+water+sand}} \quad \textbf{(3.7)}$$

$$BRD\ (SSD)_{FA} = \frac{M_{SSD}}{M_{pync+water} + M_{SSD} - M_{pync+water+sand}} \quad \textbf{(3.8)}$$

$$Apparent\ Relative\ Density_{FA} = \frac{M_{oven\ dry}}{M_{pync+water} + M_{oven\ dry} - M_{pync+water+sand}} \quad \textbf{(3.9)}$$

$$Absorption_{FA}, \% = \frac{M_{SSD} - M_{oven\ dry}}{M_{oven\ dry}} \times 100\% \quad \textbf{(3.10)}$$

Where, $BRD_{FA} = Bulk\ relative\ density\ of\ fine\ aggregate\ (relative\ to\ water\ density)$

$M_{oven\ dry} = mass\ of\ oven\ dry\ aggregate\ (g)$

$M_{pync+water} = mass\ of\ pyncometer\ and\ water\ (g)$

$M_{SSD} = mass\ of\ saturated\ surface\ dry\ aggregate\ (g)$

$M_{pync+water+sand} = mass\ of\ pyncometer\ with\ water\ and\ fine\ aggregate\ (g)$

3.1.5 Absorption Rate of Coarse Aggregate

Absorption rate refers to the rate at which a fully submerged coarse aggregate source absorbs water. In the case of this research, a repeatable methodology was required in order to have comparable coarse aggregate saturation in the testing mixtures. Specifically, a methodology was required to produce aggregate that had a saturation level of approximately 60% of its total absorption capacity. In order to achieve this goal, it was decided that timed aggregate submersion would be employed. While this method involves some inherent variability, it was used for two reasons. Firstly, the other method that was considered involved agitating a known quantity of aggregate with a known amount of water and this required a substantial amount of abrasion. This would be difficult to account for in terms of maintaining a consistent amount of abrasion across all concrete batches. Secondly, timed aggregate soaking is a more straightforward method to evaluate this property.

In order to determine the appropriate submersion time to soak the aggregate to 60% of its capacity, two rounds of absorption rate testing were conducted. The first round was performed on aggregate samples of approximately one kilogram in mass. These one kilogram samples were submerged for varying lengths of time in 20°C water, then removed from the water and allowed to drain for one minute. After the sample had drained for one minute, it was weighed then immediately brought to SSD condition and re-weighed. After the material was oven dried, the absorption amount and adhered moisture were calculated. This test set-up is shown in Figure 3.5. This round of testing was performed in order to measure the approximate soaking times necessary for full-scale testing.

Figure 3.5: Small scale aggregate soaking

After the initial round of testing, full-scale testing was employed to gauge the moisture contents that could be expected during concrete batching. Full-scale testing involved pouring water into 19L buckets filled with aggregate for varying lengths of time. The buckets were then emptied into sieving buckets, shown in Figure 3.4, which allowed the free water to flow away from the aggregate. The aggregate was allowed to drain for 1 minute before three stratified samples (top, middle, and bottom of sieve bucket) were taken and tested similarly to the first round of testing.

The absorption values found after each round of testing were compared to the absorption capacity found previously in order to determine what amount of soaking time would result in 60% of capacity absorption.

3.1.6 Desorption of Coarse Aggregate

For the purpose of this research, the desorption isotherms for the materials being used were developed based on Section 7.4 of ASTM C1498 (ASTM, 2010). This method provides a broader evaluation of the desorption behaviour of the materials, which could provide insight into the feasibility of the materials in terms of internal curing benefits.

Using saturated salt solutions, five specific RH environments were created. A summary of the saturated salt solutions and the RH environments are presented in Table 3-2. The production of saturated salt solutions was completed in accordance with ASTM E104-02: Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions (ASTM, 2007). The environments were created using air-tight containers that were housed in a cabinet intended to maintain the temperature and RH of each environment. Figure 3.6 illustrates the environments that were used to control the RH of the samples. As shown, temperature was monitored to ensure that the saturated solutions were producing the RH levels that were being studied.

Table 3-2: Aqueous Salt Solutions and Associated Equilibrium RH

Saturated Aqueous Salt Solution	Equilibrium RH (at 20° C)
Potassium Sulphate	97.6 ± 0.6%
Potassium Chloride	85.1 ± 0.3%
Sodium Chloride	75.5 ± 0.2%
Potassium Iodide	69.9 ± 0.3%
Magnesium Chloride	33.1 ± 0.2%

Samples of each coarse aggregate were placed into each of these environments and mass losses (due to water loss) were recorded every 24 hours. The aggregate samples were moved through the environments consecutively from the highest RH to the lowest RH. This allowed for controlled release of moisture from the aggregate in order to produce the desorption isotherm. Aggregate samples were progressed to the next environment when they had maintained a constant mass (within 0.1% of the specimen mass) for three consecutive daily weight measurements.

Figure 3.6: Air-tight, controlled RH environments

After the aggregate samples had been cycled through all RH environments, they were dried at 110°±5°C to determine the oven dry mass of the specimen.

The constant masses that were observed for each sample in a given RH were then used to produce an isotherm to display the mass (water) loss of an aggregate in that environment.

3.1.7 Abrasion Resistance

The abrasion resistance of an aggregate refers to aggregate durability when subjected to an imposed abrasive action. For the purpose of this research, abrasion resistance was tested using a Micro-Deval apparatus, pictured in Figure 3.7.

The testing was performed in accordance with CSA A23.2-29A (CSA, 2009). First samples were prepared by combining 750g each of two size fractions, 16-20mm and 9.5-16mm. The oven-dry mass of the samples was recorded and then allowed to soak for one hour while completely submerged in two litres of water. The water and aggregate were then added to a stainless steel jar along with an abrasive charge consisting of 5000g of magnetic stainless steel balls, which had an average diameter of 9.5 mm. The jar was secured and then allowed to rotate 12 000 times over the course of two hours.

Figure 3.7: Micro-deval abrasion testing apparatus

After this abrasive action was completed, the contents of the jar were poured over a stack of two sieves: one 4.75mm and one 1.18mm nominal diameter. The magnetic balls were cleaned and removed, all material retained on the 1.18mm sieve was dried at 110°±5°C, and this mass was then recorded. Equation 3.11 was used to then calculate the abrasion loss.

$$\%\,Loss = \frac{Mass\ of\ RCA - Mass\ of\ RCA\ after\ abrasion}{Mass\ of\ RCA} \times 100\% \qquad \textbf{(3.11)}$$

Where *Mass of RCA = oven dry mass before abrasion (g)*

Mass of RCA after abrasion = oven dry mass on 1.18 mm sieve after abrasion (g)

3.1.8 Aggregate Crushing Value (ACV)

The equipment used in the ACV test is illustrated in Figure 3.8.

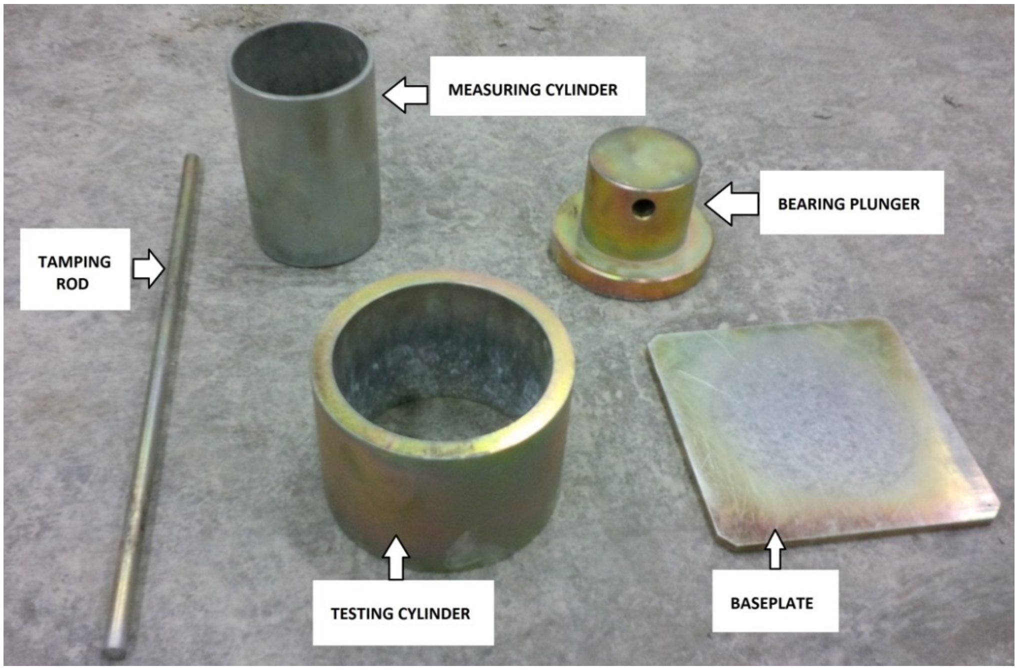


Figure 3.8: ACV testing equipment

The ACV of a material is determined using an oven-dry sample of aggregate wherein the particles have nominal diameters of 9.5-16mm. A measuring cylinder is filled with aggregate in three equal lifts, which are each tamped 25 times with a tamping rod. This cylinder determines the volume of aggregate required for each test. This volume of aggregate is then transferred to testing cylinder in three equal lifts, which are each tamped 25 times with a tamping rod. The testing cylinder is an open-ended cylinder with a wall thickness of 16 mm and an internal diameter of 154 mm. Prior to filling the testing cylinder, it is placed on a 10 mm thick baseplate. The surface of the aggregate in the testing cylinder is levelled off and the bearing plunger is inserted. The bearing plunger is circular with an outer diameter of 152 mm so it can fit within the testing cylinder. The platen of the testing frame applies load to the aggregate via the bearing plunger. Once the plunger is inserted, the load on the aggregate is increased to 400 kN at a rate of 40 kN/min. Once a 400 kN load is reached, the load is removed and the crushed aggregate is removed from the testing cylinder into a tray of known mass. The crushed aggregate is removed from the cylinder by hammering on the outside of the cylinder with a rubber mallet. All crushed material is then sieved over a 2.36 mm sieve. Material retained on the sieve is weighed and the mass is recorded as M_1 while material passing the 2.36mm sieve is weighed and that mass is recorded as M_2. The ACV is then calculated using Equation 3.12.

$$ACV = \frac{M_2}{M_1} \times 100 \qquad \textbf{(3.12)}$$

Where $M_1 = mass\ of\ material\ retained\ on\ 2.36\ mm\ sieve\ (g)$

$M_2 = mass\ of\ material\ passing\ 2.36\ mm\ sieve\ (g)$

Three samples of each material were tested and the average is reported as the ACV.

3.2 Concrete Production

3.2.1 Concrete Mixture Proportions

The concrete used in this research was derived from a mixture design previously developed for RCA research at the University of Waterloo. The designs were developed based on a direct volumetric replacement basis. The direct replacement involves replacing natural aggregate with equal volumes of RCA such that the overall volume of the concrete produced stays constant. This method is also referred to as the Absolute Volume method. The proportions used for the batching of concrete are summarized in Table 3-3.

Table 3-3: Concrete Mixture Proportions

Water (kg/m^3)*	180
Cement (kg/m^3)	487
Coarse NA (kg/m^3)**	1094
Coarse RCA1 (kg/m^3)**	972
Coarse RCA2 (kg/m^3)**	939
Volume of Coarse Aggregate (m^3/m^3 concrete)	0.412
Fine Agg. (kg/m^3)	625
Water-Cement Ratio	0.370

*water content does not include extra water added to account for aggregate absorption

**coarse aggregate values represent proportion for 100% of given aggregate type. 30% mixtures included 30% of RCA mass and 70% of NA mass

The mixtures have been standardized to have a water content corresponding to a 0.370 water cement ratio plus full saturation of aggregate. This water is included in each mixture in combinations of three phases: entrained in aggregate, adhering to the surface of aggregate, or as mixing water. The constant water content with varying aggregate moisture content can serve to affect the overall water/cement ratio of the cement, but allows for constant mixture proportions overall and serves to illustrate the differences caused by different RCA preparation techniques, which can affect the actual location of the water at the time that it is included in concrete mixtures.

Development of these concrete mixtures included the consideration of the varying levels of water absorbed by different coarse and fine aggregates as well as water adhering to the surface of presoaked coarse aggregates, as outlined in Section 3.1.5.

3.2.2 Concrete Batching Procedure

The mixing procedure was developed based on research goals as well as on requirements specific to the available mixing apparatus. A 0.2 m^3 pan mixer, pictured in Figure 3.9 was used for the preparation of all concrete mixtures.

Figure 3.9: Concrete mixer used for concrete production

Due to the number of specimens, this was the only available mixer that had the necessary capacity for the sample preparation. The mixer was not water-tight and could be seen to leak free mixing water around the concrete chute. The traditional method of concrete batching involves initially adding the coarse aggregate and a portion of the mixing water to the mixer, as discussed previously in Section 2.3. This step is to allow some water absorption into the aggregate, but results in some free-flowing mixing water that could be lost in this particular concrete mixer. The water content of the mixture in this research is of primary importance and therefore a modified method of concrete batching was employed. Instead of adding a portion of the mixing water to the coarse aggregate prior to the addition of fine materials, the fine materials (cement and sand) were added to the mixer first. This served to minimize the loss of mixing water from the mixer. The steps of the concrete batching procedure are outlined below and also illustrated in Figure 3.10:

1. Cement and fine aggregate were added to the mixer and manually mixed in order to attain full coverage of mixer
2. Half of the mixing water was added to the dry mix and mixed for approximately 30 seconds
3. The coarse aggregate, after soaking (if necessary) was added to the mixture with the remainder of the mix water
4. The concrete mixture was mixed for 3 minutes, allowed to sit for 3 minutes, and then mixed for a further 2 minutes prior to the beginning of fresh properties testing and specimen preparation

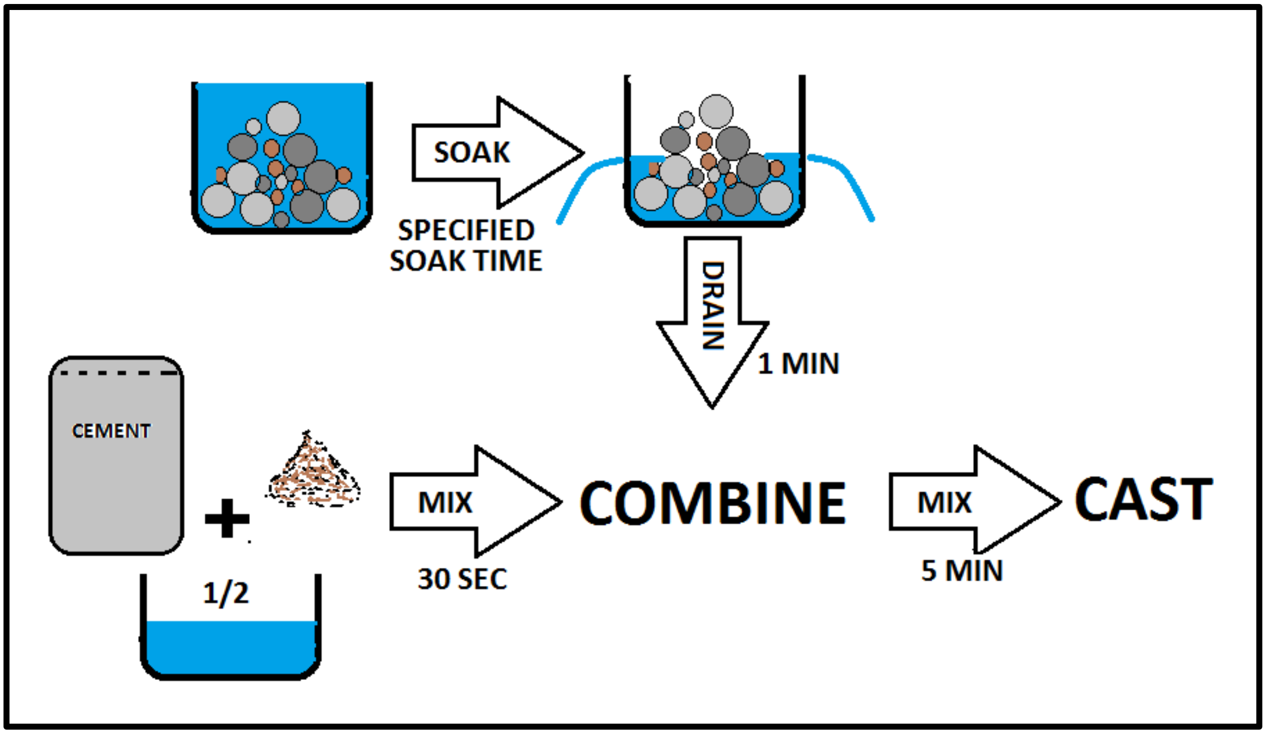


Figure 3.10: Mixing procedure

3.2.3 Aggregate Preparation

3.2.3.1 Coarse Aggregate

The coarse aggregate was prepared according to the specified mix type. The mix types included fully saturated coarse aggregate, partially saturated coarse aggregate, and oven dry coarse aggregate. In each case, a water content sample was taken following the saturation procedure in order to gauge the actual water content of each mixture.

3.2.3.2 Fully Saturated Condition

The fully saturated coarse aggregate was prepared by proportioning the specified mass of material and soaking it in the fully submerged condition for 24 hours prior to batching. This ensured that the material reached 100% saturation. At the time of batching, the material was poured into the sieves and allowed to drain for one minute prior to addition to the mixer. The adhered moisture values discussed in Section 3.1.4 were obtained using the same sieving procedures to ensure that the results were relevant to the mixing procedure.

3.2.3.3 Partially Saturated Condition

The procedure for the partially saturated condition was labour intensive and required a procedure developed during the absorption rate testing discussed previously.

During this testing, different lengths of soaking time were evaluated in order to determine what amount of soaking time resulted in aggregate moisture contents of approximately 60% of the aggregate's absorption capacity. The time was measured from the point when the aggregate sample became fully submerged until the time it was poured into the sieves to remove the soaking water from the aggregate. Similar to the fully saturated procedure, the aggregate was allowed to drain for one minute prior to being tested for moisture content and adhered surface moisture. Some additional water absorption could occur during this draining portion and this was accounted for in the absorption rate testing.

For the mixing procedure, the soaking times previously observed were employed and the same process was repeated. The aggregates were soaked for the specified times, which varied based on aggregate type, and then drained over the sieves for one minute prior to the addition to the mixture. The adhered water values found during the absorption rate testing were applied to mixture design in the form of a water correction in order to maintain the water content.

3.2.3.4 Oven Dry Condition

The oven dry aggregate mixtures were proportioned based on the oven dry masses in order to make the mixture preparation feasible. The preparation procedures used for the other two coarse aggregate conditions resulted in the loss of fine materials from the surface of each material during the draining phase. In order to maintain consistency between mixes, the oven dry aggregate was soaked and drained similarly to the other procedures prior to drying. After the material was dried it was added to the concrete mixture as discussed previously.

3.2.4 Fine Aggregate

The fine aggregate used in the concrete production was air dried to ensure that it did not contribute water to the concrete mixtures. Water was added to the mixture in order to provide full saturation of the aggregate as discussed previously.

3.2.5 Concrete Naming Convention

A total of 14 final concrete batches were produced, which resulted in 17 distinct sample sets. These sample sets were differentiated based on the aggregate type, curing regime, coarse aggregate saturation level, and RCA replacement level. A naming convention for the different concrete types was adopted in order to keep track of these variables. Figure 3.11 shows the naming convention that was adopted and used.

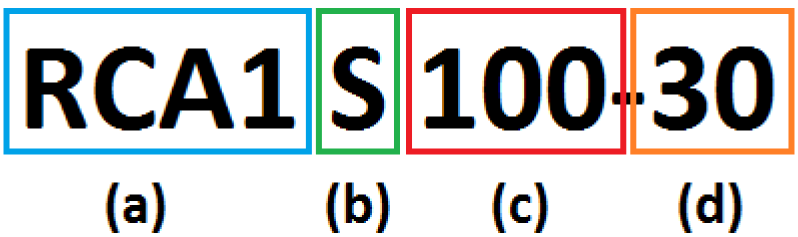


Figure 3.11: Concrete naming convention

The name for each concrete type had four distinct components, which are labelled a) through d). Component a) indicates the coarse aggregate type in the mixture. This could be NA (for natural aggregate), RCA1, or RCA2. Mixtures with both NA and an RCA type were named based on the RCA type. Component b) refers to the curing regime that the samples were subjected to. In this case, "S" indicates the specified curing regime and "M" represents moist curing. Component c) indicates the target saturation level of the coarse aggregate at the time of batching. The three saturation levels used in this study were 0%, 60%, and 100%. Finally, component d) refers to the proportion of the original NA that was replaced volumetrically by RCA. The replacement levels were 0% (for control mixtures), 30% (for "acceptable level" mixtures), and 100%. Each of these variables is discussed in detail in Section 1.3.1. Table 3-4 outlines the mixtures studied. Each mixture's designation is presented along with its corresponding curing regime, aggregate type, coarse aggregate saturation level, and RCA replacement level.

Table 3-4: Mixture Summary and Designations

Aggregate Type	Curing Regime	Coarse Aggregate Saturation	RCA Replacement	Mixture Designation
NA	Moist Curing	100%	0% (control)	NA M 100-0
NA	Specified Curing	100%	0% (control)	NA S 100-0
NA	Specified Curing	0%	0% (control)	NA S 0-0
RCA1	Moist Curing	100%	100%	RCA1 M 100-100
RCA1	Specified Curing	100%	100%	RCA1 S 100-100
RCA1	Specified Curing	60%	100%	RCA1 S 60-100
RCA1	Specified Curing	0%	100%	RCA1 S 0-100
RCA1	Specified Curing	100%	30%	RCA1 S 100-30
RCA1	Specified Curing	60%	30%	RCA1 S 60-30
RCA1	Specified Curing	0%	30%	RCA1 S 0-30
RCA2	Moist Curing	100%	100%	RCA2 M 100-100
RCA2	Specified Curing	100%	100%	RCA2 S 100-100
RCA2	Specified Curing	60%	100%	RCA2 S 60-100
RCA2	Specified Curing	0%	100%	RCA2 S 0-100
RCA2	Specified Curing	100%	30%	RCA2 S 100-30
RCA2	Specified Curing	60%	30%	RCA2 S 60-30
RCA2	Specified Curing	0%	30%	RCA2 S 0-30

3.3 Fresh Properties

3.3.1 Aggregate Saturation

Coarse aggregate was saturated prior to concrete batching according to the results of the absorption rate testing described in Section 3.1.5. After saturation, but before the aggregate was added to the concrete mixer, a small sample was taken in order to gain an estimate of the material's actual saturation level. Because batching took place immediately after soaking the aggregate, the results of the aggregate saturation test could not be compared to design saturations prior to batching.

Saturation testing was performed using a procedure developed based on CSA A23.2-12A, but modified to suit the strict time restrictions. A sample of aggregate weighing approximately 200 g was taken from the middle of a draining sieve and immediately weighed to obtain the total soaked mass of the sample. The sample was then towel dried until it was judged to be in surface dry condition and then re-weighed. This mass was recorded and the sample was dried at 110 ± 5

°C. Once the sample had reached a constant dry mass, this was recorded and Equations 3.13 and 3.14 were used to find the saturation level and the adhered moisture level of the sample taken.

$$Absorption, \% = \frac{M_{SD} - M_{DRY}}{M_{DRY}} \times 100\% \qquad \textbf{(3.13)}$$

$$Adhered\ Moisture, \% = \frac{M_{SOAK} - M_{SD}}{M_{DRY}} \times 100\% \qquad \textbf{(3.14)}$$

Where $M_{SD} = mass\ of\ aggregate\ in\ surface\ dry\ condition\ (g)$

$M_{DRY} = mass\ of\ aggregate\ in\ oven\ dry\ condition\ (g)$

$M_{SOAK} = total\ mass\ of\ soaked\ aggregate\ (g)$

The aggregate was then soaked for 24 hours and the process was repeated to gain the saturated surface dry moisture content of the sample. This was compared to the previously gained absorption amount to gain a percent saturation. This secondary step was only performed in the case of 60% saturation, since it was assumed that providing the same saturation procedure would result in 100% saturation.

The values that these equations yielded were assumed to be representative of the coarse aggregate used in the batching and were used in the subsequent comparisons.

3.3.2 Slump

The slump of the fresh concrete was tested in accordance with the procedures outlined in CSA A23.2-5C (CSA, 2009). The metal mould used in the testing was in the shape of a frustum cone with end diameters of 100 mm and 200 mm; with an overall height of 300 mm.

Fresh concrete was placed into the dampened mould in three equal volume lifts. A steel tamping rod with a diameter of 16 mm and a rounded end was used to apply 25 blows over the surface of each layer of concrete. Each blow was through the top layer and in the case of the second and third layers the blows penetrated 25 mm into the previous layer. After the third layer of concrete was placed and rodded, the surface of the concrete was levelled by screeding the material above the top lip of the cone.

Once the top was levelled, the cone was removed from the concrete vertically over a period of approximately 5 seconds, allowing the concrete to slump freely. The cone was then flipped and set beside the concrete to use as a reference to measure the distance that the top level of concrete displaced vertically. Three measurements were taken in order to produce an average that takes into account the differential settlement of the top layer. Figure 3.12 illustrates the measurement of slump on a sample of fresh concrete.

Figure 3.12: Slump measurement of fresh concrete

3.3.3 Air Content

The air content of each concrete mixture was measured according to the procedures outlined in CSA A23.2-4C. The procedures are similar to those outlined previously in Section 3.3.2, except the concrete was placed into a pressure vessel instead of a frustum cone and was consolidated between lifts. The pressure vessel was cylindrical in shape with internal diameter and height dimensions of approximately 206 mm and 212 mm, respectively. The air meter used in this testing procedure is shown in Figure 3.13.

Three equal layers of concrete were placed and rodded similar to procedure CSA A23.2-5C (CSA, 2009). However, each layer was consolidated using a rubber mallet after rodding to ensure that most entrapped air bubbles were released from the material. This vibration was provided with a rubber-headed mallet.

Figure 3.13: Air meter and associated equipment for air content testing

After the vessel was filled and the surface was levelled, the mass of the vessel and concrete were recorded for use in density calculations that follow. The pressure cylinder lid was then attached to the vessel in such a way that an air-tight seal was formed between the lid and the vessel. Any voids between the lid and the surface of concrete were filled with water, and then air under a standardized pressure was released into the vessel. The amount of air that could penetrate into the concrete gave an indicator of the air content of the concrete. Values of air content were then recorded to the nearest tenth of a percent.

3.3.4 Density

The density of the fresh concrete after batching was measured in accordance with CSA A23.2-6C (CSA, 2009). The pressure vessel described in Section 3.3.3 had a volume of approximately 7

L and therefore could be used to measure the density. The standard prescribes a vessel of this size be used for concrete with a maximum nominal aggregate size of 28mm or less, which the concrete in this research did.

Figure 3.14: Vessel used in Air Content and Density Testing

Immediately after the pressure vessel was compacted and vibrated and the surface had been levelled, the mass of the vessel and sample were recorded. Using this value and the known volume and mass of the vessel, the density of the fresh concrete was calculated. The vessel after being filled and levelled is shown above in Figure 3.14.

3.4 Hardened Properties

3.4.1 Density

The measurement of the density of the hardened concrete at the time of testing was performed in order to gauge the in-batch variability of the concrete. Outliers in density may be related to improper casting and could represent reason to disregard certain results.

All samples were cast in accordance with the procedures outlined in CSA A23.2-9C, and therefore each sample was a cylinder in shape. Prior to performing each hardened concrete testing procedure, the volume and mass of each sample were measured and recorded in order to calculate density. The volume was calculated based on measurements of sample dimensions taken using digital calipers.

3.4.2 Compressive Strength

Compressive strength of each sample was performed in accordance with CSA A23.2-9C (CSA, 2009). After casting and curing, each specimen had its bearing faces smoothed using a mechanical grinding machine. Following grinding, the dimensions of each cylinder (diameter and height) were measured and recorded. These measurements were used to calculate the actual area of the compression face of the concrete as well as to ensure that the cylinder adhered to the 2:1 height-to-diameter ratio required for this test. No samples were found to have a ratio lower than 1.8:1 and therefore no corrections were necessary.

Those specimens that were moist cured prior to testing were maintained in this moisture condition until testing was performed.

Testing was performed on the compressive strength testing machine, which is shown in Figure 3.15. The machine consisted of a lower bearing block that moved vertically to impart load on the specimen, and an upper bearing block, which was spherically seated to allow for rotations to engage the entire surface of the specimen. The upper bearing block was attached to a digital load cell, which recorded the compressive load being applied to the sample.

The loading rate of the sample was maintained between 0.15 MPa/s and 0.35 MPa/s. Once the sample was observed to fail, the maximum load resisted by the sample (in kN) was recorded. This value was used with the measured diameter to calculate the maximum compressive strength of the specimen.

The failure type for each specimen was recorded, and a visual assessment was performed in order to gauge whether the failure plain within the concrete passed largely through the aggregate or the cement matrix. The six most common failure types are summarized in Figure 3.16.

Three specimens for each mixture/age/curing condition were tested and the average of the three results was used as the compressive strength.

Figure 3.15: Compressive strength testing machine

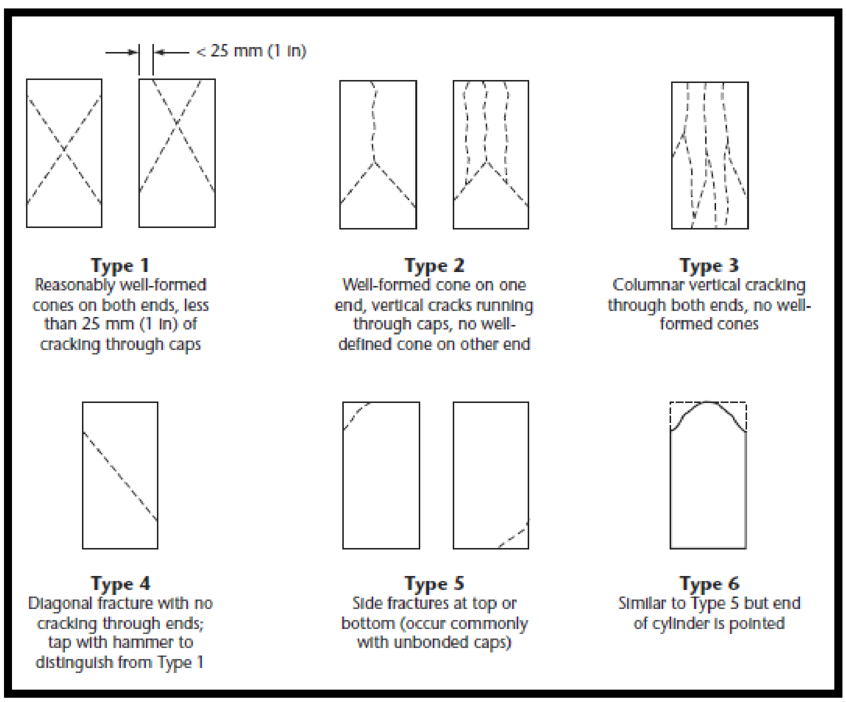


Figure 3.16: Sketches of types of fracture of concrete specimens (CSA, 2009)

3.4.3 Splitting Tensile Strength

The splitting tensile strength of concrete samples was tested in accordance with the procedures outlined in CSA A23.2-13C (CSA, 2009). Cylindrical samples were prepared similarly to the procedure outlined in Section 3.4.2. The samples dimensions and mass were measured and recorded prior to testing.

Samples were placed and centered on a cast-iron aligning jig (Figure 3.17) which included bearing strips of plywood placed on diametrically opposite sides of the cylinder. The jig was placed and centered in the compressive strength testing machine pictured in Figure 3.15.

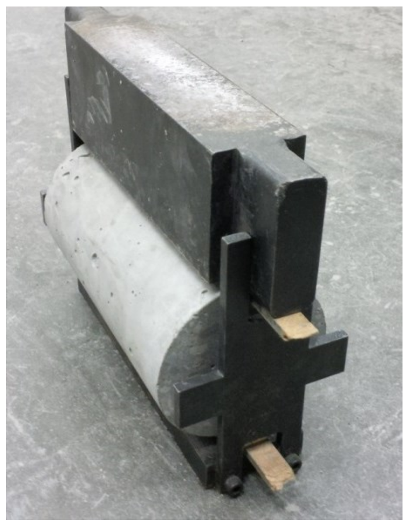


Figure 3.17: Splitting tensile strength aligning jig

Once centered, the specimen was loaded at a rate within the range of 700 kPa/min to 1400 kPa/min. The load applied was measured using the digital load cell within the testing machine, which also recorded the peak value at the time of failure. This peak load (in kN) was recorded and the splitting tensile strength was calculated.

The splitting tensile strength of each specimen was calculated using Equation 3.15. Three specimens for each mixture/age/curing condition were tested and the average of the three results was used as the splitting tensile strength.

$$T = \frac{2 \cdot P}{\pi \cdot l \cdot d} \quad \textbf{(3.15)}$$

Where $T = splitting\ tensile\ strength, MPa$

$P = maximum\ applied\ load\ indicated\ by\ the\ testing\ machine, N$

$l = length, mm$

$d = diameter, mm$

3.4.4 Static Modulus of Elasticity

The static modulus of elasticity (E_c) was performed in accordance with the procedure outlined in ASTM C469/C469M−10. Cylindrical samples were prepared similarly to the procedure outlined in Section 3.4.2. The samples dimensions and mass were measured and recorded prior to testing.

Samples were tested in two high capacity servo-hydraulic testing frames capable of applying load up to 40% of the concrete's capacity, or about 200 kN, at a rate of approximately 1.9 kN/s. Prior to testing, each specimen was fitted with a halo assembly compressometer-extensometer. The assembly was fitted with two linear variable differential transformers (LVDTs), which measured the vertical and transverse strains of the specimen during the loading procedure. The LVDTs used were capable of measuring changes in length of $1x10^{-4}$ mm and measured the strains within the sample throughout the duration of the test.

Samples were centred in the halo assembly through the use of a wooden centering frame. This is illustrated in Figure 3.18.

The testing procedure included loading the sample to 40% of its capacity three successive times, and measuring the strains in the sample in both the longitudinal (vertical) and transverse (horizontal) directions. Between each loading, the sample was unloaded to a compressive force of approximately 1kN at the same absolute rate as the loading, but negative in value. The initial loading served to "seat" the specimen in order to eliminate any settling in the subsequent loading cycles.

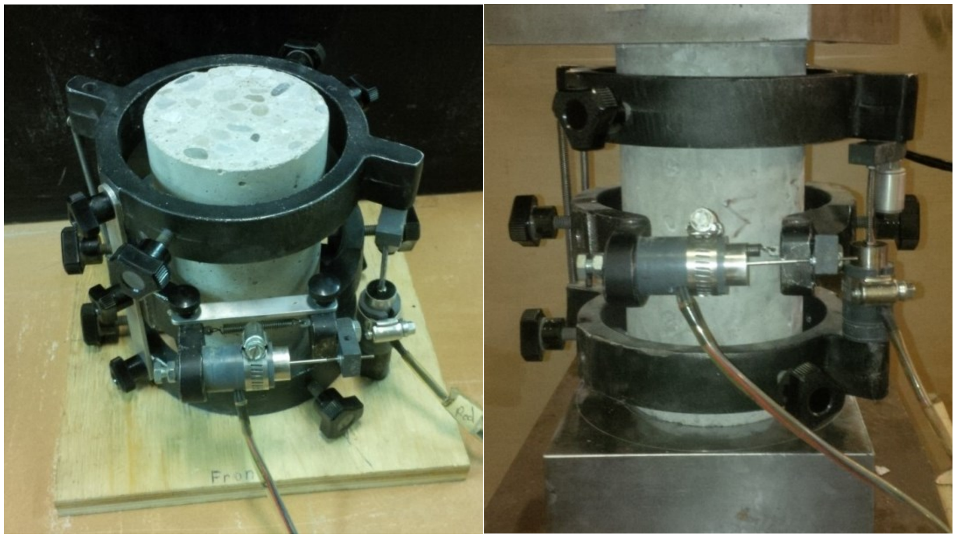


Figure 3.18: Halo transducer assembly for modulus of elasticity testing

The E_c of a specimen is a secant modulus, meaning that it essentially represents the slope of the linear portion of concrete's stress-strain curve. This linear portion is assumed to extend to at least 40% of the concrete's ultimate strength and therefore this is the stress value considered as the upper bound in the E_c calculations. The lower bound of the linear portion is defined by a strain of 5×10^{-5}. The Poisson's ratio of a concrete sample is the negative of the ratio of transverse strain to the corresponding axial strain resulting from an axial stress below the proportional limit of the material. It is calculated within the linear region of concrete's stress strain relationship and compares the change in the concrete's longitudinal strain with the change in the concrete's transverse strain. Figure 3.19 illustrates these bounds as well as the equations used to calculate the E_c and Poisson's ratio values of a sample ($\varepsilon_{t1,2}$ indicate transverse strains, which are not shown on the plot but that correspond to the longitudinal strains $\varepsilon_{1,2}$).

The longitudinal and transverse strains in the second and third loading cycles were used to calculate the E_c and Poisson's ratio, respectively. Due to the geometry of the halo assembly, the readings from the LVDTs were required to be scaled in order to get the actual longitudinal and transverse strain values of the specimen. Three samples were tested for each mixture/curing condition at ages of 28 days and 91 days.

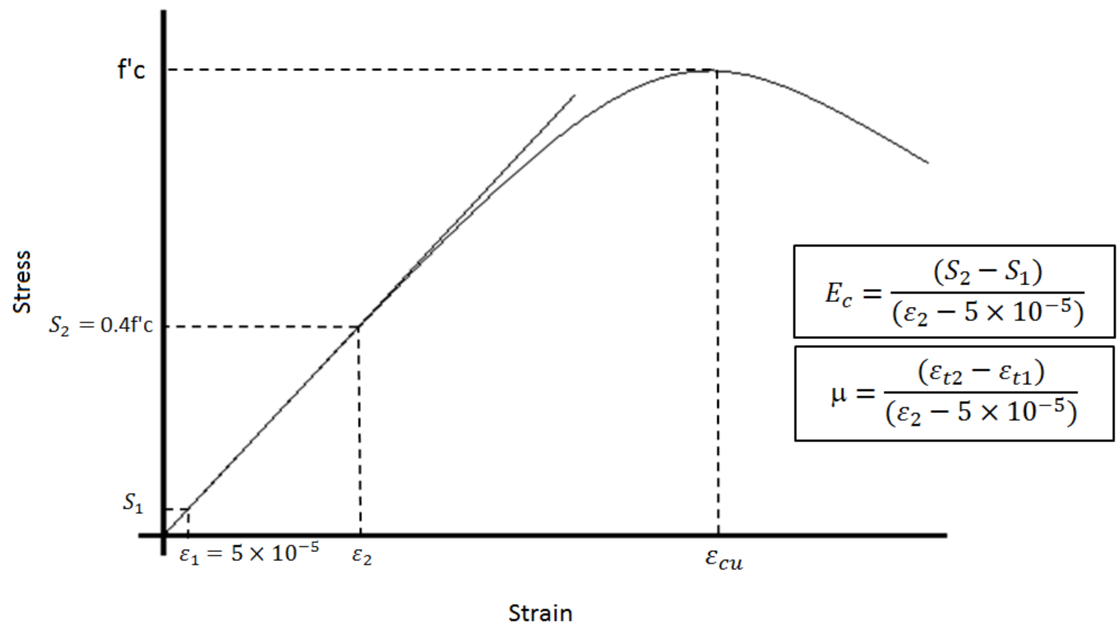


Figure 3.19: E_c and Poisson calculations on stress-strain curve for concrete

3.4.5 Linear Coefficient of Thermal Expansion

The linear coefficient of thermal expansion (LCTE) of the concrete was measured according to a modified procedure based off of ASTM C531 (ASTM, 2012). Samples were initially marked to show vertical lines indicating diametrically opposite sides of the samples. Using a cold temperature epoxy, aluminum strain points were attached to the samples along these vertical lines, with two points on each side of each specimen. The strain points were placed using a 100 mm spacer to ensure that each reading had a similar gauge length. Samples were exposed to the environment within the concrete lab (RH: 50% ± 10%, Temp: 21 ± 2°C) for 48 hours prior to the beginning of testing to allow the exposed surfaces to equilibrate to the environmental conditions. The epoxy was allowed to harden during the equilibration phase of the concrete.

Using a digital laser thermometer, the surface temperature of each specimen was measured and recorded. A digital strain gauge was then used to measure the spacing between each set of strain points; this gauge was capable of measuring with accuracy to 0.001 mm. After all specimens had been measured, they were placed in an insulated cooler that was placed open in a freezer with a temperature of approximately -15°C for a period of 24 hours. After this period the coolers were closed and then removed from the freezer. Samples were removed from the coolers individually and the temperatures and strains were measured and recorded again. The samples were then exposed to the lab environment again for 24 hours before re-measuring. This cycle was repeated for two freezing cycles. Figure 3.20 illustrates the digital strain gauge during testing as well as a sample with diametrically opposite mounted strain points.

LCTE testing was performed on two samples for each mixture/curing condition at ages of 28 days and 150 days. Subsequent to the 28 day testing, all samples were exposed to laboratory conditions until the 150 day testing.

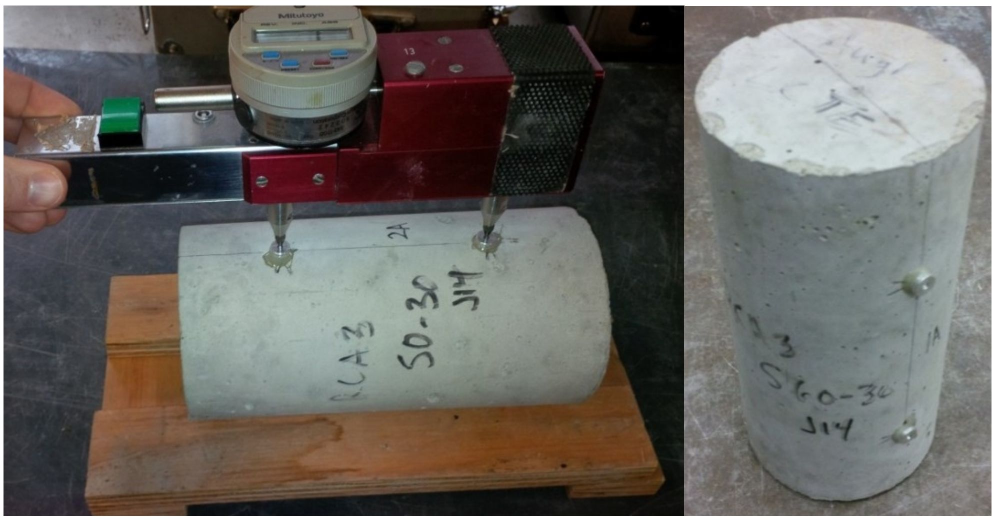


Figure 3.20: LCTE sample and testing procedure

3.4.6 Permeable Porosity of Concrete

The porosity of the concrete was determined using a pressure test procedure developed at the University of Waterloo based on ASTM C642 and ASTM C 1202.

The preparation of the test specimens included cutting concrete cylinders into three specimens with the approximate dimensions of 100 mm diameter and 50 mm height. Since cutting involved the use of water stream cooling, the wet samples were allowed to dry for a day prior to the beginning of testing in the case of the exposed curing samples.

Prior to testing, the initial dimensions and mass of each specimen were measured and recorded. These values were used to calculate an initial moisture condition and a specimen density. The samples were then placed into desiccators, which were depressurized to -90 kPa for three hours, then submerged in de-aired water and allowed to remain in the depressurized environment for another hour. After this hour the samples were allowed to remain submerged in water under ambient pressure for 20 hours. Figure 3.21 shows the dessicators used for the de-pressurized submersion.

Figure 3.21: Permeable porosity testing assembly

After 20 hours of soaking, the samples were weighed under water in order to gain the buoyant mass of the sample, then brought to SSD condition and re-weighed. The samples were then dried in ovens set at 110°±5°C for 48 hours, then re-weighed in the oven-dry condition. Equation 3.16 was used for the calculation of permeable porosity.

$$P_t = \frac{(M_s - M_d)}{V_s \times \rho_w} \times 100\% \quad \textbf{(3.16)}$$

Where P_t = Total permeable porosity (volume %)

V_s = Measured volume of specimen (mm^3)

M_d = Oven-dry mass of the specimen in air (g)

M_s = Saturated surface-dry mass of the specimen in air (g)

ρ_w = Density of Water (g/mm^3)

3.5 Statistical Evaluation Methods

3.5.1 Least Significant Difference

The results of each test were evaluated to gauge their statistical significance. This evaluation was performed by calculating the least significant difference (LSD). This value represents the smallest difference between two mean values, which can be considered statistically significant at 95% confidence. The LSD was calculated in each case using analysis of variance (ANOVA) and modified Bonferroni t-test.

This evaluation method considers variations in a single factor and therefore a separate LSD was calculated for each complement of samples for a given variation. For instance the compressive strength of RCA1 S100-100, RCA1 S60-100, and RCA1 S0-100 could all be compared with a single LSD value as each represents a variation in only the saturation level of the RCA. A sample of the procedure of this calculation is presented in Appendix A.

3.5.2 Standard Deviation and Coefficient of Variation

Where test results are presented in large groupings that preclude the use of LSD evaluation, standard deviations of the measured results are presented in order to indicate the level of variation. Standard deviations are a measure of data spread within a set of results that have the same units of measurement as the data.

Coefficients of variation (COV) are also presented with some results. Similar to standard deviation, COV is a measure of data spread however it is normalized to the mean of the data and is presented as a percentage. COVs can be more easily compared between data sets due to the normalization, which mitigates the effects of differences in means.

CHAPTER 4

RESULTS AND DISCUSSION

Testing was performed according to the procedures outlined previously and the results are shown in the following sections. The results are arranged into sections, which include aggregate properties, fresh properties of concrete, and hardened properties of concrete. After the general results are presented, discussion of specific research objectives is presented in Chapter 5.

4.1 Aggregate

Figure 4.1 outlines the aggregate tests that were performed as well as the key questions to be answered through these tests.

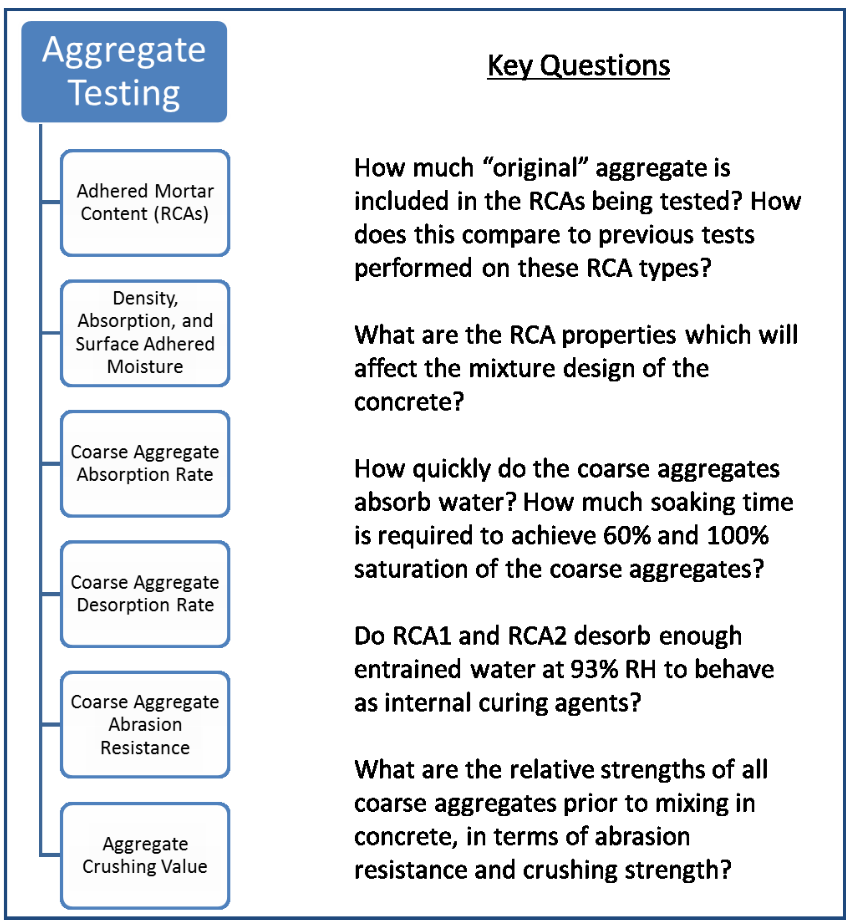


Figure 4.1: Key questions to be answered through aggregate testing

4.1.1 Adhered Mortar Content

The thermal method used for removal of adhered mortar was largely effective. By visual inspection it is estimated that more than 90% of the mortar adhered to original aggregate was removed during the process. Figure 4.2 illustrates part of RCA2 sample after removal of the adhered mortar. The image on the left shows the coarse fraction with minimal adhered mortar remaining while the image on the right shows the material that passed through the 4.75 mm sieve and was therefore considered to be adhered mortar.

Figure 4.2: Sample of RCA2 after removal of adhered mortar

The average results of the adhered mortar testing are summarized in Table 4-1. Adhered mortar testing was only performed on the RCA samples. Each fraction size for each RCA type was tested three times. The standard deviations for each fraction are also presented.

Table 4-1: Aggregate Testing Results

Aggregate Type	Adhered Mortar (%)				Weighted Average
	Fine Fraction (> 4.75 mm, < 16	Std Dev	Coarse Fraction (> 16 mm, < 20 mm)	Std Dev	
RCA1	41.9%	3.7%	34.3%	2.4%	40.3%
RCA2	49.5%	9.2%	26.7%	5.3%	44.3%

Both RCA1 and RCA2 had similar overall adhered mortar contents, however the differences between the aggregate in each size fraction were more pronounced. Both RCAs had higher concentrations of adhered mortar within the fine fraction of the aggregate. Both RCAs also had lower concentrations of adhered mortar in their coarser fractions however RCA2's coarse fraction had considerably less, with a difference of 22.8% as compared to RCA1's 7.5% difference. The gradation-based averages skewed heavily towards the fine fraction and therefore those results tended to govern the weighted average. The results of RCA2 had more variation, which indicates that the material is less homogenous than RCA1. This could make it more difficult to accurately classify.

These results may explain in part the higher absorption of RCA2 as compared to RCA1. A higher overall adhered mortar content increases the amount of porous material within the RCA's structure.

During the testing process it was observed that the adhered mortar of RCA2 required less effort to remove. This may indicate a weaker existing Interfacial Transition Zone (ITZ) between the original aggregate and adhered mortar, which is more easily overcome by the imposed thermal stresses. This may also be due to the relative weakness of the adhered mortar within RCA2. This lack of strength can be observed through the high amount of fine mortar material, which can be "rubbed off" of RCA2.

Previous study of RCA1 and 2 yielded adhered mortar contents of 46.4% and 49.6%, respectively. In both cases, these values represent approximately 10% more adhered mortar than was found in the current research. This discrepancy may be accounted for by differences in aggregate preparation. Since the current research involved the saturation and thereby "washing" of the coarse aggregate, both samples were washed of any fine adhered material prior to testing.

4.1.2 Density, Absorption, and Surface Adhered Moisture

4.1.2.1 Coarse Aggregate

The results of the testing were generally consistent with the results of previous testing of each material and are shown below in Table 4-2. The values shown for each property are averages based on three tests. The standard deviations for the results of these three tests are also included in order to indicate the variability of the results.

Table 4-2: Coarse Aggregate Material Properties

	Natural Aggregate	Std Dev	RCA1	Std Dev	RCA2	Std Dev
Absorption Capacity (%)	1.53%	0.19%	4.72%	0.30%	6.93%	0.44%
Adhered Moisture (%)	1.21%	0.03%	1.86%	0.23%	2.39%	0.30%
Bulk Relative Density	2.66	0.017	2.36	0.078	2.28	0.013
Apparent Dry Relative Density	2.77	0.005	2.65	0.079	2.70	0.024
Bulk Density (Oven Dry Rodded) (kg/m^3)	1692	3.62	1401	8.2	1353	32.0

Absorption capacities were found to be similar to previous results, with RCA2 exhibiting the largest absorption capacity, followed by RCA1, then the natural aggregate. The adhered moisture exhibited a similar trend. The moisture-related values summarized in Table 4-2 were used to develop concrete mixtures with relatively constant moisture contents.

For reference, according to the current guidelines for Ontario's Ministry of Transportation, only the natural aggregate meets the absorption requirements for use in pavements or other transportation structures (OPSS, 2013).

The apparent relative density that includes only the impermeable portion of each aggregate type indicated that RCA2 was slightly more dense than RCA1, but less dense than the natural aggregate.

The bulk relative density values, which include the voids or pores within the aggregate, indicated that RCA2 had a higher void content than RCA1, which despite RCA2's higher apparent relative density serves to drop the overall density below that of RCA1.

The bulk densities of the materials indicate that the overall density of RCA1 is higher than RCA2. These values were used during concrete mixture proportioning to maintain proportional volumes of coarse aggregate in each mixture.

4.1.2.2 Fine Aggregate

Table 4-3 summarizes the properties of the fine aggregate used in the production of the concrete mixtures. Values shown represent the averages of three tests. Standard deviations for these tests are also presented.

Table 4-3: Fine Aggregate Material Properties

		Std Dev
Bulk Relative Density (oven Dry)	2.51	0.15
Bulk Relative Density (SSD)	2.55	0.15
Apparent Relative Density	2.62	0.17
Absorption (%)	1.61%	0.11%

These results fall within the typical scope for natural fine aggregate. The absorption capacity of the material was used to proportion the concrete mixtures as it affected the mixture water available during mixing.

4.1.3 Absorption Rate of Coarse Aggregate

The specific goal of the absorption rate testing was to determine the soaking time required for an aggregate type to reach 60% of its maximum saturation. Typically absorption rate testing produces an isotherm, but due to the specific goal of this testing isotherms were not produced for each aggregate type.

At the conclusion of testing, it was found that in order to achieve approximately 60% saturation of the natural aggregate, RCA1, and RCA2, soaking times of 10 seconds, 30 seconds, and 90 seconds were required, respectively. Times were chosen to the nearest 5 seconds in order to ease the concrete production procedure.

During concrete production, moisture samples were taken in order to gauge the actual saturation levels of each mixture. The results of these tests are included and discussed in Section 4.2.1.1.

4.1.4 Desorption of Coarse Aggregate

The results of the desorption testing are illustrated in Figure 4.3. Each aggregate type exhibited different desorption behaviour as can be seen in the three isotherms. RCA1 is shown in red while RCA2 is shown in blue. The desorption behaviour of the natural aggregate is shown for reference. At each RH level, the error bars shown represent one standard deviation in either direction.

The isotherms displayed are in terms of percentage of total retained moisture not the amount of retained moisture. Due to the differences in overall absorption capacity 100% retained water indicates the highest total water level in RCA2, then RCA1, and the lowest in NA. The vertical red dashed line on the plot indicates the 93% RH threshold, which is considered to be the approximate level at which internally entrained water should desorb in order to provide benefits to the hydration process.

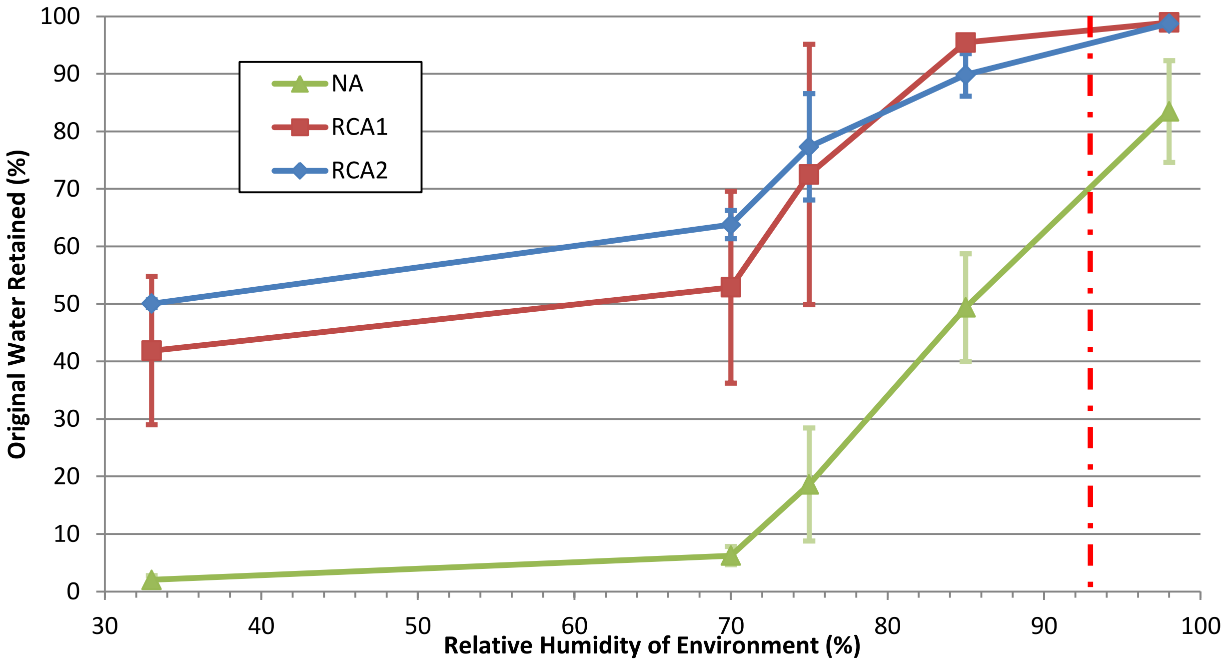


Figure 4.3: Desorption isotherms for coarse aggregates

Both RCAs retained most of their entrained moisture in the 98% RH environments and 90% or more of their entrained moisture in the 85% RH environment. Very little moisture was found to be drawn out at the 93% RH level. This indicates that the materials do not desorb as large a proportion of their water as would be desirable for internal curing applications. They do however provide some water in these conditions, and may therefore provide some small value. The relatively small error bars indicate that the results found are generally repeatable and reliable. At lower RH levels, the variation within the results increases, but these RH levels do not largely impact the internal curing suitability of the materials.

A considerable amount of desorption occurs in both RCA types between RH levels of 85% and 70% as RCA1 and 2 lose approximately 40% and 25% of their entrained moisture respectively across this humidity gradient. Below the 70% RH level, it appears that the material tends to retain the entrained moisture. At the 33% RH level RCA1 and 2 still retain approximately 40% and 50% of their initially entrained water respectively.

For comparison, the NA appears to desorb its entrained moisture approximately linearly until approximately 5% of the initially entrained water remains at the 70% RH level. Below 70% RH the entrained water level appears to drop such that very little entrained moisture remains at the 33% RH level.

Based on the desorption values found, the Bentz equation was applied to in order to determine what mass of each aggregate type would be necessary for the given concrete mixtures in order to permit full internal curing. Detailed discussion of this equation is presented in Section 2.2.5. The calculated masses considering both a 93% RH threshold and an 85% RH threshold are included in Table 4-4.

Table 4-4: Mass of Aggregate Required for Full Internal Curing

RH (%)	Mass Required (kg/m^3 of concrete)		
	RCA1	RCA2	NA
93	20523	15420	8844
85	10874	7101	5181

Considering the 93% RH threshold for hydration benefits, neither RCA1 nor RCA2 provide nearly enough desorbed water to provide full hydration. The 100% replacement mixtures of RCA1 and RCA2 provide approximately 5% and 6% of the masses required, respectively. Interestingly, despite the NA's much lower absorptive capacity, its desorption characteristics actually appear to make it a better (though still not adequate) internal curing candidate than the RCAs. This may be due to the differences in pore structure between NA and RCA. Pores sizes govern the capillary forces on water, which affect how readily the water can be drawn out. The pores in NA may be larger, which would reduce these capillary forces. The concrete mixtures involving 100% saturated NA provides approximately 12% of the required mass for full internal curing.

These results suggest that the RCAs studied within this research cannot perform as typical internal curing agents as they retain the bulk of their entrained moisture past the point where more water would be considered most helpful to the hydration process.

It is possible that the saturated aggregates within concrete could help to alleviate the effects of moisture gradients within curing concrete that result in stress gradients (Grasley et al., 2006). As the internal RH level of concrete drops to ambient levels, the exposed surfaces of the concrete drop first, which results in a moisture gradient. As the concrete dries, the internal pore fluid pressure drops thereby initializing drying shrinkage. Since the pore fluid pressure drops on the outside of the concrete faster than the inside, stress gradients are formed due to differential shrinkage. Since the water entrained in the RCA appears to largely remain in the aggregate at RH levels of 93%, it may be available at later stages of hydration. When external drying reduces the internal RH of concrete to the 70% level, the RCA may be able to desorb a more substantial amount of its entrained water. This largely depends on the pore structure of the concrete at this point in time and whether water could flow out of the RCA. Retaining a less severe initial moisture gradient within the concrete could allow the concrete to develop more strength to resist the onset of shrinkage cracking.

4.1.5 Abrasion Resistance

The results of the abrasion resistance testing of each aggregate type are summarized in Table 4-5.

Table 4-5: Abrasion Resistance (as measured by Micro-Deval)

Aggregate Type	Sample 1	Sample 2	Abrasion Loss
Natural Aggregate	10.8%	10.4%	10.6%
RCA1	16.1%	16.3%	16.2%
RCA2	23.4%	23.8%	23.6%

The natural aggregate exhibited the lowest loss of material as a result of the abrasive effort. RCA1 and RCA2 exhibited approximately 50% and 120% less abrasion resistance than NA, respectively. The substantially lower abrasion resistance in the RCA materials could be explained by the presence of adhered mortar in the aggregate. The ITZ in the RCA represents a plane through which tensile failure within the material could occur more easily. This could be especially true in the case of RCA2, which was not properly cured and presumably had a very high water-cement ratio. The reduced densities of adhered mortar due to its high porosity could also serve to explain the relative ease with which it was removed from the original aggregate. RCA2 also included more adhered mortar than RCA1, as discussed in Section 4.1.1. This could further contribute to the material's decreased abrasion resistance.

Figure 4.4 illustrates each of the aggregate types both before and after being subjected to abrasive effort. All of the materials can be observed to have become rounded and lost some of their original angularity, however this is much more obvious in the RCA samples. All of the material on the surface of RCA2, which could be removed by rubbing the material, can be seen to no longer be present.

For reference, the Ontario Ministry of Transportation places a maximum degradation value of 17% for aggregate to be used in structures, sidewalk, curb and gutter, and concrete base, and 14% for aggregate to be used in pavements. Using these guidelines, the natural aggregate and RCA1 are acceptable for use in structures, sidewalk, curb and gutter, and concrete base, and only the natural aggregate is acceptable to be used in pavements (OPSS, 2013).

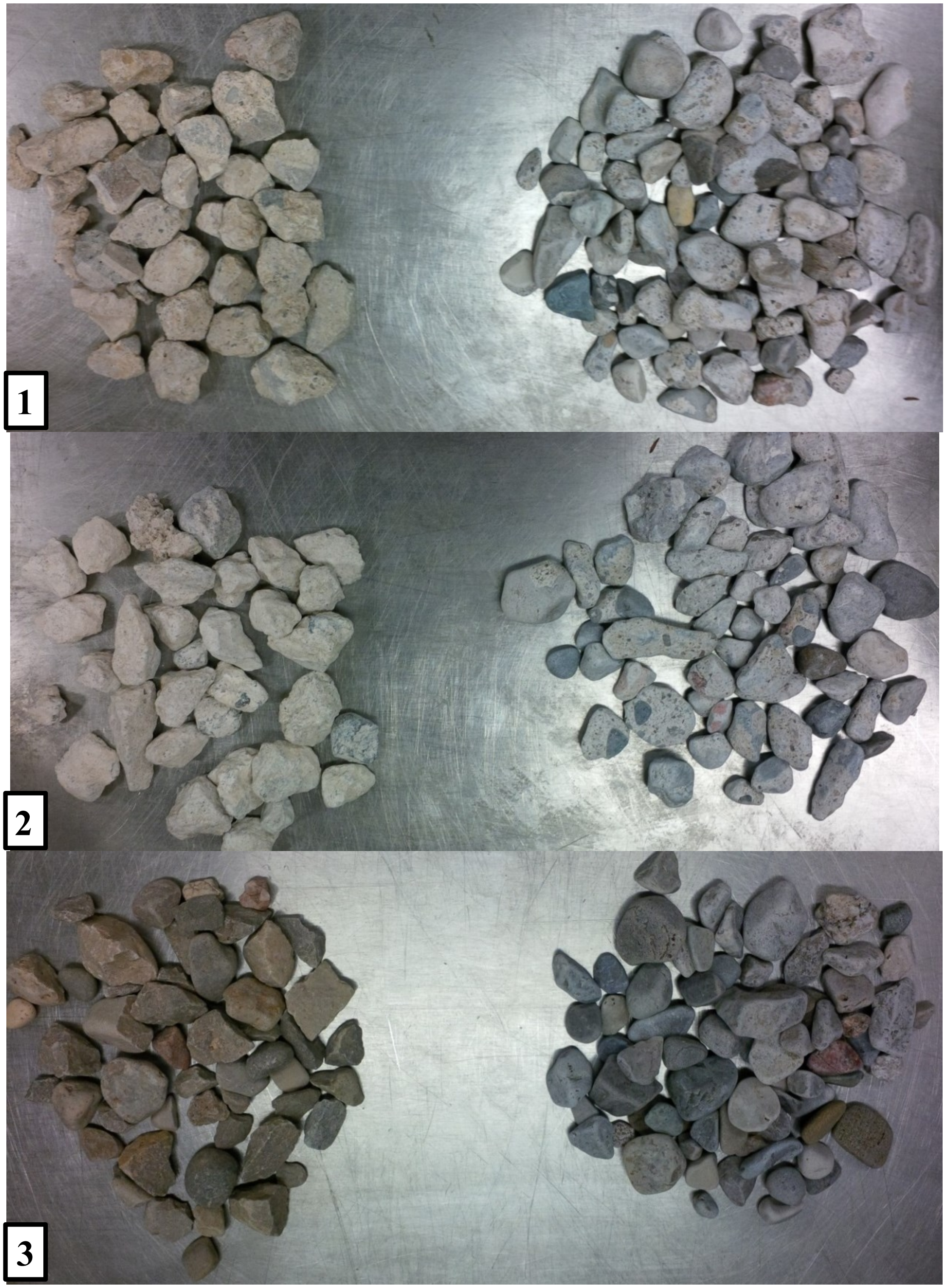


Figure 4.4: Aggregate before and after abrasion testing: RCA1 (1), RCA2 (2), NA(3)

4.1.6 Aggregate Crushing Value

During the ACV testing, audible cracks and pops were observed as aggregate crushed. This was mostly observed during the first half of the 400kN loading. The results of the ACV testing are summarized below in Table 4-6.

Table 4-6: Aggregate Crushing Value Results

Aggregate Type	Sample 1	Sample 2	Sample 3	Average ACV	Std. Dev.
Natural Aggregate	17.9%	19.5%	19.0%	18.8%	0.7%
RCA1	25.8%	25.7%	26.7%	26.1%	0.5%
RCA2	28.0%	28.1%	28.5%	28.2%	0.2%

ACV values represent the fraction of the material that passes a 2.36mm sieve over the total mass of the sample. Stronger materials will crush less and will therefore have ACV values, which are lower. The results indicate that the natural aggregate had the highest strength and RCA1 had a higher strength than RCA2. This result was expected based on the results of adhered mortar, abrasion, and density testing.

It is hypothesized, based on these, results that in high performance concrete where aggregate strength governs the strength of the concrete, concrete produced with an equivalent volume of RCA1 will perform better than that produced with RCA2.

While performing ACV testing, the applied plunger load and displacement were recorded at 1kN intervals. By using this data and making some reasonable assumptions, it is possible to approximate the average secant modulus for each confined aggregate sample. This method was used as part of previous RCA testing at the University of Waterloo (Butler et al., 2013b).

The assumptions necessary are as follows (adapted from Butler, 2012):

- Stress values calculated are considered to be average axial stresses as the area over which the plunger is in contact with the individual aggregate particles cannot be easily calculated. Instead, the gross area of the interior of the ACV cylinder was taken as the area over which the load compresses the aggregate sample.

- Initial depth of the rodded aggregate sample was assumed to be approximately 100 mm given that each sample was prepared using the same steel measuring cylinder.

Based on these assumptions, the curves shown in Figure 4.5 were developed.

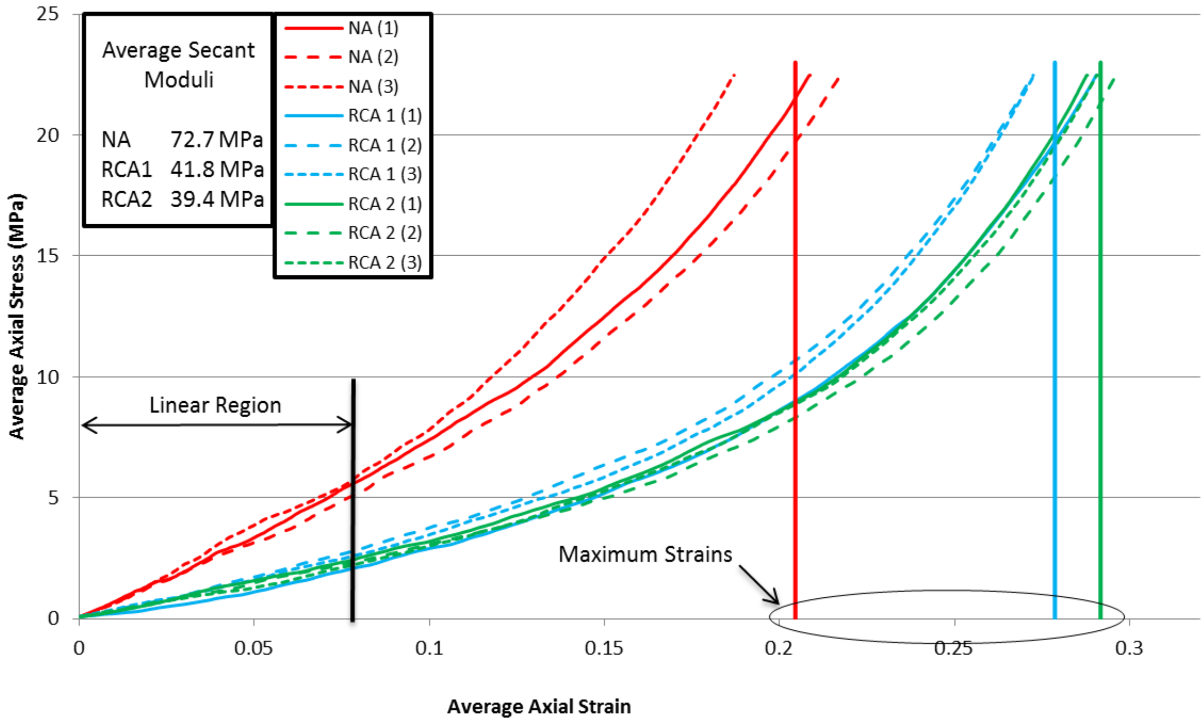


Figure 4.5: Average secant moduli of confined aggregate samples

As each aggregate type was tested three times, each modulus is made up of an average of these three trials. Based on the curves shown, it was estimated that the materials each behaved approximately linearly up to strain of 0.1 mm/mm. This was therefore chosen as the region to consider when calculating the secant modulus, and is marked in the figure. For each test, the secant modulus was calculated using Equation 4.1.

$$\text{Secant Modulus}_{Coarse\ Aggregate} = \frac{(\sigma_{max} - \sigma_{initial})}{(\varepsilon_{max} - \varepsilon_{initial})} \qquad \textbf{(4.1)}$$

Where, $\sigma_{max} = the\ maximum\ axial\ stress\ within\ the\ linear\ region\ (MPa)$

$\sigma_{initial} = the\ initial\ axial\ stress\ within\ the\ linear\ region\ (MPa)$

$\varepsilon_{max} = the\ maximum\ axial\ strain\ within\ the\ linear\ region$

$\varepsilon_{initial} = the\ initial\ axial\ strain\ within\ the\ linear\ region$

Using these values, an average secant modulus was then developed. The natural aggregate was found to exhibit much more stiff behaviour under axial loading, while both RCAs performed similarly. These results appear to correlate well to the results of the ACV testing, which implied that the natural aggregate could support the applied load with greater resistance to crushing (and therefore axial deformation and strain). As in the ACV results, the RCAs behaved similarly, with RCA1 displaying slightly higher results.

4.1.7 Aggregate Conclusions

Based on the aggregate testing, the following conclusions were made:

- Both RCA types were comprised of approximately 40% mortar by mass.
- In comparison with the natural aggregate, both RCA1 and RCA2 exhibited higher absorptive capacities (1.53%, 4.72%, and 6.91% respectively) and lower bulk densities (1692, 1401, and 1353 kg/m^3 respectively). These results are due to the presence and relative quality of any adhered mortar in the aggregates. NA, with no adhered mortar, had the lowest absorption and highest bulk density while the poor quality of RCA2's mortar phase resulted in the highest absorption and lowest bulk density.
- None of the three aggregate types desorbed significant amounts of entrained water at 93% RH and therefore could not be considered strong candidates for use as internal curing agents by the generally accepted guidelines.
- ACV results indicate that the aggregates listed in order of decreasing strength are: natural aggregate, RCA1, and RCA2. ACV results also indicate that both RCA types are considerably less stiff than the natural aggregate. This is due to the presence and relative strength of adhered mortar. The method by which RCA2 is produced creates a relatively weak mortar phase, which causes the lowest ACV results. Based on previous results, this could correlate to the relative tensile strengths of concretes produced using these aggregate.
- Based on currently existing MTO abrasion and absorption specifications, neither RCA1 nor RCA2 are suitable for use in concrete structures. Other researchers have found that low abrasion and absorption values in RCA do not necessarily correlate to lower concrete strength.

4.2 Concrete Results

4.2.1 Fresh Properties

The fresh concrete properties were measured directly after concrete mixing, while sample casting was underway. Figure 4.6 outlines the fresh properties tests as well as the key questions, which each test aims to address.

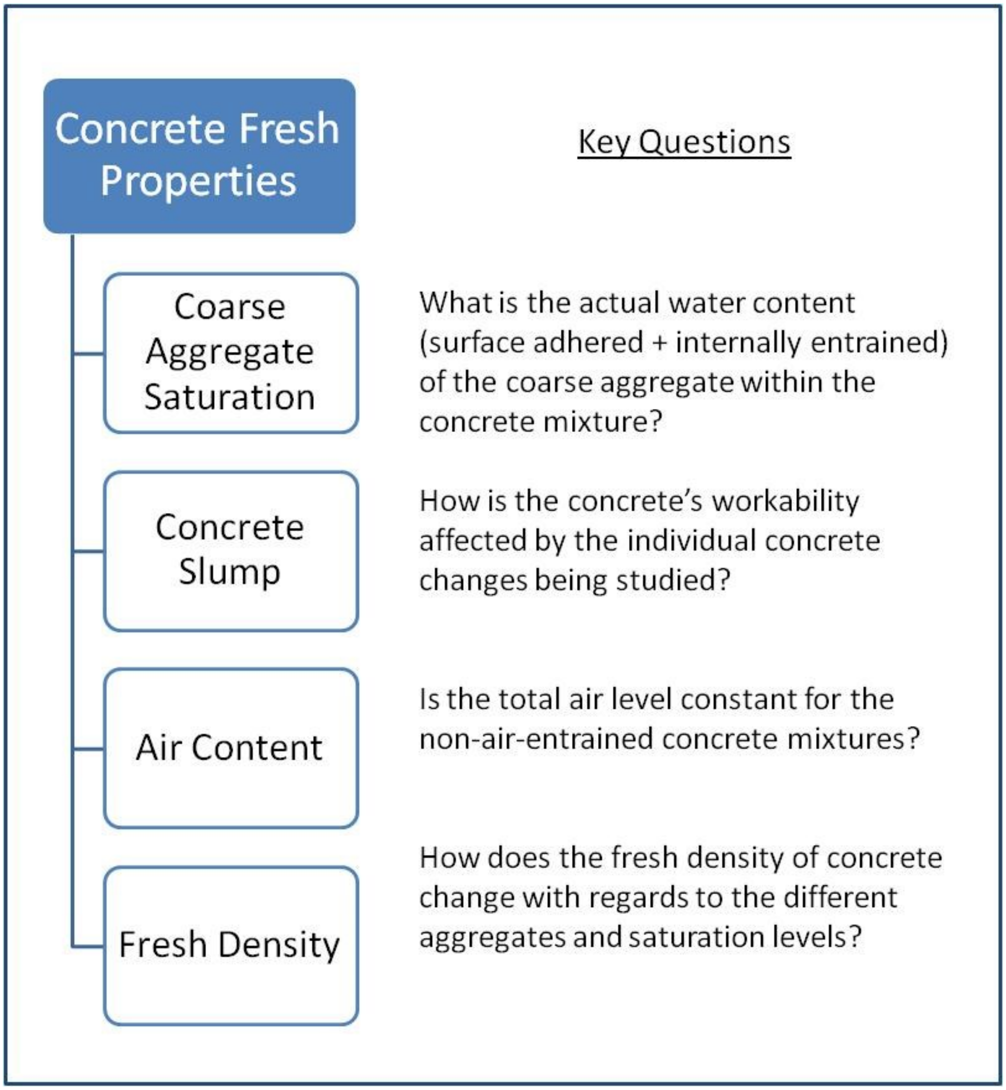


Figure 4.6: Key questions to be answered through fresh properties testing

4.2.1.1 Aggregate Saturation

Tests performed parallel to the batching procedure provided an estimation of the saturation of the coarse aggregate that was being used in the concrete mixtures. This test was used to confirm the actual saturation levels achieved during the coarse aggregate preparation.

In each case, the saturation refers to the surface dry moisture content as compared to the absorption capacity of that sample. This is considered to be the level of water entrainment within the aggregate at the time of mixing, and does not include the surface adhered water, which is considered to be part of the mix water. Figure 4.7 illustrates the measured saturations for each aggregate in the 60% saturation mixtures. The type of aggregate is noted in brackets below the mixture name due to the partial replacement mixtures, which included both RCA and NA. The colours in Figure 4.7 represent the different 60% saturated concrete mixtures. The coarse aggregate of the 30% RCA replacement mixtures included both RCA and NA, which are both shown for these mixtures.

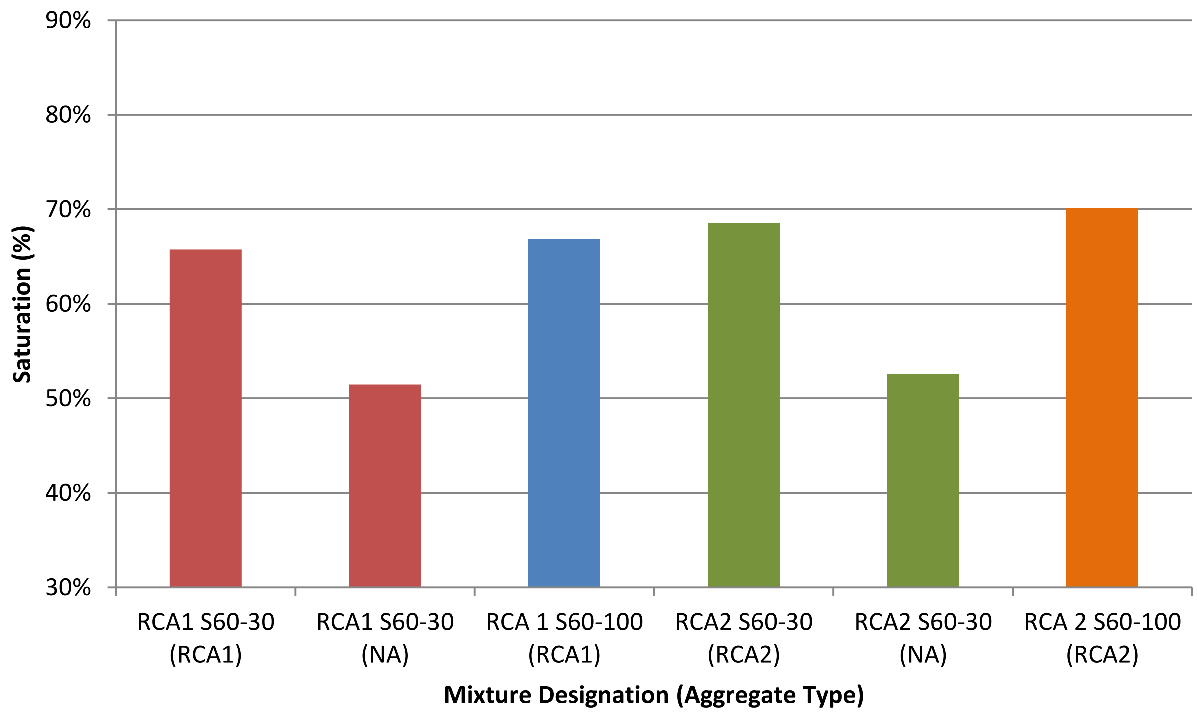


Figure 4.7: Actual aggregate saturation values

At the 60% design saturation, it can be seen that all RCA saturations appear to be higher than the original design value, ranging from 66%-70%, while both NA saturations were lower than the 60% target. These findings could be due to a number of factors. The time taken to remove the samples and take them to the testing area could allow for continued absorption of water. During this time, some surface adhered water could possibly migrate into the absorptive materials, thereby increasing the apparent saturation. The findings could also be indications of the natural variability associated with the saturation procedure based off of the absorption rate of an aggregate. These measured values as well as the surface adhered moisture values were used in conjunction with the mix design to determine the total and effective w/c ratios within the concrete mixtures. Despite these findings, the mixtures will hereafter be referred to as 60% saturated to maintain consistency.

Based on the measured saturations and adhered surface moisture levels, the total water/cement (w/c) ratio and effective w/c ratio were determined for each mixture. The total w/c ratio represents the ratio between the mass of all of the water in the concrete mixture and that of the cement. Aggregate that is not fully saturated is known to absorb mixing water in concrete and it is assumed that the aggregate becomes fully saturated prior to the final set of concrete. The water that is absorbed into the aggregate is not available to the initial hydration reaction and it is therefore not considered to be effective in the hydration reaction. Consequently, the effective w/c ratio represents the ratio between the mass of all effective water and that of the cement. The absorption capacities of the RCAs were higher than that of the NA. In order to maintain a constant effective w/c ratio between mixtures, the level of ineffective water (contained within coarse aggregate) and subsequently the total w/c were increased in the RCA concrete mixtures. These values, as well as the other fresh properties of the mixtures, are summarized below in Table 4-7.

As shown, the variations in water content had an effect on the water cement ratios in each mixture, with the effective ratios ranging from 0.32 to 0.37. Owing to the larger amount of water entrained in the aggregate, the total w/c ratios have an even wider range of 0.39-0.52.

Table 4-7: Fresh Properties for all mixtures

Mixture Designation	Adhered Moisture	RCA SD Moisture Content	Saturation Percentage	Total W/C	Effective W/C	Fresh Density (kg/m3)	Air Content	Slump (mm)
NA S100-0, M100-0	1.0%	1.5%	100%	0.39	0.34	2436	1.8%	85
NAS0-0	0.0%	0.0%	0%	0.42	0.37	2421	2.1%	51
RCA1 S100-100, M100-100	1.4%	5.7%	100%*	0.43	0.32	2323	2.1%	58
RCA1 S60-100	1.2%	3.2%	67%	0.44	0.32	2341	1.1%	118
RCA1 S0-100	0.0%	0.0%	0%	0.48	0.37	2329	1.9%	102
RCA1 S100-30	1.4%	4.3%	100%*	0.45	0.34	2396	1.9%	83
RCA1 S60-30	1.1%	3.1%	66%	0.40	0.33	2394	1.6%	93
RCA1 S0-30	0.0%	0.0%	0%	0.44	0.37	2398	1.8%	68
RCA2 S100-100, M100-100	2.6%	7.8%	100%*	0.47	0.33	2316	1.9%	62
RCA2 S60-100	2.1%	4.8%	70%	0.48	0.33	2296	1.7%	112
RCA2 S0-100	0.0%	0.0%	0%	0.52	0.37	2314	2.0%	105
RCA2 S100-30	2.3%	5.8%	100%*	0.41	0.33	2396	1.8%	91
RCA2 S60-30	1.3%	4.7%	69%	0.40	0.32	2381	1.5%	100
RCA2 S0-30	0.0%	0.0%	0%	0.45	0.37	2387	2.0%	78

As mentioned previously, the saturation percentage for 100% mixtures were considered to be 100% based on the previous experience with the materials; however the adhered moisture values were taken into consideration when determining the effective w/c ratio.

4.2.1.2 Slump

Within the full set of mixtures examined, both the aggregate replacement percentage and the aggregate saturation percentage were varied. Both the factors were seen to affect the workability as measured by slump. Figure 4.8 illustrates the variations in slump given changes in both of these variables.

Each replacement level mix can be viewed at 3 distinct batching conditions. These are 0% aggregate saturation (high additional mixing water correction), ~60% aggregate saturation (small additional mixing water correction), and 100% aggregate saturation (negative mixing water correction).

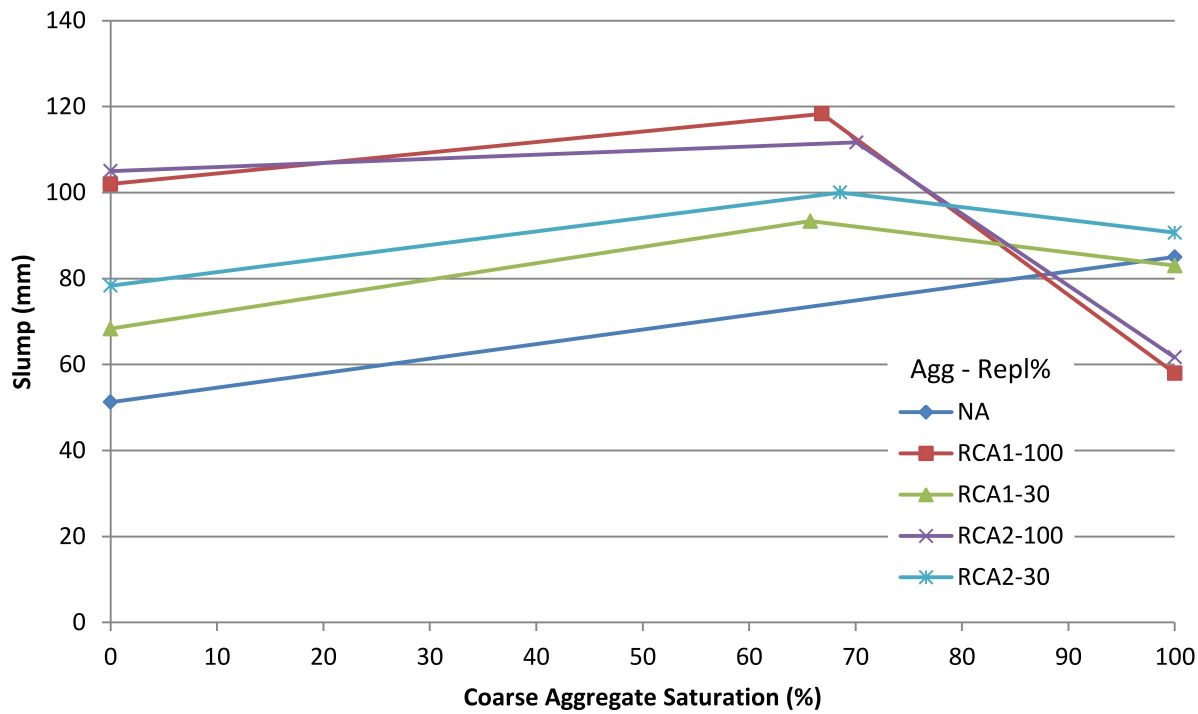


Figure 4.8: Slump values for different RCA saturation levels

The 100% replacement mixtures and the 30% replacement mixtures of both RCA types behave as distinct groups. This is expected as both types receive similar magnitudes of moisture adjustment.

The 100% replacement mixtures exhibit slumps of approximately 100 mm at 0% saturation, 115-120 mm at 60% saturation, and approximately 60 mm at 100% saturation. All slump measurments were taken approximately 7-10 minutes after the beginning of concrete mixing. While the 0% saturated mixtures have the highest levels of initally free mixing water, they also have a large amount of dry and highly absorptive coarse aggregate. The instantaneous absorption rate of dry RCA is very high and reduces as the saturation increases (Ferreira et al., 2011). Therefore it is assumed that the RCA quickly absorbs a significant amount of the free mixing water, resulting in slump values at the design level. At the 60% saturated level, the 100% replacement mixtures contain aggregate that produce a less severe moisture gradient, which could result in less early-age absorption, and thereby more free mixing water to positively affect workability. The adhered moisture could also form a mortar coating when it comes into contact with cement in the mixing procedure. This would inhibit moisture transport between the aggregate and paste. At 100% saturation, the fact that RCA has high adhered moisture and that no extra mixing water is required to saturate the aggregate combine to result in a slight decrease in the mixing water added to hit the w/c target. This results in the lowest amount of free mixing water at early ages. This, combined with the high angularity of the RCA result in low workability.

Similar effects are seen in the 30% replacement mixtures, but the severity of these is reduced by the lower absorption potential and angularity of the overall coarse aggregate.

Interestingly when compared to the control mixture, 30% coarse aggregate replacement does not appear to have a pronounced effect on the workability of mixtures when the coarse aggregate are 100% saturated. There is an observable difference at the 0% saturation level, which illustrates that the mixing water added to compensate for RCA absorption is not fully absorbed at the time of casting.

4.2.1.3 Air Content

Since there were no air-entraining admixtures used in the production of these concrete mixtures, any air content measured would reflect entrapped air. As shown in Table 4-7, all mixtures had air contents in the range of 1.1% - 2.1%. The CAC's concrete design handbook estimates that the level of entrapped air in the concrete mixture should be between approximately 1.5% and 2% based on the relative amount of fine aggregate and the maximum nominal coarse aggregate size (Kosmatka et al., 2011). These results are illustrated below in Figure 4.9.

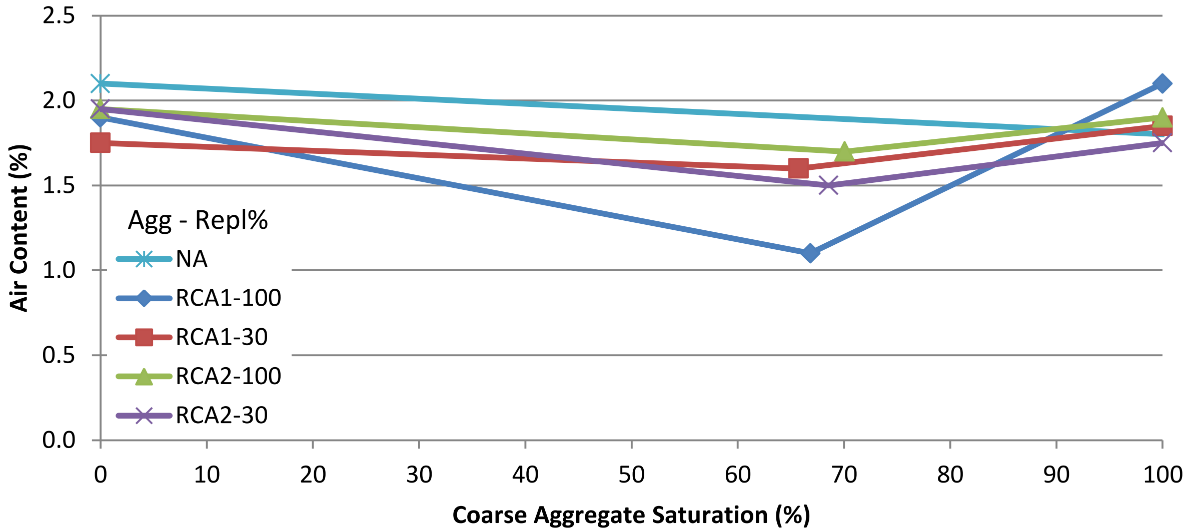


Figure 4.9: Entrapped air contents for different RCA saturation levels

Figure 4.9 illustrates that for each replacement amount, the mid-level saturation condition resulted in the lowest air content. This is probably due to the workability being highest for these mixtures. Increased workability could make the consolidation procedures used in the air test more effective. In all cases, the entrapped air content would be considered reasonable for a non-air-entrained concrete.

4.2.1.4 Density

The fresh density, or unit weight, of concrete is generally measured as part of a quality control procedure, especially when working with high or low density concretes. For the purpose of this study, the fresh densities are considered to gauge the initial effects of RCA replacement and saturation levels on density. Figure 4.10 illustrates the observed results.

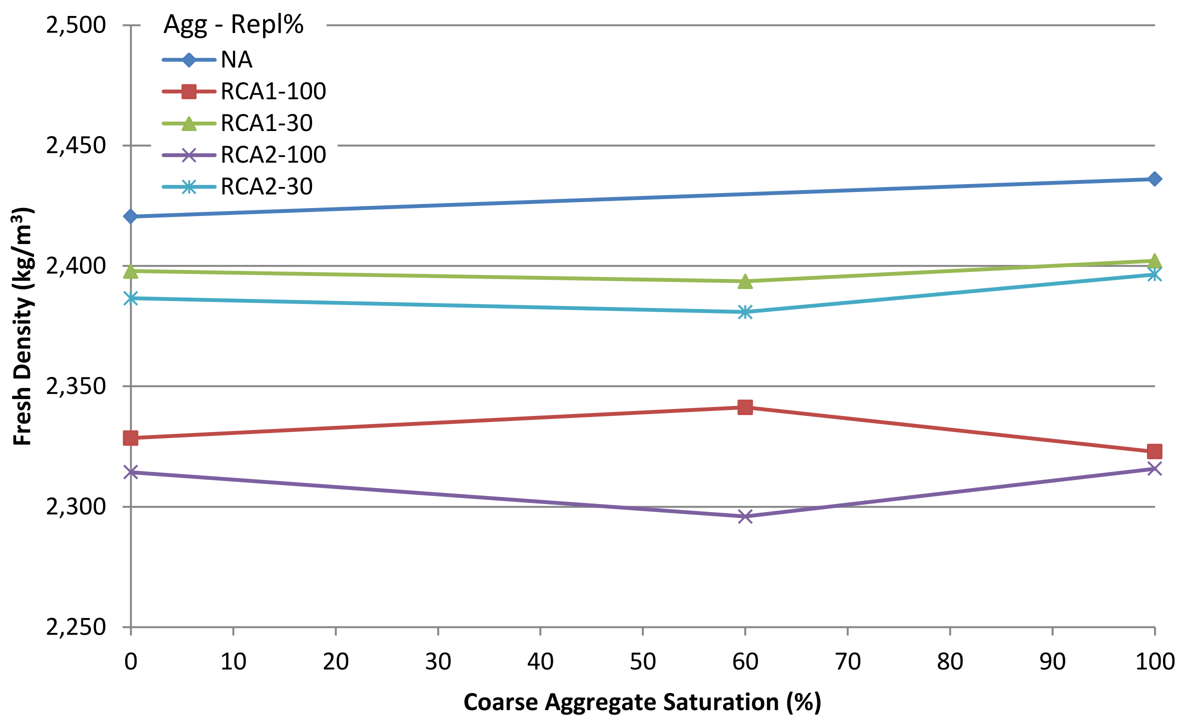


Figure 4.10: Fresh densities for different RCA saturation levels

Intuitively, increasing the replacement amount of natural aggregate with RCA reduces the density overall. Though the scale of Figure 4.10 exaggerates this reduction for illustrative purposes, the density reduction is on the order 5% and 1.5% for 100% and 30% replacement, respectively.

Four of the five replacement amounts exhibit the highest fresh density in the 100% saturated case with a slight decrease in the 60% saturated case. This may be due to the higher w/c ratios in the 60% saturated mixes due to the higher-than-expected absorptions. In all cases, the difference between the minimum and maximum density does not exceed 20 kg/m^3.

4.2.1.5 Fresh Property Conclusions

The conclusions that can be drawn from the fresh properties testing are as follows:

- The actual coarse aggregate saturation within the 60% saturated case exhibited considerable variation, which is a potential indicator of the impracticality of the timed soaking method of achieving a target saturation (excluding the fully saturated case).

- Effective water/cement ratios ranged between 0.32 and 0.37 while total water/cement ratios were between 0.39 and 0.52 for all mixtures. These results indicate that while the differences between the effective water/cement ratios of the concrete mixtures are relatively small, the total level of water in each mixture can vary significantly. This large difference in entrained water is what provides the potential for RCA to contribute value to certain concrete mixtures and applications.
- For each given replacement level the 60% saturated case exhibited the highest slump, possibly due to reduced moisture transport between coarse aggregate and cement matrix caused by aggregate coating. Aggregate coating could occur when the moisture adhered to the surface of soaked RCA comes into contact with cement in the batching procedure, producing a mortar, which fully coats the RCA particle. This coating could restrict how well water could flow into the unsaturated pores of the RCA. In addition to the effects on workability, this could indicate that effective water-cement ratios are not fully accurate when considering partially saturated RCA.
- The slumps of the 30% replacement mixtures were less severely affected by changes in aggregate saturation than the 100% replacement mixtures. This is reasonable considering the difference in the magnitudes of the water adjustments in the two types of concrete mixtures.
- The entrapped air contents of all mixtures ranged between 1.1% and 2.1%. These values are acceptably close to the values predicted by the CAC concrete design handbook, and indicate that the addition of RCA does not significantly affect the entrapped air levels of concrete.
- The fresh density of mixtures was not greatly affected by coarse aggregate saturation, but was very sensitive to RCA type and replacement amount. Changes in RCA saturation do not change the material constituents of the mixture, so the unsaturated portions of the coarse aggregate at the time of testing represent the only differences between mixtures with different saturation levels. For RCA2, which has an absorption capacity of 6.9%, representing 41.2% of a mixture's volume, the maximum that these differences could potentially be is 2.9%. In practice the RCA will absorb mixing water, which will reduce this difference in fresh density.

4.2.2 Hardened Properties

The following properties were tested on the concrete in its hardened state, at ages ranging from 7 to 150 days. As discussed in Section 3.2.5, the mixtures are referred to using their aggregate type (NA, RCA1, and RCA2), curing regime (moist curing or specified curing, refer to Section 1.3.1.4), aggregate saturation level (0%, 60%, and 100%), and natural aggregate replacement level (0%, 30%, and 100%). These variables in this order form the basis for the naming convention of the mixtures. Figure 4.11 presents the hardened concrete tests as well as the key questions to be answered through these tests. Analysis related to specific objectives, including statistical significance evaluation, is presented later, while the following sections present all results and makes only general conclusions.

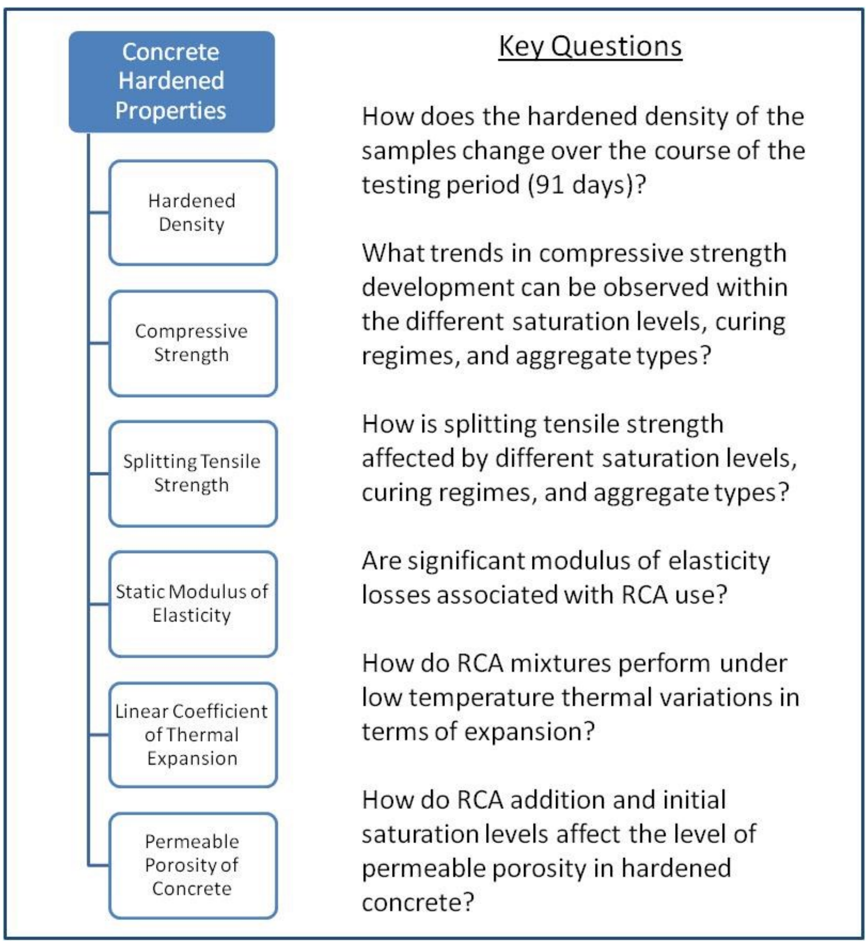


Figure 4.11: Key questions to be answered through hardened properties testing

4.2.2.1 Hardened Density

The density of hardened concrete was measured prior to the compressive strength testing as described in Section 2.5.1. The results of the density testing are illustrated in Figure 4.12, Figure 4.13, and Figure 4.14 for NA, RCA1, and RCA2 mixtures, respectively. In each figure, the fresh density for each mixture is included at the 0 days age for reference.

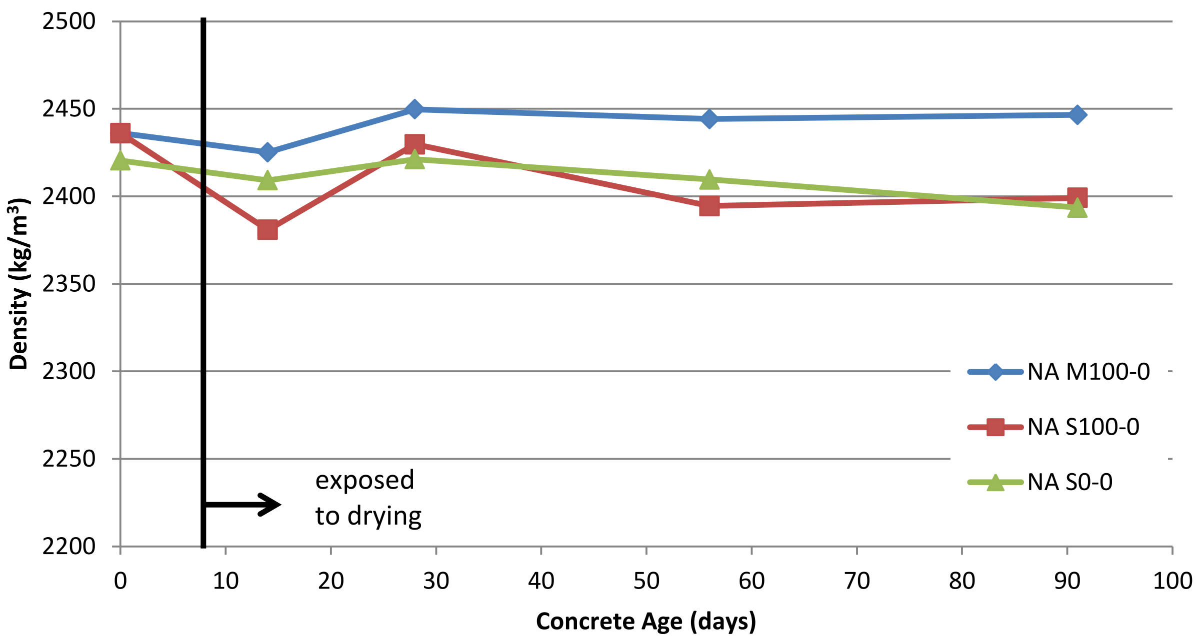


Figure 4.12: Density for NA mixtures over 91 days from casting

All of these figures include one mixture that was cured under moist conditions. The saturation conditions of these concretes are different from the rest of the mixtures, which were exposed to drying in low RH conditions after 7 days of burlap curing as part of spec-curing. The age at which the mixtures were exposed to drying are indicated in each figure. In each case, the moist-cured mixtures exhibit higher density than their less-cured counterpart. This is likely due in part to more complete hydration, but also includes more entrained water at the time of testing. In each moist-cured case, the density increases in comparison to fresh density and then maintains a relatively static density afterwards.

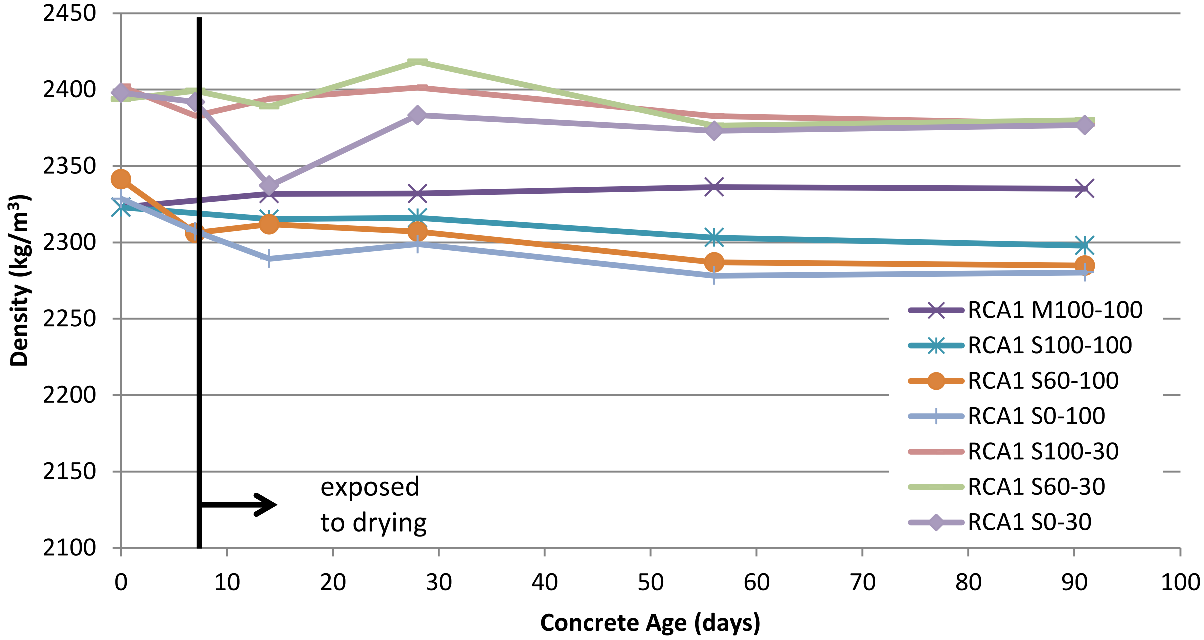


Figure 4.13: Density for RCA1 mixtures over 91 days from casting

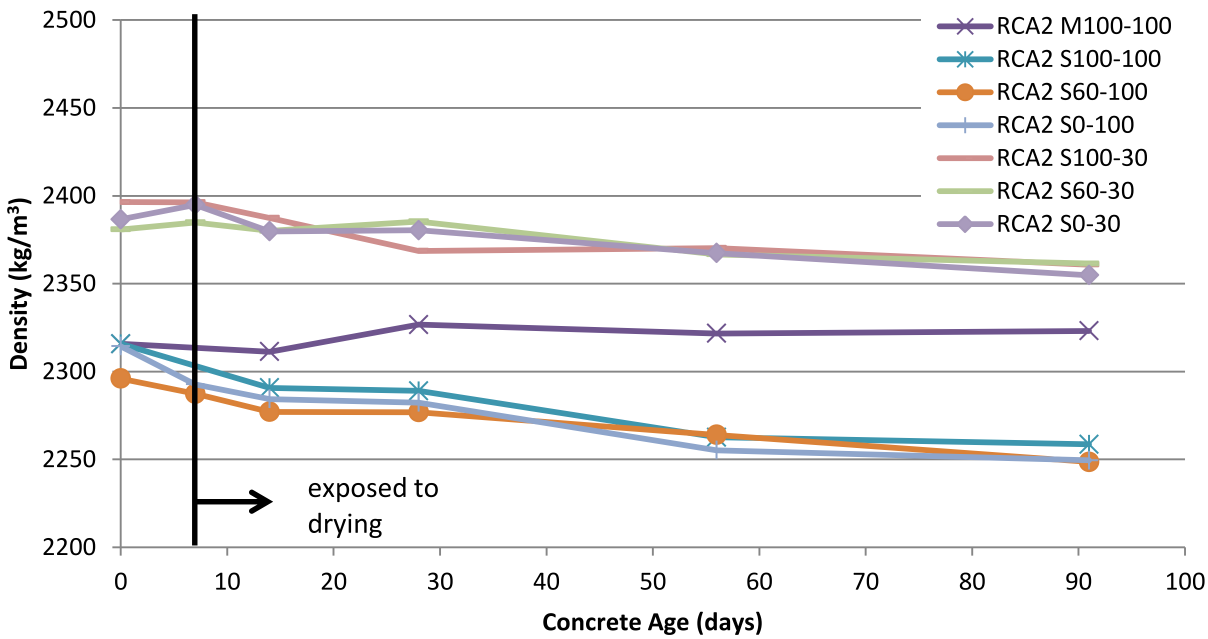


Figure 4.14: Density for RCA2 mixtures over 91 days from casting

In all three density plots, the specimens exposed to specified curing exhibit a general negative trend over time. Since the samples did not decompose over this time, this negative trend indicates material drying.

When comparing each saturation level within a given aggregate replacement level, all mixes appear to behave similarly in terms of magnitude and rate of density loss. The average losses for the 100% aggregate replacement are higher than the average losses for the 30% replacement. This reflects the difference in the levels of initially entrained water. Similarly, the RCA2 mixtures lost more moisture than their RCA1 counterparts due to higher absorption capacity and overall water entrainment.

Interestingly, the purely NA mixtures lost more average moisture than either of the 30% RCA mixtures. This may be an indication that water, which would be lost in the absence of coarse RCA, is being retained within the aggregate instead of lost. While this could provide some benefit, it could also introduce issues relating to freeze thaw durability of the concrete by introducing reservoirs within the concrete. A statistical analysis of these observations is discussed later.

4.2.2.2 Compressive Strength

Compressive strength was tested according to the procedure outlined in Section 3.4.2. The initial compressive strength measurements were taken at the age of 7 days and then subsequently at 14, 28, 56, and 91 days. Figure 4.15, Figure 4.16, and Figure 4.17 illustrate the compressive strength development for the natural aggregate, RCA1, and RCA2 mixtures, respectively. All mixtures were developed with the NA mixture as a basis and therefore the 28 day compressive strength of the NA M100-0 mixture is considered the design compressive strength. The value of this design strength is 48.7 MPa. This design strength is shown on each compressive strength plot as a point of reference. Statistical analyses of the following results are included later as they pertain to the specific objectives of this research.

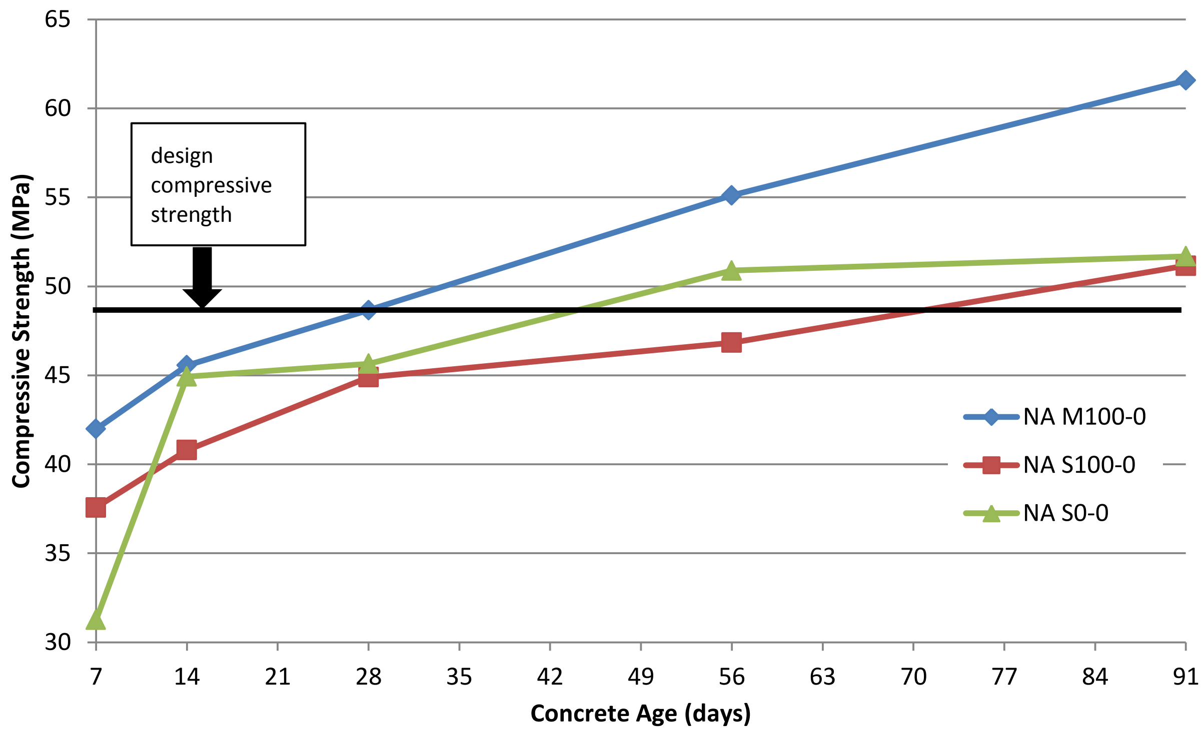


Figure 4.15: Compressive strength development for NA mixtures over 91 days from casting

The natural aggregate mixtures were used as controls when considering the research objectives. When considering the mixtures separately as in Figure 4.15, the effects of spec-curing conditions can be observed. To varying degrees, the moist cured samples exhibited higher compressive strength than the mixtures subjected to specified curing. The moist cured samples exhibited compressive strengths 8% higher than the specified curing at 28 days and 20% higher by 91 days. This is potentially due to the availability of moisture to continue the hydration process in a rich concrete mixture, where unhydrated cement particles can remain after the initial mixing water is consumed. The spec-cured mixtures performed similarly, with some early-age variations between the saturated and unsaturated mixtures. The unsaturated mixture exhibited a relatively low early strength as compared to the other two mixtures. This could be a reflection of the higher initial w/c ratio due to moisture corrections in the mixing water. This was not observed at later ages, and the unsaturated mixture appeared to perform slightly better than the saturated mixture in terms of compressive strength at all subsequent testing ages.

Due to the low absorption capacity of the NA, the moisture corrections were considerably smaller than those of the RCAs. Coarse moisture correction accounted for only 8% of total mixing water in NA S0-0 as compared to 25% in RCA3 S0-100. While this is not unsubstantial, it may begin to explain why NA S100-0 and NA S0-0 performed similarly.

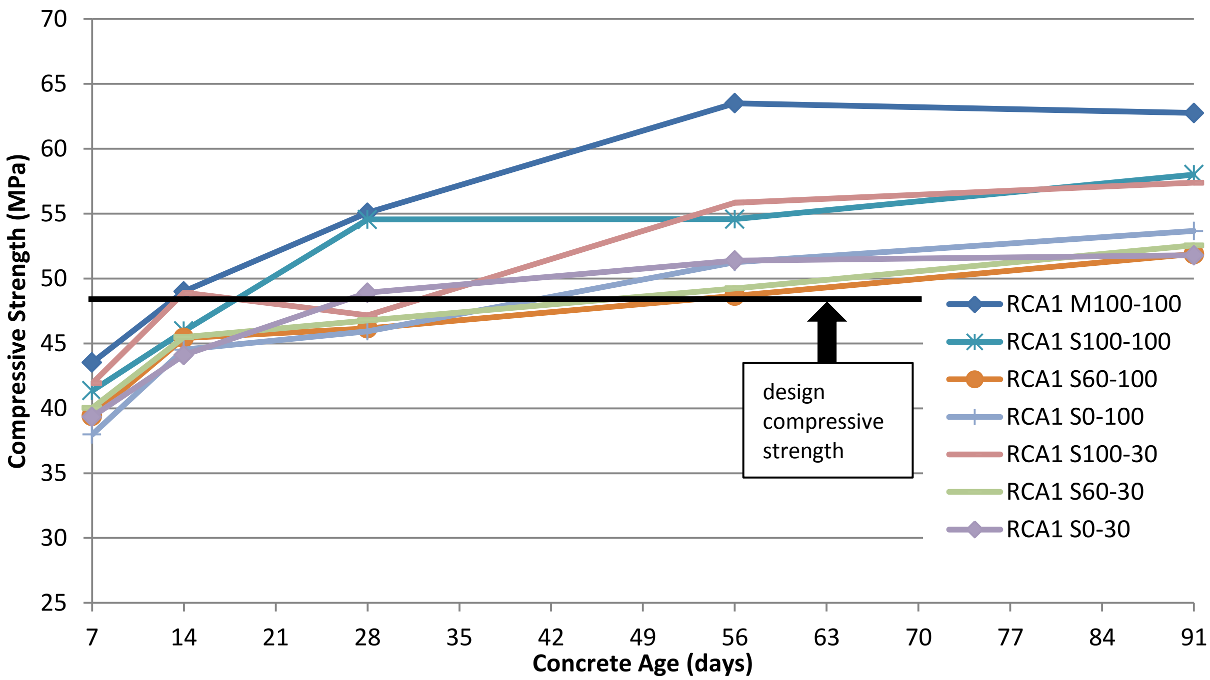


Figure 4.16: Compressive strength development for RCA1 mixtures over 91 days from casting

Figure 4.16 illustrates the compressive strength results for all mixtures with RCA1 incorporated. Similar to the NA case, the mixture that was subjected to moist curing exhibited the highest compressive strength at the majority of the testing ages. The magnitude of the benefit of curing appears to be reduced in the case of RCA1. The largest difference between RCA1 S100-100 and RCA1 M100-100 was a 16% improvement in compressive strength at 56 days for the moist cured concrete. At all other ages, at 95% confidence there was no statistical difference between the two mixtures.

Generally it appeared that the 0% and 60% saturated mixtures behaved similarly, and at a lower level than the 100% saturated mixtures. At 28 days, RCA1 S100-30 exhibited lower strength than its trend otherwise indicated, but otherwise behaved similarly to RCA1 S100-100.

Under the spec-curing conditions, the RCA1 mixtures appeared to experience late age (>7 days) compressive strength gains. Similar findings have been made in studies of internally cured concretes (Bentz & Weiss, 2011). While it was found that RCAs do not desorb water ideally for internal curing, the negative effects on compressive strength gain of the later age drying period may be buffered by the entrained water.

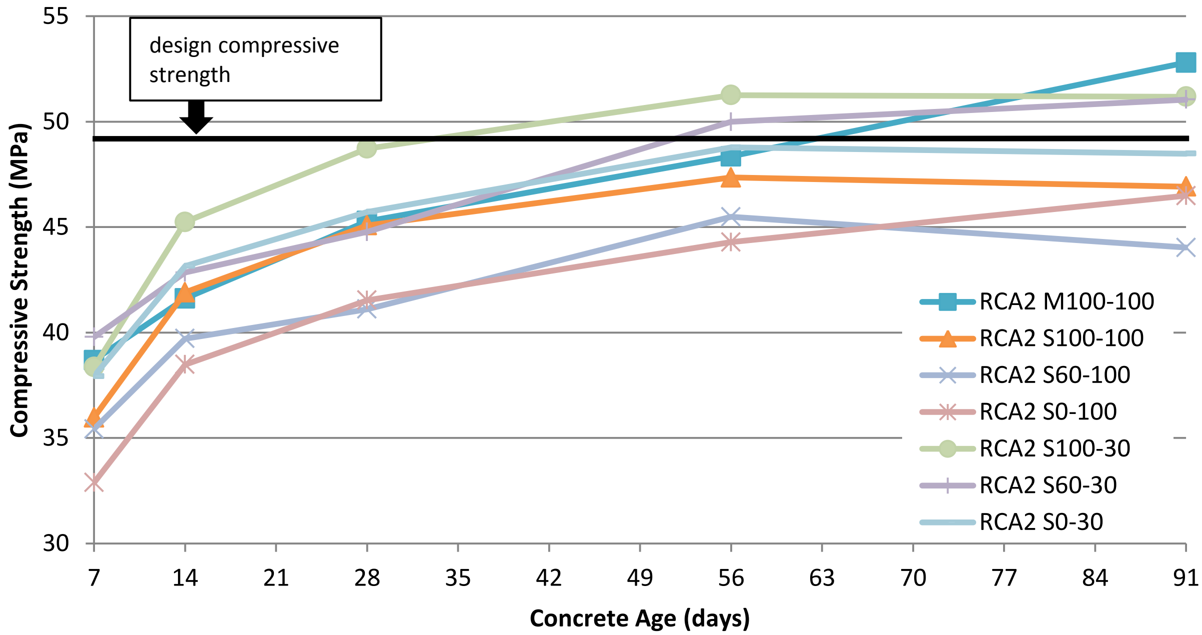


Figure 4.17: Compressive strength development for RCA2 mixtures over 91 days from casting

The compressive strengths of the mixtures containing RCA2, shown in Figure 4.17, showed slightly different trends in comparison with the other two mixture types. The moist-cured mixture did not appear to perform significantly better than the spec-cured mixtures, only exhibiting the highest compressive strength at the 91 day age. RCA2 M100-100 appeared to exhibit a similar strength gain rate to RCA2 S100-100 until the 91 day age where the moist curing appeared to increase the overall compressive strength.

In terms of the spec-cured mixtures, the effect of poorer RCA quality appeared to have a larger impact than saturation conditions as the 30% replacement mixtures all exhibited higher average compressive strengths than the 100% replacement mixtures. The saturation effects within each replacement level are less pronounced in the RCA2 mixtures than in the RCA1 mixtures, however it appears that the 100% saturation mixtures developed the highest compressive strength at early ages. In-depth analysis of this trend are presented in Chapter 5.

Table 4-8 summarizes the statistical evaluation of the mixtures with 100% replacement of coarse NA with RCA. Both 0% and 100% coarse aggregate saturation are compared at 28 and 91 day concrete ages.

Table 4-8: Statistical comparison of compressive strength at 28 and 91 days (100% Replacement)

	NA S100-0	RCA1 S100-100	RCA2 S100-100	NA S0-0	RCA1 S0-100	RCA2 S0-100
Mean Comp. Strength (MPa) (28 day)	44.9	54.5	45.1	45.6	45.9	41.5
STD DEV (MPa)	0.1	3.2	0.6	1.6	1.2	0.9
COV (%)	0.3	6.0	1.3	3.4	2.6	2.2
LSD (MPa)	**7.4**			**4.8**		
Mean Comp. Strength (MPa) (91 day)	51.2	58.0	46.9	51.7	53.7	46.5
STD DEV (MPa)	0.6	5.7	0.8	1.2	1.0	1.1
COV (%)	1.1	9.8	1.7	2.4	1.9	2.3
LSD (MPa)	**12.9**			**4.3**		

RCA1 exhibited the highest compressive strength within each grouping shown. The only statistically significant difference between RCA1 and NA was at 28 days with full saturation. In comparison with RCA2, the compressive strength of RCA1 was significantly higher with full saturation at 28 days and with 0% saturation at 91 days. In-depth comparison of these mixtures and aggregate types are discussed later.

4.2.2.3 Splitting Tensile Strength

Splitting tensile strength was measured in accordance with the procedure outlined in Section 3.4.3. Measurements were taken at 28 days and 91 days age for each mixture type. Figure 4.18, Figure 4.19, and Figure 4.20 illustrate the results for the mixtures containing NA, RCA1 and RCA2 respectively. The error bars shown in each figure indicate one standard deviation each in the positive and negative direction. Using the design compressive strength discussed previously, the design tensile strength was calculated as 4.0 MPa. This strength is denoted for reference with the splitting tensile results. It was calculated based on the tensile strength estimation equation, Equation 4.2 (Neville, 1997):

$$f_t = 0.3(f_c)^{2/3} \tag{4.2}$$

Where, $f_t = the\ splitting\ tensile\ strength\ of\ concrete\ (MPa)$

$f_c = the\ compressive\ strength\ of\ concrete\ (MPa)$

In-depth statistical analyses of the following results are included later as they pertain to the specific objectives of this research.

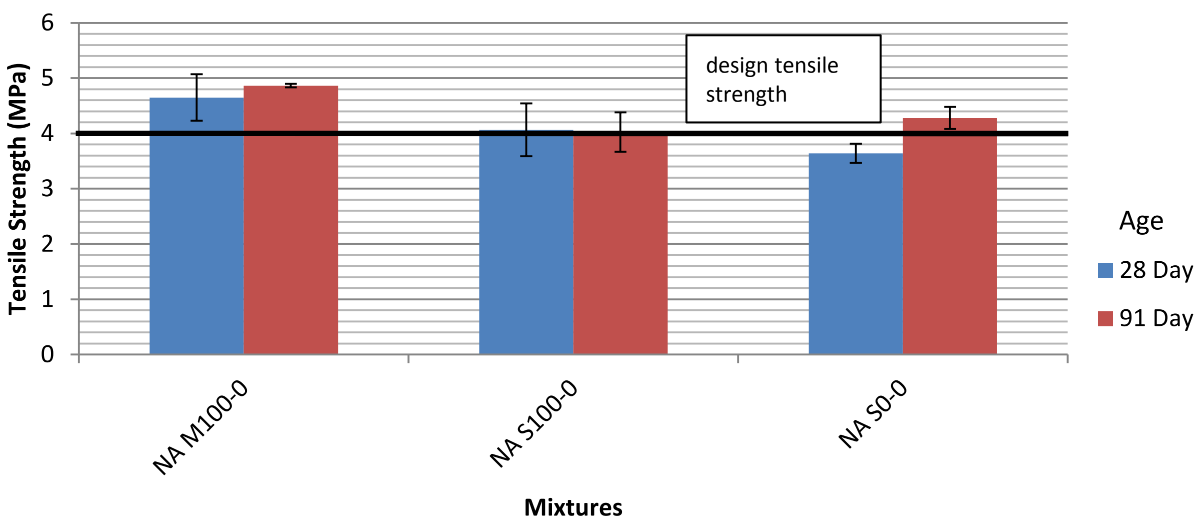


Figure 4.18: Splitting tensile strength development for NA mixtures over 91 days from casting

In Figure 4.18, the splitting tensile strength of NA concrete appears to be affected by the curing condition of concrete as the moist-cured samples exhibited statistically significant higher tensile strength than the spec-cured samples at either tested age. While some variation is evident, the splitting tensile strengths for the spec-cured samples are statistically the same, at 95% confidence.

Figure 4.19 shows that the replacement amount of RCA1 appears to affect the splitting tensile strength, while the curing condition appears to have less of an effect. The tensile strength of RCA1 M100-100 and RCA1 S100-100 are statistically the same, but both are significantly lower than that of NA M100-0. Variations in the saturation level in the 100% replacement mixtures do not appear to greatly influence the splitting strength of the concrete, as all mixtures exhibit tensile strength of approximately 3.5 MPa.

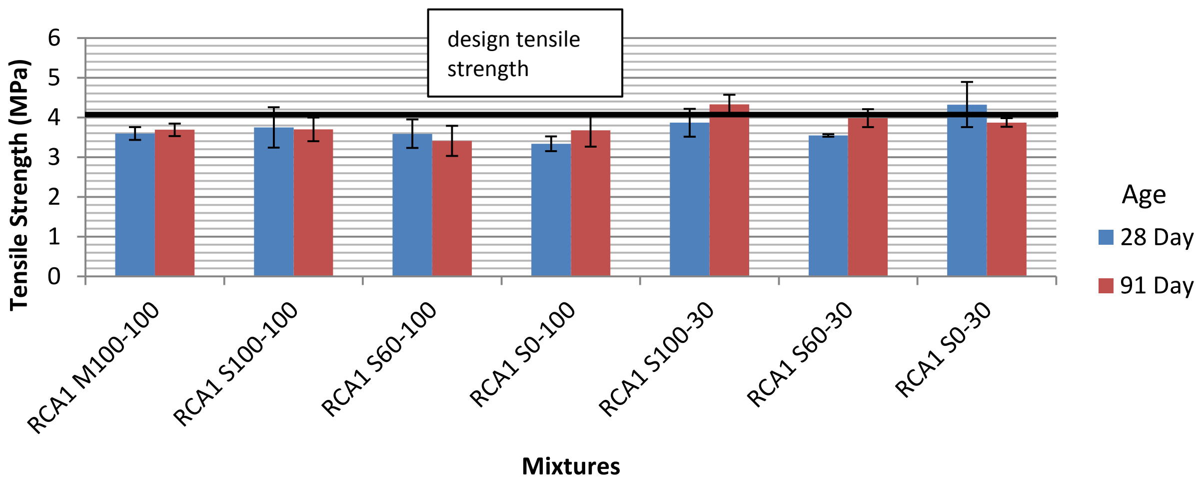


Figure 4.19: Splitting tensile strength development for RCA1 mixtures over 91 days from casting

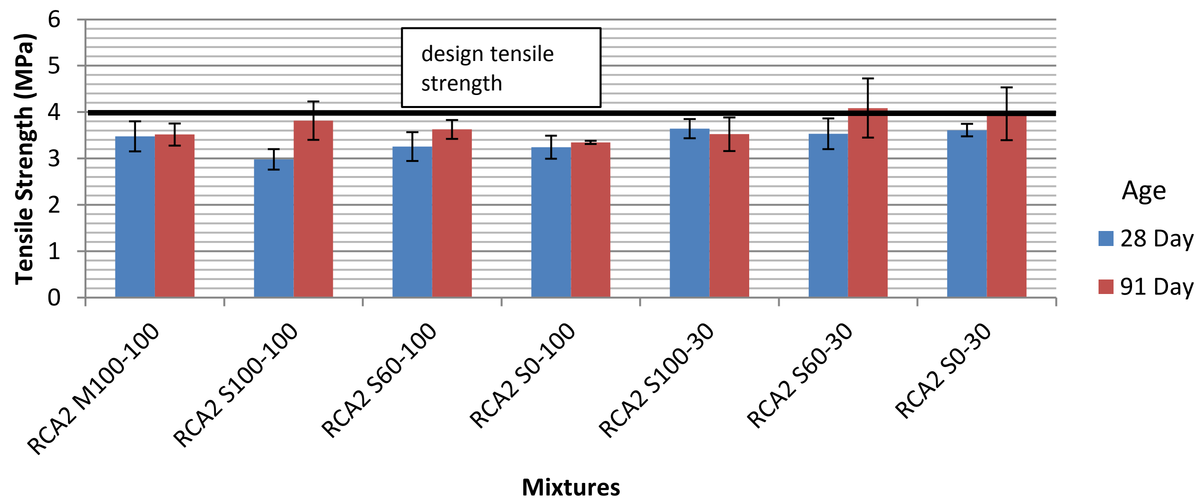


Figure 4.20: Splitting tensile strength development for RCA2 mixtures over 91 days from casting

Since tensile strength depends largely on the ITZ and the strength of coarse aggregate, this may indicate that saturated RCA provides some benefit in terms of mitigating the effects of spec-curing on the ITZ. However this mitigation seems to be at the expense of the initial quality of the ITZ as even the moist-cured RCA mixture exhibited a tensile strength loss of approximately 1 MPa in comparison to NA M100-0.

The 30% replacement mixtures exhibit higher average tensile strengths than the 100% replacement mixtures. These mixtures are at similar strength levels to the corresponding NA mixtures. This seems to indicate that the splitting tensile strength of mixtures incorporating 30% of RCA1 is not greatly affected. The 30% replacement mixtures seem to exhibit higher variability between testing ages than the 100% replacement mixtures.

The splitting tensile strength results for the RCA2 mixtures appear to follow the same trend as the RCA1 mixtures. The 100% replacement mixtures all exhibited roughly the same splitting tensile strength, regardless of curing, although there was noticeable difference between the 28 day and 91 day tests.

In the case of RCA2, the 30% replacement mixtures did not have significantly higher tensile strength than the 100% mixtures.

4.2.2.4 Modulus of Elasticity

The modulus of elasticity was tested in accordance with the procedures outlined in Section 3.4.4. Three samples of each mixture type were tested at ages of 28 and 91 days. Figure 4.21, Figure 4.22, and Figure 4.23 illustrate the results of this testing for mixtures containing NA, RCA1, and RCA2 respectively. The error bars shown in each figure indicate one standard deviation each in the positive and negative direction. In-depth statistical analyses of the following results are included later as they pertain to the specific objectives of this research.

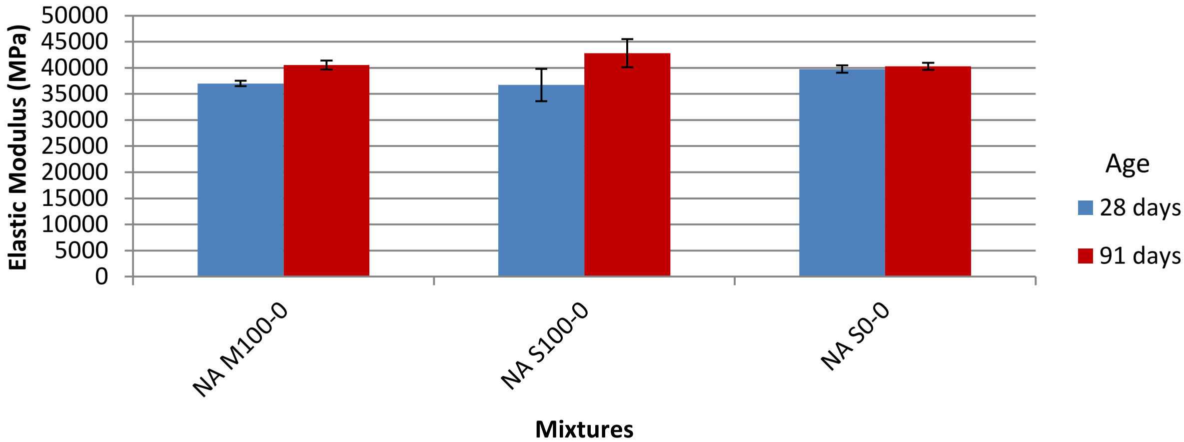


Figure 4.21: Elastic modulus development for NA mixtures over 91 days from casting

The moduli for all three NA mixtures were similar to each other. The 100% saturated mixtures both exhibited stiffening between measurements at 28 days and 91 days, but the magnitudes of both were similar. The 0% saturation mixture did not exhibit this stiffening phenomenon, but was measured to have an elastic modulus that was similar to the 91 day modulus of the other two mixtures.

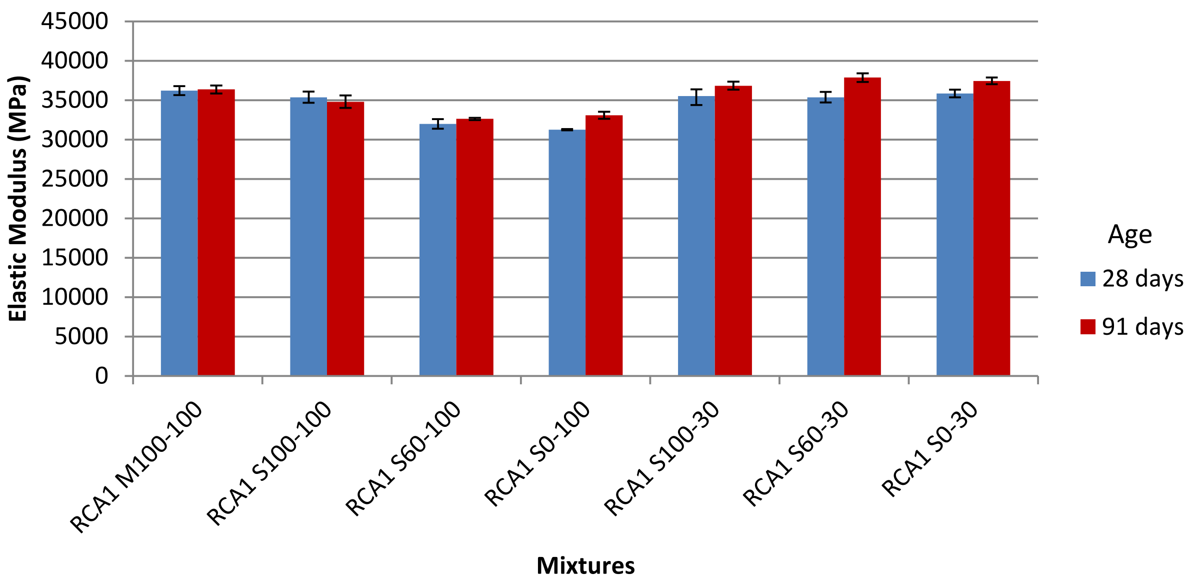


Figure 4.22: Elastic modulus development for RCA1 mixtures over 91 days from casting

The moduli of elasticity for RCA1 were comparable to those of the NA mixtures. Under both curing regimes, the 100% replacement and saturation mixtures were not statistically different than the 28 day NA moduli, however they did not experience a similar stiffening. The 100% replacement mixtures, which were not initially saturated were seen to exhibit lower moduli at both ages than the saturated mixture.

The 30% replacement mixtures all behaved similarly and exhibited stiffening between the ages of 28 days and 91 days, but not to the same extent as the NA mixtures.

The moduli of elasticity for all of the RCA2 mixtures were generally lower than those of the NA mixtures. Both 100% saturation and replacement mixtures exhibited similar moduli at 28 days, but the moist cured sample experienced significant stiffening at the 91 day test. This is at least partially due to the skewing effect of an outlier sample within the sample set, which exhibited a modulus of 40 GPa.

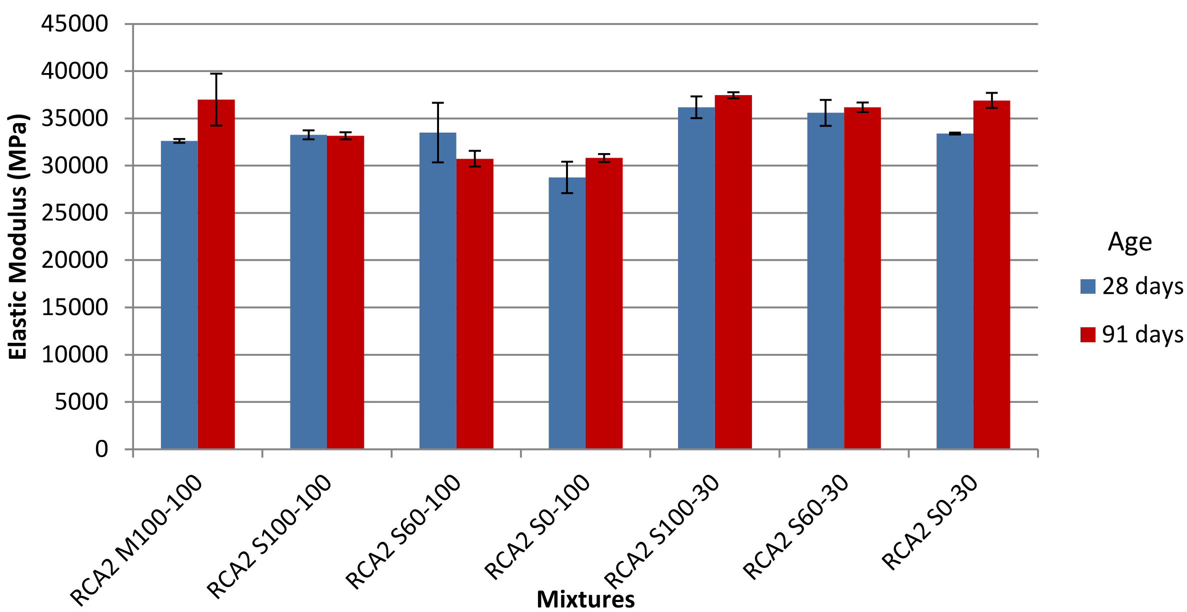


Figure 4.23: Elastic modulus development for NA mixtures over 91 days from casting

Similar to the RCA1 mixtures, the unsaturated, 100% replacement mixtures exhibited the lowest moduli of elasticity. These were lower than the corresponding RCA1 mixtures.

Also similar to RCA1, the mixtures prepared with only 30% RCA exhibited higher moduli with similar magnitudes to the corresponding RCA1 mixtures. While there is some variation, the average values of these moduli indicate that the saturation has a much reduced effect at this level of replacement.

Table 4-9 summarizes the results of applying five equations that are commonly used to estimate the modulus of elasticity for concrete to the concrete mixtures tested within this study. The table shows the average error (in GPa) associated with each equation for a given mixture type. The error is calculated as the difference between the calculated value and the experimentally obtained value. For each mixture, the smallest error value is highlighted.

Table 4-9: Elastic Modulus Prediction Expression Average Error Results

		28 days					91 days				
	Repl%	ACI 318	ACI 363R	ACI 318-11	CSA (8-1)	CSA (8-2)	ACI 318	ACI 363R	ACI 318-11	CSA (8-1)	CSA (8-2)
NA	-	-6.41	-8.99	-3.63	-6.67	-7.95	-7.63	-10.84	-5.37	-9.04	-9.28
RCA 1	100%	0.19	-2.76	0.42	-2.78	-1.42	1.42	-2.09	1.24	-2.49	-0.28
	30%	-2.93	-5.76	-0.65	-3.91	-4.52	-2.65	-6.10	-0.77	-4.65	-4.34
RCA 2	100%	-0.99	-3.28	-1.22	-3.71	-2.49	1.10	-1.74	0.66	-2.36	-0.49
	30%	-2.84	-5.54	-1.19	-4.26	-4.40	-3.32	-6.41	-1.92	-5.38	-4.95

*All error values are in units of GPa

These results were calculated using the estimation equations 4.3-4.7. The equations were developed and recommended by the ACI and the CSA for normal weight concretes. The five equations represent accepted methods to estimate E_c for concrete and this comparison helps to indicate which equation is best suited for estimating E_c of RCA concrete.

$$ACI\ 318: \quad E_c = 4730(f'_c)^{0.5} \tag{4.3}$$

$$ACI\ 363R: \quad E_c = 3320(f'_c)^{0.5} + 6900 \tag{4.4}$$

$$ACI\ 318\text{-}11: \quad E_c = 4300\rho^{1.5}(f'_c)^{0.5} \times 10^{-6} \tag{4.5}$$

$$CSA\ (8\text{-}1): \quad E_c = (3300\sqrt{f'c} + 6900)(\frac{\rho}{2300})^{1.5} \tag{4.6}$$

$$CSA\ (8\text{-}2): \quad E_c = 4500\sqrt{f'c} \tag{4.7}$$

Where $E_c = modulus\ of\ elasticity\ (GPa)$

$f'_c = compressive\ strength\ of\ concrete\ (MPa)$

$\rho = density\ of\ concrete\ (kg/m^3)$

In general, all equations appeared to predict the RCA mixtures' moduli of elasticity reasonably well despite the use of RCA. The NA mixtures however, were considerably under estimated by each equation. The equation put forth in ACI 318-11 appears to be the best suited to measure the modulus of both NA and RCA concretes. The consideration of the concrete's density with a much higher factor applied to it than the compressive strength appears to make the equation very relevant for the analysis of RCA concrete. The equation produced reasonable results for both RCA1 concretes with high compressive strength and relatively low density as well as RCA2 concretes with low compressive strength and low density.

The 28 day moduli for the 100% replacement mixtures appeared to better estimated by the original ACI equation, however this improvement was only marginally better than the ACI 318-11 equation, which also provided a reasonable estimate for these mixtures.

4.2.2.5 Linear Coefficient of Thermal Expansion

The linear coefficient of thermal expansion (LCTE) was measured in accordance with the procedure outlined in Section 3.4.5. The LCTE measurements were taken at 28 days and again at approximately 150 days. Unlike previous tests, the later-age testing was performed on samples that had been exposed to the laboratory conditions associated with the spec-curing protocol. Figure 4.24 illustrates the results of the testing at both ages for all mixture types. The graph indicates the average LCTE value for each mixture and the error bars represent one standard deviation in either direction for the collected data. The error bars provide indications of the repeatability of the test procedure. In-depth statistical analyses of the following results are included later as they pertain to the specific objectives of this research.

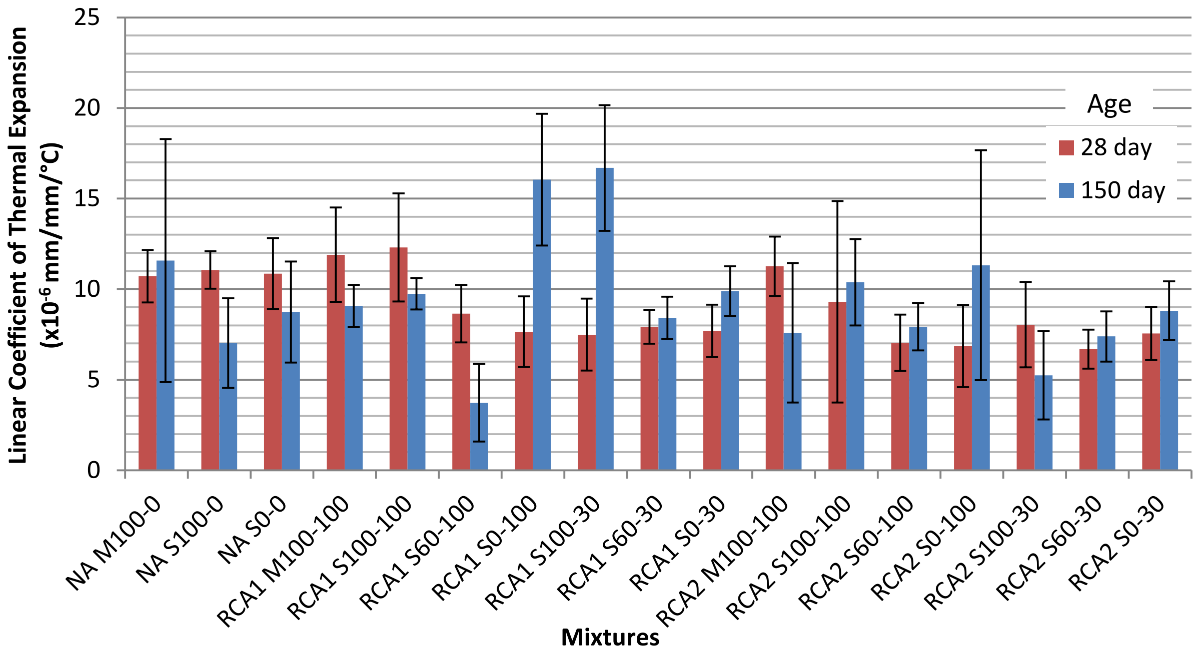


Figure 4.24: Linear coefficient of thermal expansion

The results indicate a wide variation in the LCTE both between mixture types and within given mixture types. This could indicate a limitation of the test procedure or the non-linear expansion behaviour of concrete under thermal variations below 0°C.

The majority of the results ranged between 5 and 15 $x10^{-6}$(mm/mm)/°C. This approximates the range given by Neville (Neville, 1997) for air-cured concretes with various types of aggregate, which is from $7.41x10^{-6}$/°C to $13.1x10^{-6}$/°C.

At 28 days, the mixtures containing some amount of RCA exhibited lower thermal expansion behaviour, with the exceptions of the 100% saturated RCA1 mixtures and the 100% saturated and moist-cured RCA2 mixture. While the samples were allowed time to acclimatize to a lower-RH environment, it is possible that these samples may have retained some portion of their absorbed water, which could influence the thermal expansion behaviour at freezing temperatures.

At 150 days, the thermal expansion measurements varied from the 28 day measurements. In some cases this variation was extreme and may indicate the potential for variable results within the test procedure rather than a significant change in the thermal behaviour of the material. At low temperatures, the thermal expansion behaviour of a cement paste varies significantly depending on its moisture content. This is one of the reasons that typical thermal expansion testing is performed at higher temperatures and constant RH levels. The current research focuses on the effects of changes in moisture levels and therefore the differences in moisture content between concrete types were maintained. These differences in moisture content could combine with different maximum and minimum testing temperatures to inconsistently magnify changes in LCTE values. With the exception of the outliers, the LCTE values remain in the same general range as the 28 day test.

The LCTE of a rigid concrete pavement can have significant effect on the performance of the pavement in a given environment. Any reductions observed in concrete produced with RCA could benefit the long-term durability performance of the pavement.

4.2.2.6 Permeable Porosity of Concrete

The permeable porosity of the concrete mixture was measured in accordance with the procedures outlined in Section 3.4.6. The tests were performed at the concrete ages of 28 days and 91 days and the results of these tests are illustrated in Figure 4.25. The figure shows the average results and the associated error bars represent a standard deviation in both the positive and negative direction based on the collected data. The permeable porosity is a percentage based on the volume of the concrete as determined through submerged weighing. In-depth statistical analyses of the following results are included later as they pertain to the specific objectives of this research.

At both testing ages, the measured permeable porosities for the mixtures ranged from approximately 13% to approximately 20%. The error associated with the data indicates that there was not wide variance within a given mixture. The differences between the 28 day and 91 day ages are quite small. The only mixture that exhibits a statistically significant change between ages, as measured by a t-test with 95% confidence is RCA2 M100-100. This is largely due to the very small variation in measurements, not to a large difference in the average total permeable porosity.

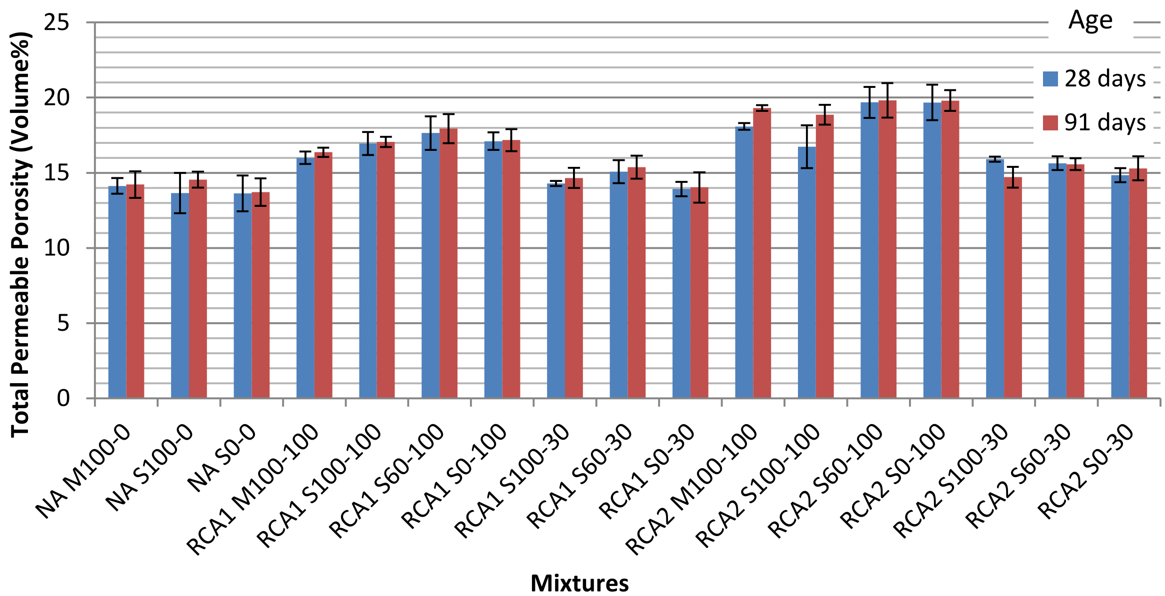


Figure 4.25: Total permeable porosity

The mixtures that include RCA material exhibit higher permeable porosity than the NA mixtures in most cases. This change is more evident in RCA2 mixtures, which have higher aggregate absorption values. In the 30% replacement mixtures, both RCA1 and RCA2 exhibit only small differences as compared to the NA mixtures. Permeable porosity values of RCA1 concretes are higher than those of NA concretes; however the compressive strengths of RCA1 are also higher than those of the NA mixtures. The effect of high porosity of concrete is typically a decrease in compressive strength. This indicates that the negative effects that are generally ascribed to concretes with high porosity are not necessarily present in RCA concretes.

Figure 4.26 and Figure 4.27 illustrate the water absorbed into concrete samples throughout the course of the test at the 28 day and 91 day ages, respectively. The graphs show the initially entrained water at the beginning as well as the water absorbed throughout the course of the testing procedure. The water absorption values are expressed as a percentage of the oven-dry mass of each sample.

The effect of moist curing is evident in the increases in water throughout the course of the testing. The moist-curing regime appeared to keep the permeable pores in the samples almost saturated as very little extra water was absorbed in the three moist-cured mixtures. Those samples, which were subjected to 21 days in the exposed condition (after 7 days of spec-curing), absorbed a much higher percentage of water throughout the course of the testing, particularly in those samples that had 100% aggregate replacement.

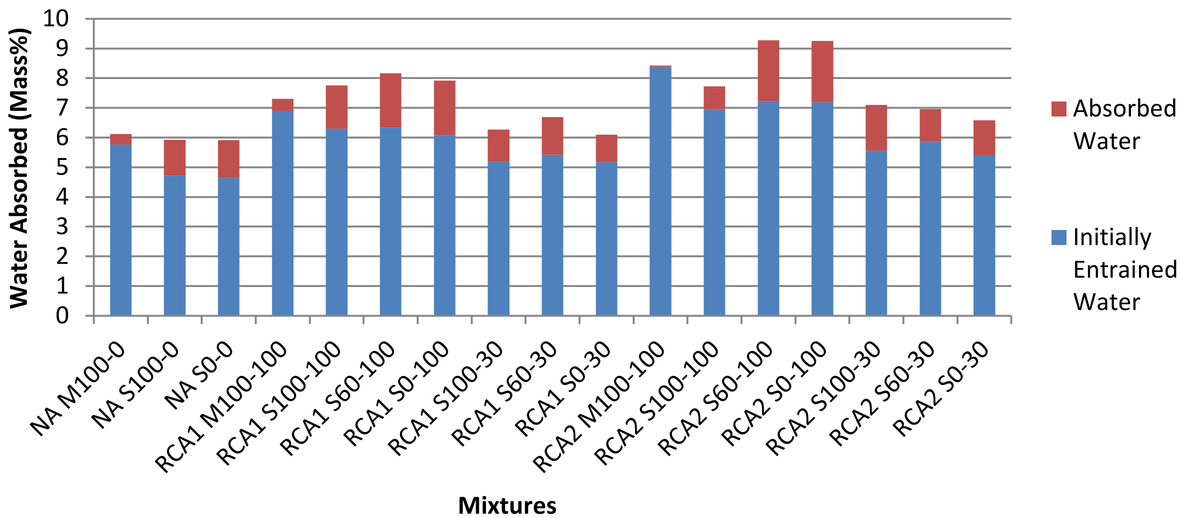


Figure 4.26: Absorbed and entrained water percentage (28 days)

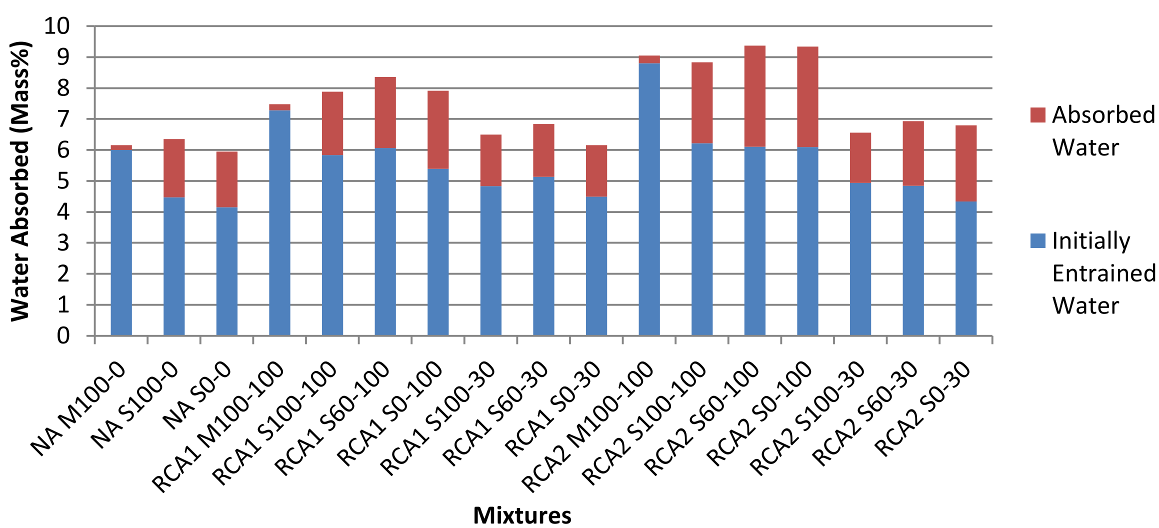


Figure 4.27: Absorbed and entrained water percentage (91 days)

The drying out of the exposed concrete was more pronounced at the age of 91 days in the spec-cured samples. This manifests itself in a larger gap between the initially entrained water and the overall level of absorbed water. A significant amount of water still remains in the concrete at this time, however it should be recognized that the cutting procedure adds water prior to testing.

While the initially entrained water levels drop, the overall absorbed water amounts do not change significantly in any of the mixtures, except for the previously mentioned RCA2 S100-100.

If water absorption (as a function of permeable porosity) is considered to be reduced by internal curing-like processes over the course of the testing, then it appears as though this is not consistently taking place in the RCA concretes. The differences between the curing comparisons for NA mixtures without significant amounts of entrained water are similar to those of the RCA concrete's with entrained water. Any benefits of internal curing on permeable porosity are not observed within these results.

As they are all based on the same data set, Figure 4.26 and Figure 4.27, closely follow the trends displayed in Figure 4.25. The difference between mass-based and volume-based measurement may serve to make differences more pronounced as the mass of 100% RCA mixtures is proportionately less than the other two replacement levels (0% and 30%).

4.2.2.7 Hardened Properties Conclusions

The general results of the hardened properties tests are summarized in the following list:

- All spec-cured concrete specimens were observed to gradually lose entrained moisture through drying over the course of the testing, as observed through decreasing density. This result is intuitive, and represents reasonable behaviour for concretes cured according the specifications of the MTO.
- The mixtures with 30% RCA lost less moisture than the NA mixtures, despite higher overall water contents, which indicates that the RCA may have helped to retain moisture normally lost from concrete due to drying.
- All moist-cured samples exhibited similar compressive strength-development behaviour, which continued to the end of testing. The observable difference between these samples and the spec-cured samples indicate that exposure to drying of concrete after 7 days of moist curing has a negative effect on compressive strength in relation to moist curing. This reinforces the idea that the typically specified method for concrete curing can have

negative consequences and presents opportunities for the development of strategies for improved concrete performance.

- Spec-cured RCA2 samples generally reached a compressive strength plateau by the age of 56 days, but RCA1 samples appeared to experience later age compressive strength gains, which is a characteristic of some internally cured concretes. This indicates that although the RCAs do not desorb water like traditional internal curing agents, they may provide some benefit to spec-cured concretes.
- The inclusion of different RCA types is found to affect the compressive strength of concrete differently. In decreasing order of compressive strength at 91 days, the mixture types were RCA1, NA, and then RCA2. The opposite effects observed between RCA1 and RCA2 indicate that the inclusion of RCA is not necessarily detrimental to concrete strength, and that proper identification of RCA within the concrete industry could result in more efficient use of this construction material.
- The variations that caused a decrease in the splitting tensile strength of concrete were, in decreasing order of effect: RCA content, RCA type, curing regime used, then aggregate saturation. The inclusion of either good or poor quality RCA in concrete resulted in tensile strength losses. This could be significant to the use of RCA in the concrete industry, specifically in applications where concrete's tensile strength is an important design consideration.
- In terms of elastic modulus, the RCA1 mixtures generally behaved similarly to the NA mixtures, with the exceptions of RCA1 S60-100 and RCA1 S0-100, which were relatively lower. RCA2 mixtures all exhibited lower elastic moduli than NA and RCA1 mixtures. This indicates that the quality of RCA, specifically in terms of the absorption capacity and therefore the density, has an impact on the E_c of RCA concretes, which could have relevance to concrete applications wherein the E_c is a governing factor.
- The elastic modulus equation from ACI318-11 provides the best estimates for the E_c of the RCA concretes under the given conditions, though it was found to underestimate the E_c of the NA mixtures. In practice, the estimation of the E_c of RCA concretes should consider the concrete density to produce accurate estimates.

- At 28 days, the LCTEs of RCA mixtures were typically lower than those of the NA mixtures although the 100% saturated, 100% replacement mixtures were not statistically unique from the control mixtures. When LCTE was measured at 150 days, changes in the testing environment and sample moisture conditions may have resulted in the noticeably different and variable results. Thermal response of concrete is an important consideration, especially in the concrete paving industry. If RCA's addition to concrete causes a reduction of the low-temperature thermal expansion of the material then this increases the material's effective value in this industry.
- 100% replacement of NA with RCA in concrete resulted in increased permeable porosity. 30% replacement of NA with RCA in concrete also resulted in an increase, but the magnitude of this increase is smaller.
- The initially entrained water levels measured prior to pressurized soaking of concrete samples, confirm the findings of the hardened density testing. Specifically, these findings are that RCA samples lost less moisture than the NA mixtures, despite higher overall water contents. This indicates that the RCA may have helped to retain moisture normally lost from concrete due to drying.
- The level of initially trained water in drops significantly more between the ages of 28 and 91 days in RCA concretes than in NA concretes. The total absorption level of all types of concrete at both testing ages is not largely affected.
- Internal curing effects are not observed in the permeable porosity results.

CHAPTER 5

ANALYSIS AND DISCUSSION OF RESEARCH OBJECTIVES

The results of desorption test indicate that neither RCA desorb significant water at 93%RH. The permeable porosity testing indicates that no internal curing is taking place within the concrete samples. However, there do appear to be effects caused by the inclusion of saturated RCA in concrete. Some these effects are studied in the following comparisons of the variations in saturation of aggregate, curing condition, and aggregate replacement level.

5.1 Saturation Comparisons

One of the objectives of this study was to determine how the saturation levels of the coarse aggregate affect the properties of concrete produced using coarse RCA. During this study, the overall water content for a given aggregate replacement amount was kept constant. This water was initially added into the mixture as part of three phases; the mixing water, the water adhered to the coarse aggregate, or the water entrained within the coarse aggregate. The amount of water in each of these phases was varied as follows. The aggregate saturation water was included wholly within the aggregate (100% saturation), wholly within the mixing water (0% saturation), or partially in each of the aggregate and mixing water (60% saturation). The total and effective water-cement ratios are summarized in Table 4-7 of Section 4.2.1.1. All mixture types within this section were cured according to the specified curing regime outlined in Section 1.3.1.4. This means that they were exposed to drying conditions after 7 days of moist curing with burlap.

As discussed in Sections 4.2.1.2 and 4.2.1.4, the slump and fresh density of each mixture type varied with the RCA saturation. The concretes exhibited their highest slump values in the 60% saturation mixtures and their lowest in the 100% saturation mixtures. This could be due to the presence and absence of extra mixing water, respectively, because of the absorption behaviour of RCAs. It has been found that RCA has high initial absorption rates, which taper off as saturation levels increase. This could contribute to the 60% saturated mixtures' tendency to not absorb extra mixing water as fast as the 0% saturation mixtures, thus resulting in higher initially available mixing water and higher slump values. RCAs have also been found in the desorption tests outlined in Section 4.1.4 to retain their absorbed moisture. This could explain the tendency for 100% saturation mixtures to not contribute any of the absorbed water within the aggregate to the mixing water and thereby slump development. Figure 5.1 outlines the key questions relating to the saturation variations in coarse aggregate. The effects of these variations in saturation were examined in each of the hardened concrete properties that were studied within the scope of this study.

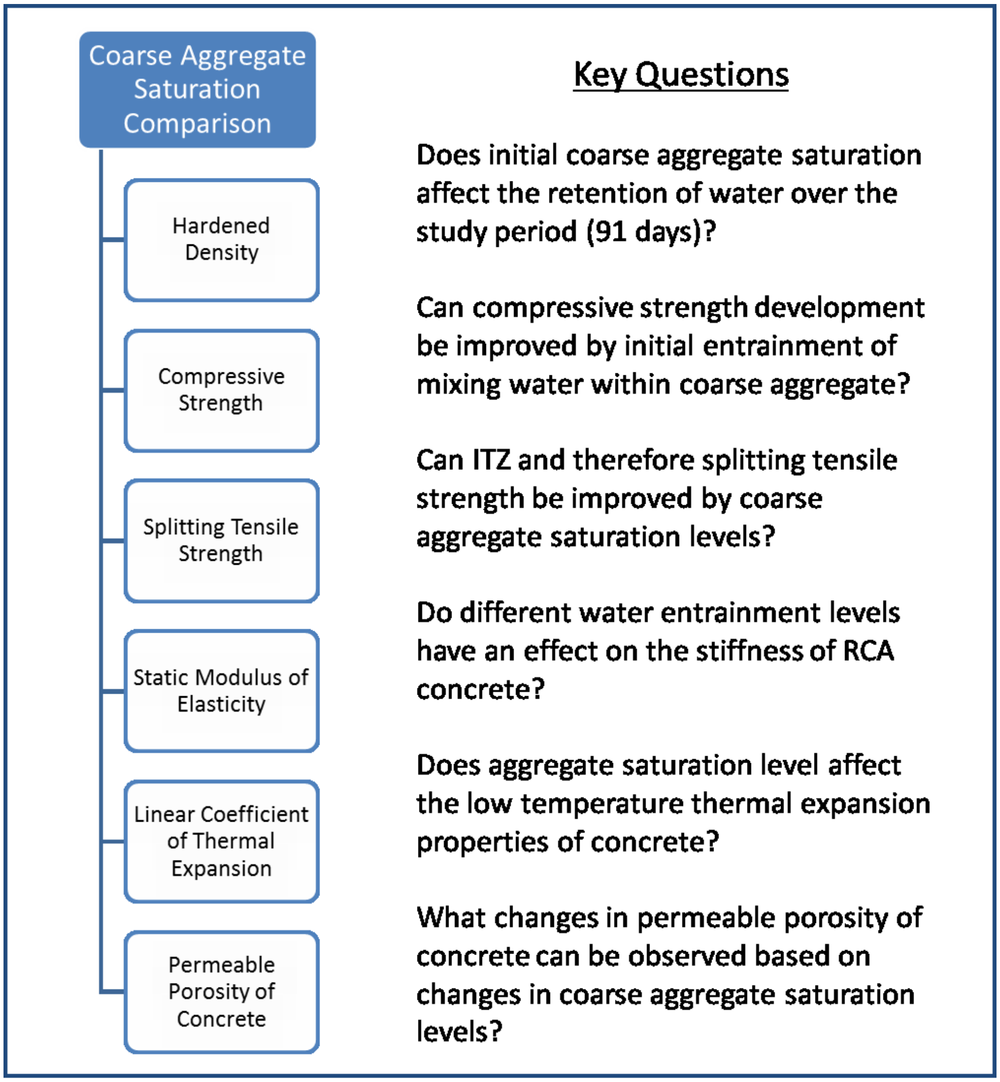


Figure 5.1: Key questions regarding the effects of variation of coarse aggregate saturation

5.1.1 Hardened Density

Figure 5.2 illustrates the hardened densities for all mixture types that included 100% replacement of natural aggregate (NA) with RCA. The densities are presented as measured, and the decreases shown correspond to moisture losses from the exposed specimens due to drying. At seven days, the specimens were exposed to the laboratory conditions and this is considered to be the onset of drying. To assess the differences in hardened density values between the mixtures, a statistical analysis based on the 5% LSD (least significant difference) values was carried out at the ages of 28 and 91 days. Table 5-1 tabulates this statistical evaluation.

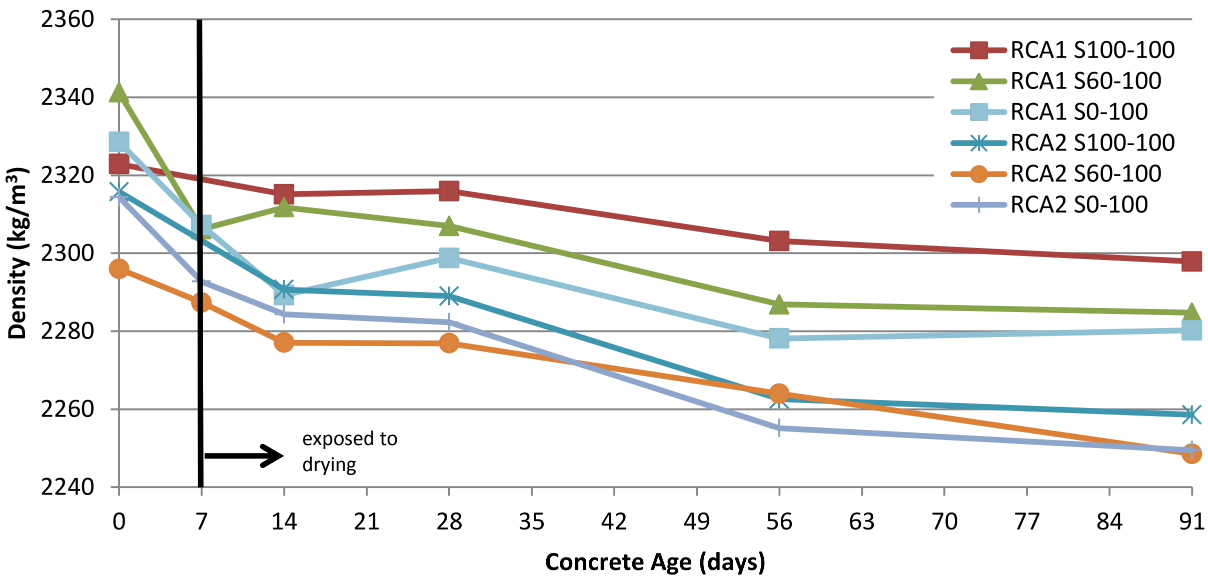


Figure 5.2: Hardened density for saturation comparison (100% replacement)

Table 5-1: Statistical Comparison of Hardened Density at 28 and 91 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean Density (kg/m^3) (28 day)	2429.7	2421.2	2315.9	2307.0	2298.8	2401.3	2418.3	2383.2	2289.0	2276.9	2282.3	2368.7	2385.4	2380.4
STD DEV (kg/m^3)	12.3	10.3	9.0	8.5	6.2	9.9	28.2	14.9	9.1	4.1	2.7	15.3	2.3	9.0
COV (%)	0.5	0.4	0.4	0.4	0.3	0.4	1.2	0.6	0.4	0.2	0.1	0.6	0.1	0.4
LSD (kg/m^3)	**39.7**		**30.9**			**74.6**			**23.1**			**40.0**		
Mean Density (kg/m^3) (91 day)	2399.1	2393.5	2297.9	2284.8	2280.2	2377.6	2380.0	2376.7	2259.4	2248.5	2249.5	2360.8	2361.4	2354.8
STD DEV (kg/m^3)	9.3	6.4	2.7	4.3	2.3	5.3	8.8	6.8	10.2	17.0	2.4	4.4	4.3	12.3
COV (%)	0.4	0.3	0.1	0.2	0.1	0.2	0.4	0.3	0.5	0.8	0.1	0.2	0.2	0.5
LSD (kg/m^3)	**27.9**		**12.5**			**27.5**			**44.5**			**30.8**		

The mixtures displayed in Figure 5.2 divide into two distinct groupings due to the type of RCA used in each. RCA1 has a higher density than RCA2 and that largely contributes to the disparity. At 28 days, the differences in hardened density due to saturation changes were not statistically significant for any aggregate type. However, at 91 days the hardened density of the 100% saturated RCA1 mixture was found to be significantly higher than the other saturation levels. Since this test is considered as a measure of moisture retention, this indicates that the 100% saturated RCA1 mixture retained significantly more moisture than the 0% and 60% saturated mixtures, while this was not observed in the RCA2 mixtures.

Overall, the RCA1 mixtures lost less moisture than the RCA2 mixtures, which correlates well with the higher absorption of RCA2 and therefore the higher total w/c ratio.

Within each grouping, the 100% saturated mixtures largely retain the highest densities throughout the course of testing, though these differences are not always statistically significant. This may be due to some retained moisture within the RCA but could also correspond to more complete hydration, resulting in a greater percentage of the water becoming chemically bound within the concrete. The 0% and 60% saturated mixtures appear to lose water similarly throughout the course of the test and exhibit largely the same densities.

Figure 5.3 illustrates the density evolution for the mixtures containing 30% RCA replacement by volume. The saturations range from 0-100% and encompass the time from casting to 91 days.

Similar to the 100% replacement mixtures, the mixtures exhibited a general loss of moisture over the course of the testing schedule. In this case, both the overall density change and the differences due to the RCA saturation are considerably smaller than the 100% replacement mixtures. Due to the reduced RCA content, there is proportionately less water entrained in these mixtures initially.

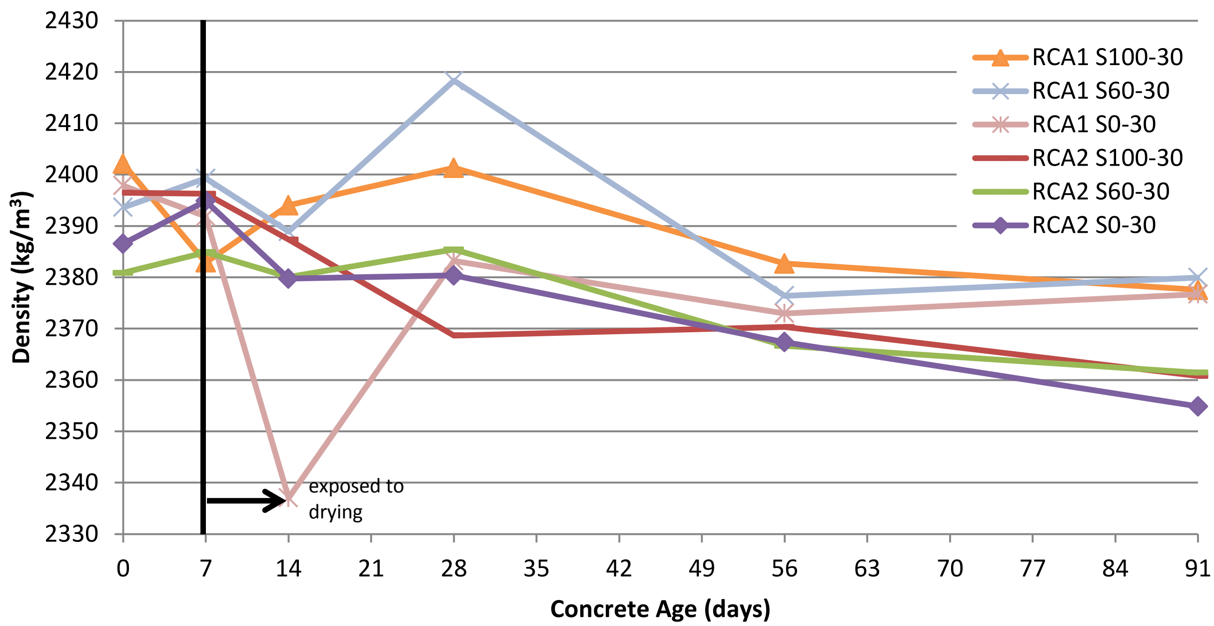


Figure 5.3: Hardened density for saturation comparison (30% replacement)

The mixtures appear to divide into two groupings due to the aggregate density, although these groupings do not become obvious until the later testing ages. Based on the statistical analysis, the differences observed within these groups are not statistically significant. This is also due to the smaller proportion of different-density aggregates within the mixtures.

Two maxima, which are not readily explainable, can be observed within this plot. An abnormally high density measurement is observed within RCA1 S60-30 at 28 days and an abnormally low measurement is observed in RCA1 S0-30 at 14 days. Neither point appears to exhibit the trend of the remaining data points. As shown in Table 5-1, the standard deviation of the RCA1 S60-30 values of hardened density was considerably larger than in other mixtures indicating variability within the results. Both mixtures were cast and tested on corresponding days and may indicate a repeatable testing error. These spikes are not considered to correlate to observable phenomena usually associated with 30% replacement mixtures of RCA.

Saturation of aggregate does not appear to play a significant role in density change at the 30% level of aggregate replacement.

5.1.2 Compressive Strength

Table 5-2 presents the statistical analysis of the compressive strength values. Figure 5.4 shows the compressive strength development for 100% RCA replacement mixtures over the course of 91 days. For each RCA type, saturations of 0%, 60%, and 100% are shown.

Table 5-2: Statistical Comparison of Compressive Strength Values at 28 and 91 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean Comp. Strength (MPa) (28 day)	44.9	45.6	54.5	46.2	45.9	47.2	46.8	48.9	45.1	41.1	41.5	48.7	44.8	45.7
STD DEV (MPa)	0.1	1.6	3.2	1.5	1.2	0.4	1.5	1.2	0.6	0.4	0.9	0.3	1.1	1.9
COV (%)	0.3	3.4	6.0	3.2	2.6	0.9	3.2	2.5	1.3	0.9	2.2	0.6	2.5	4.2
LSD (MPa)	**3.9**		**8.4**			**4.4**			**2.6**			**5.0**		
Mean Comp. Strength (MPa) (91 day)	51.2	51.7	58.0	51.9	53.7	57.4	52.6	51.8	46.9	44.0	46.5	51.2	51.1	48.5
STD DEV (MPa)	0.6	1.2	5.7	0.4	1.0	0.6	0.6	1.8	0.8	1.4	1.1	0.5	0.9	1.0
COV (%)	1.1	2.4	9.8	0.7	1.9	1.0	1.2	3.4	1.7	3.3	2.3	0.9	1.8	2.0
LSD (MPa)	**3.4**		**12.9**			**4.4**			**4.2**			**3.2**		

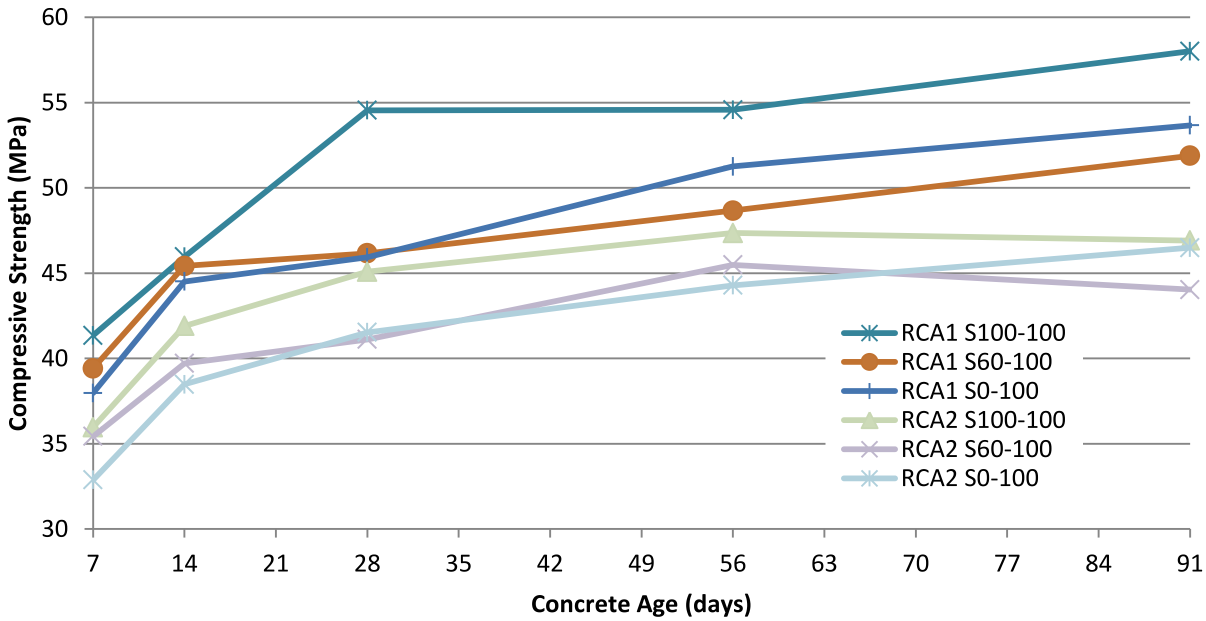


Figure 5.4: Compressive strength development for saturation comparison (100% replacement)

In this Figure 5.4, the relative contributions of RCA1 and RCA2 can be observed. All three RCA1 mixtures exhibit significantly higher compressive strengths than their corresponding RCA2 mixtures at 91 days. This seems to be in agreement with previous findings regarding these two aggregate types (Butler et al., 2013b).

Within each aggregate type, the strength development appears to be affected by the aggregate saturation level. Although the magnitudes are different, the early strength gain appears to last longer in the 100% saturated mixtures. Statistically significant gains can be seen to happen between the ages of 14 and 28 days for both 100% saturated mixtures in comparison to the other saturation level mixtures, for which the strength gain appears to be retarded. By the age of 91 days, the disparity between saturation levels is no longer statistically significant. The compressive strengths of the 100% saturated mixtures are still higher, but no longer significantly so. In the case of the RCA1 mixtures, this appears to be due to a relatively large spread in the 100% saturated results data, which subsequently increases the associated LSD value.

In both RCA types, the 60% saturation mixtures perform more poorly at later ages than the other two saturation levels, but this difference is not statistically significant. The cause of this is unclear. It is theorized that the differences in aggregate preparation could cause this effect. The soaked RCA had a film of water adhered to its surfaces when it was added to the mixture. This water could have formed a mortar coating around the aggregate similar to the film discussed previously (Tam et al., 2005), which would limit the moisture transport between the aggregate and cement paste. This could effectively raise the w/c of the 60% saturated mixtures by trapping the extra water from mixing water corrections outside of the aggregate at early ages. In this scenario, the 100% saturated mixtures would seal in the full absorption capacity and the 0% saturated mixtures would not form this initial coating, allowing for greater absorption. This could account for the 60% mixture's relatively low strength.

Figure 5.5 shows the compressive strength development for the mixtures, which contain only 30% replacement of NA with RCA.

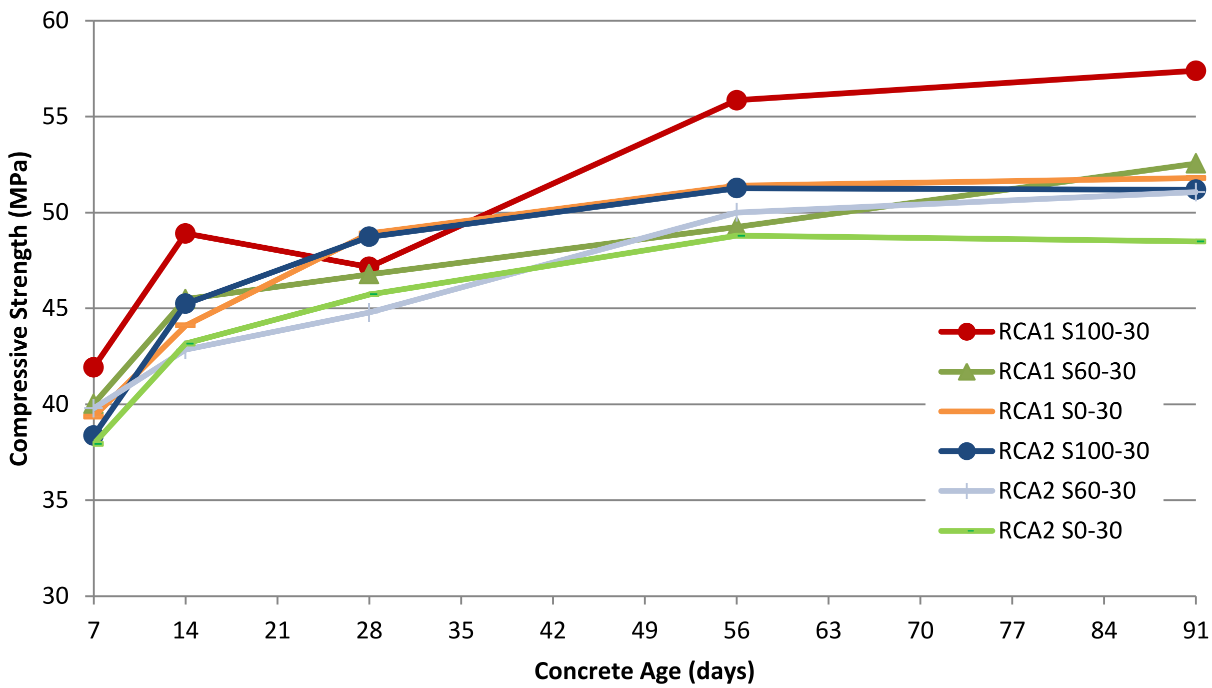


Figure 5.5: Compressive strength development for saturation comparison (30% replacement)

The mixtures generally show a similar but less pronounced version of the results seen in Figure 5.4. With the exception of the 28 day strength of RCA1 S100-30, the 100% saturation mixtures show the highest strength within their aggregate type. In this case the RCA2 mixtures and the 0% and 60% saturated RCA1 mixtures all display similar strength development over the course of the test and result in strengths approximately 5MPa lower than RCA1 S100-30, which is statistically higher at 91 days. With the exception of RCA1 S100-30 at 91 days, there were no statistically significant differences observed at the 30% RCA replacement level.

While this appears to support the idea that 30% replacement of NA with RCA is generally acceptable, it also indicates that 100% saturation is most beneficial for RCA in terms of concrete compressive strength under these conditions.

Figure 5.6 illustrates the relative compressive strength of 100% saturated mixtures as compared to their corresponding 0% saturated mixtures over time. The horizontal line represents equivalency between the mixtures. Points above "1" correspond to an increase in compressive strength in 100% saturated mixtures. 30% and 100% aggregate replacement mixtures are considered.

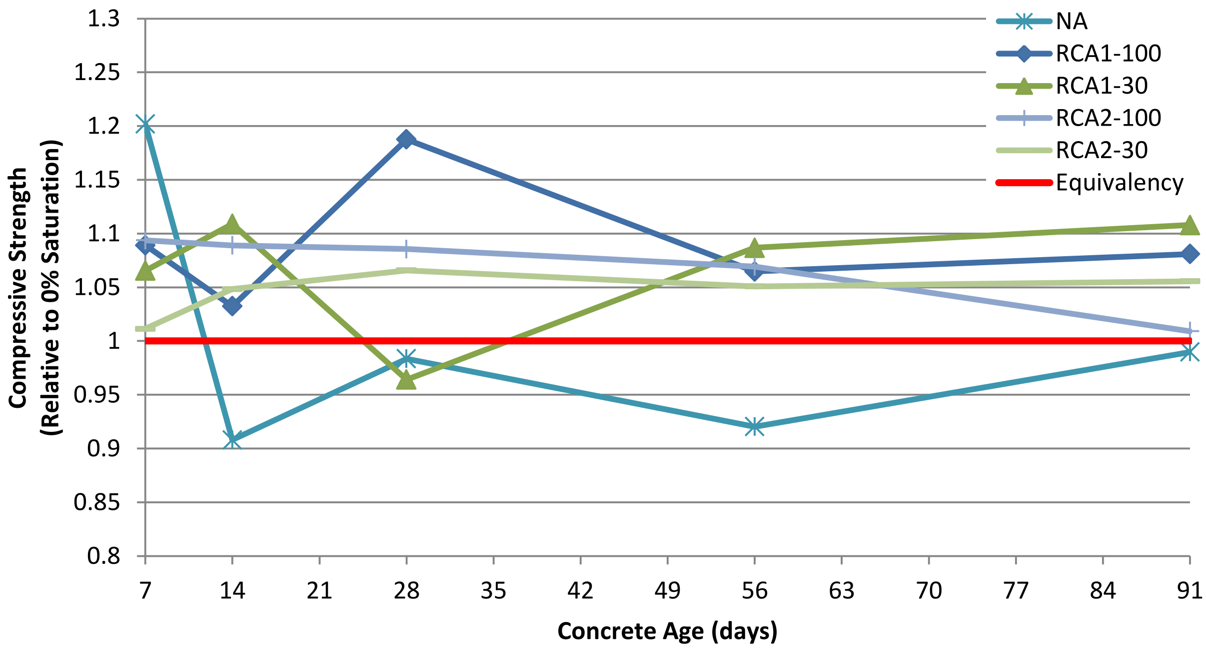


Figure 5.6: Comp. strength of 100% saturated mixtures normalized to 0% saturated mixtures

Figure 5.6 illustrates that the compressive strengths of the 100% saturated NA mixtures are generally reduced in comparison to the compressive strengths of the 0% saturated NA mixtures. The 7 day strength is 20% higher in the saturated mixture, but this quickly reduces and does not reach the level the 0% NA compressive strength again.

Alternatively, all RCA mixtures tested appear to benefit in terms of compressive strength gain from full saturation of coarse aggregate. At 28 days, the compressive strength of the 30% replacement mixture of RCA1 appears to be approximately 4% lower than the 0% saturation mixture, but otherwise all mixtures exhibit compressive strength gains. These strength gains are largely on the order of 5-10% throughout the course of testing and appear in both 30% and 100% replacement mixtures.

5.1.3 Splitting Tensile Strength

Figure 5.7 and Figure 5.8 illustrate the splitting tensile strength of mixtures at 100% and 30% RCA replacement respectively. Table 5-3 summarizes the statistical evaluation of the tensile strength results at 28 and 91 days.

Table 5-3: Statistical Comparison of Tensile Strength Values at 28 and 91 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean Tens Strength (MPa) (28 day)	4.1	3.6	3.7	3.6	3.3	3.9	3.5	4.3	3.0	3.3	3.2	3.6	3.5	3.6
STD DEV (MPa)	0.5	0.2	0.5	0.4	0.2	0.3	0.0	0.6	0.2	0.3	0.2	0.2	0.3	0.1
COV (%)	11.8	4.8	13.5	10.0	5.5	7.4	0.9	13.1	7.5	9.5	7.6	5.6	9.3	3.7
LSD (MPa)	**1.3**		**1.4**			**1.4**			**1.0**			**0.9**		
Mean Tens Strength (MPa)(91 day)	3.6	4.3	3.7	3.4	3.7	4.3	4.0	3.9	3.8	3.6	3.3	3.5	4.1	4.0
STD DEV (MPa)	0.6	0.2	0.2	0.4	0.4	0.2	0.2	0.1	0.4	0.2	0.0	0.4	0.6	0.6
COV (%)	16.8	4.7	6.6	11.1	11.1	5.5	5.7	2.8	10.8	5.6	0.9	10.2	15.7	14.4
LSD (MPa)	**1.6**		**1.4**			**0.8**			**1.0**			**2.1**		

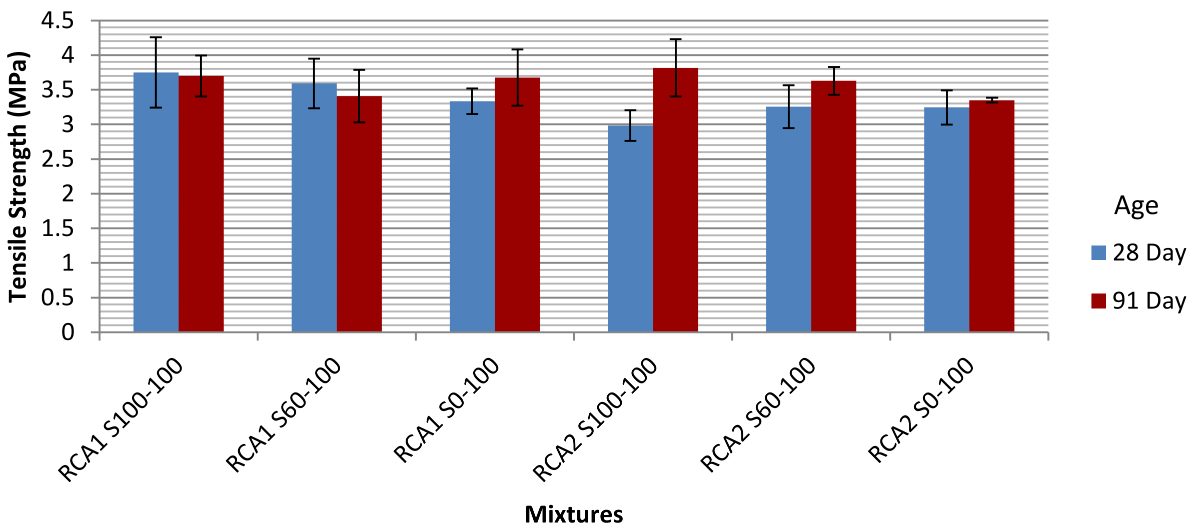


Figure 5.7: Tensile strength development for saturation comparison (100% replacement)

The effect of saturation on the splitting tensile strength of RCA concrete is small. Previously it was found that the effect on compressive strength was in the order of 5-10%. Since splitting tensile strength is approximately related to the square root of the compressive strength, the effect may be too small to observe given the nature of the splitting tensile test. None of the variations observed based on coarse aggregate saturation were found to be statistically significant at 28 or 91 days and at 95% confidence.

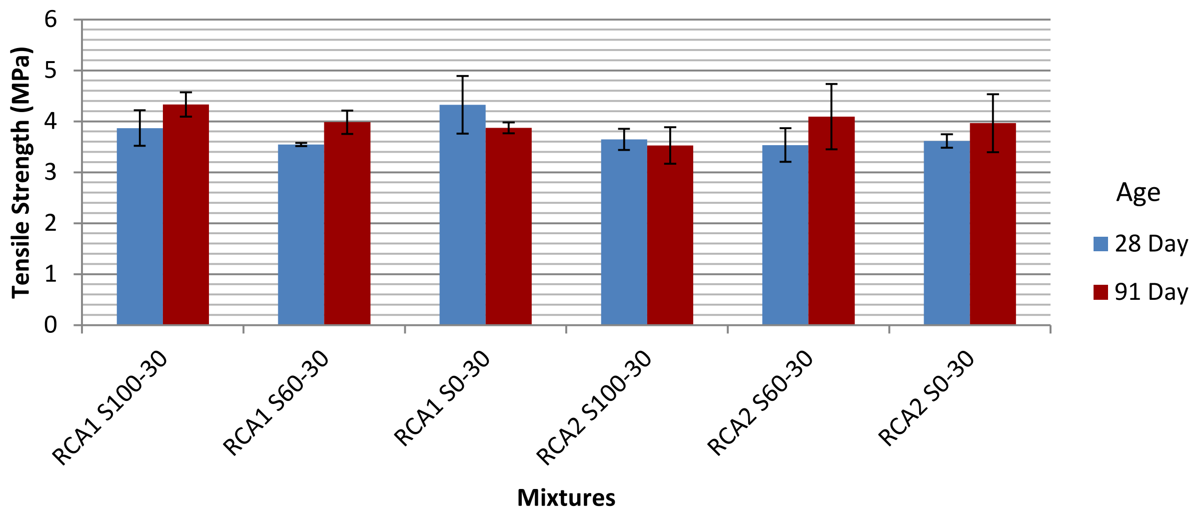


Figure 5.8: Tensile strength development for saturation comparison (30% replacement)

Similar to the 100% replacement mixtures, there is no statistically significant trend in the splitting tensile strength results for the 30% replacement mixtures with regards to aggregate saturation. Overall, these mixtures exhibit higher tensile strength than the 100% replacement mixtures.

5.1.4 Modulus of Elasticity

Figure 5.9, Figure 5.10 , Figure 5.11, and Figure 5.12 present the elastic moduli for each mixture as saturation of RCA varies.

Figure 5.9 and Figure 5.10 show the actual measured values while Figure 5.11 and Figure 5.12 show these values as normalized to the square root of the measured compressive strength and the density to the exponent 1.5. This normalization technique was chosen based on the results of Section 4.2.2.4, which found that the method of estimating elastic modulus using these terms was most accurate. The results were normalized to determine if any observable trends in elastic modulus could be seen that were not due to the significant changes in concrete density and compressive.

As shown, the measured moduli were all lower for RCA concretes than the NA concretes, regardless of the aggregate saturation levels. The 100% replacement mixtures were also observed to have lower E_c values than the 30% replacement mixtures.

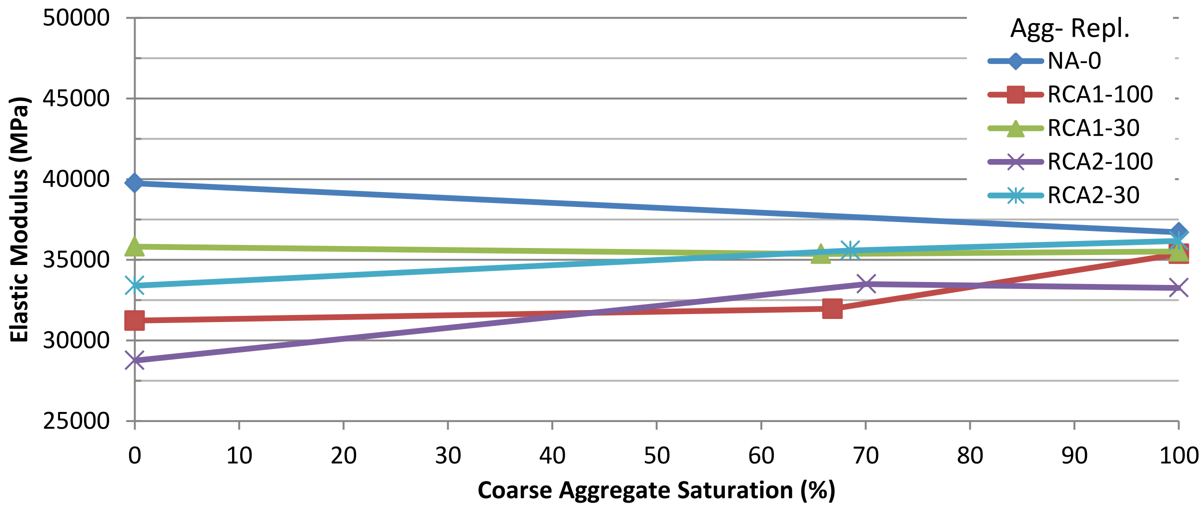


Figure 5.9: Elastic modulus vs aggregate saturation (28 day)

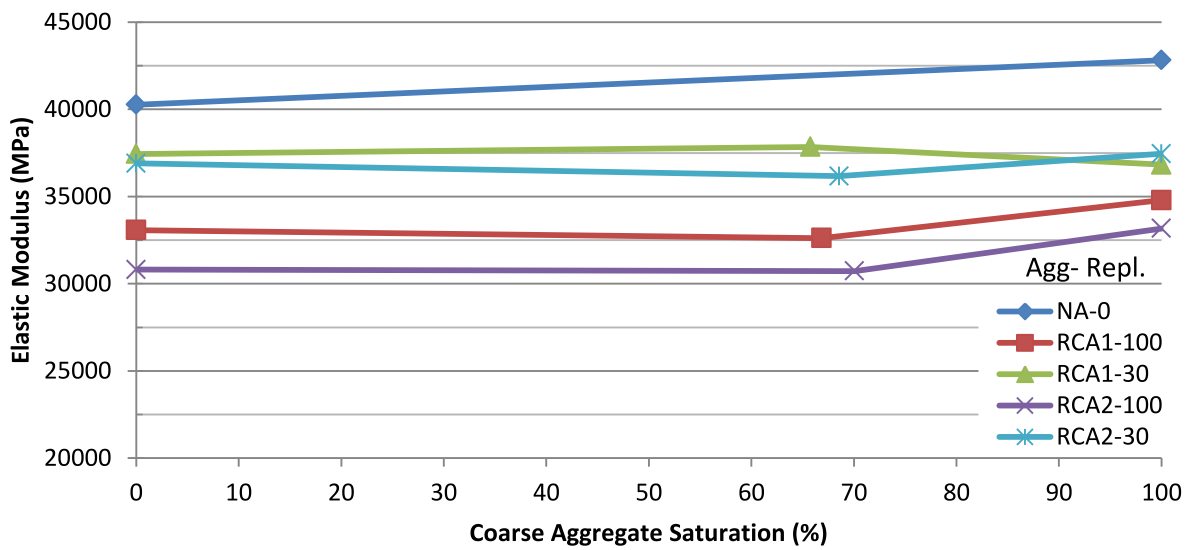


Figure 5.10: Elastic modulus vs aggregate saturation (91 day)

Table 5-4: Statistical Comparison of Elastic Modulus Values at 28 and 91 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean MOE (MPa) (28 day)	36707	39755	35365	31963	31233	35513	35363	35824	33261	33507	28763	36176	35589	33401
STD DEV (MPa)	3082	691	722	614	82	870	658	490	467	3159	1669	1155	1376	96
COV (%)	8.4	1.7	2.0	1.9	0.3	2.4	1.9	1.4	1.4	9.4	5.8	3.2	3.9	0.3
LSD (MPa)	**7806**		**2123**			**2667**			**8036**			**4013**		
Mean MOE (MPa) (91 day)	42820	40270	34793	32613	33080	36829	37850	37441	33166	30732	30813	37456	36170	36903
STD DEV (MPa)	2705	668	792	153	445	524	548	416	369	841	433	328	512	795
COV (%)	6.3	1.7	2.3	0.5	1.3	1.4	1.4	1.1	1.1	2.7	1.4	0.9	1.4	2.2
LSD (MPa)	**6886**		**2054**			**1929**			**2264**			**2232**		

When mixtures are evaluated based on elastic modulus values and saturation level changes in the coarse aggregate, mixtures with 100% RCA that is 100% saturated display significantly higher moduli than the corresponding 0% and 60% saturated mixtures. This effect is not observed at the 30% replacement level or in the NA mixtures.

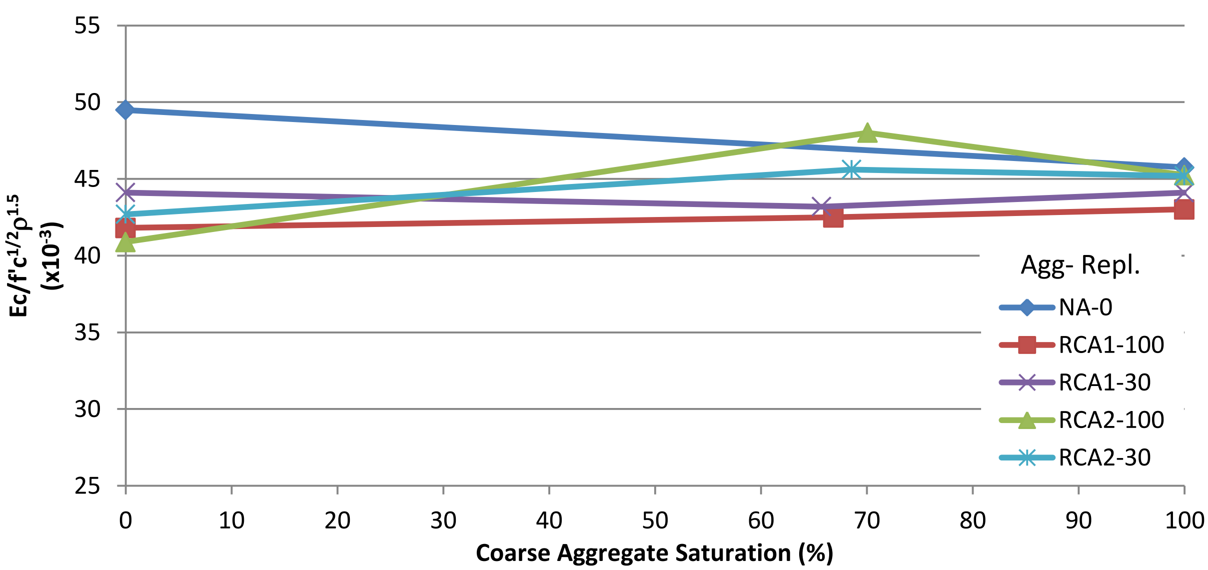


Figure 5.11: Elastic modulus normalized to $f'c^{1/2}\rho^{1.5}$ (28 day)

When the elastic modulus results are normalized any effects of saturation can be seen. These effects appear to be minimal as all RCA mixtures generally remain constant independent of the saturation levels. This indicates that the statistical variations observed previously were due in large part to changes in compressive strength and density.

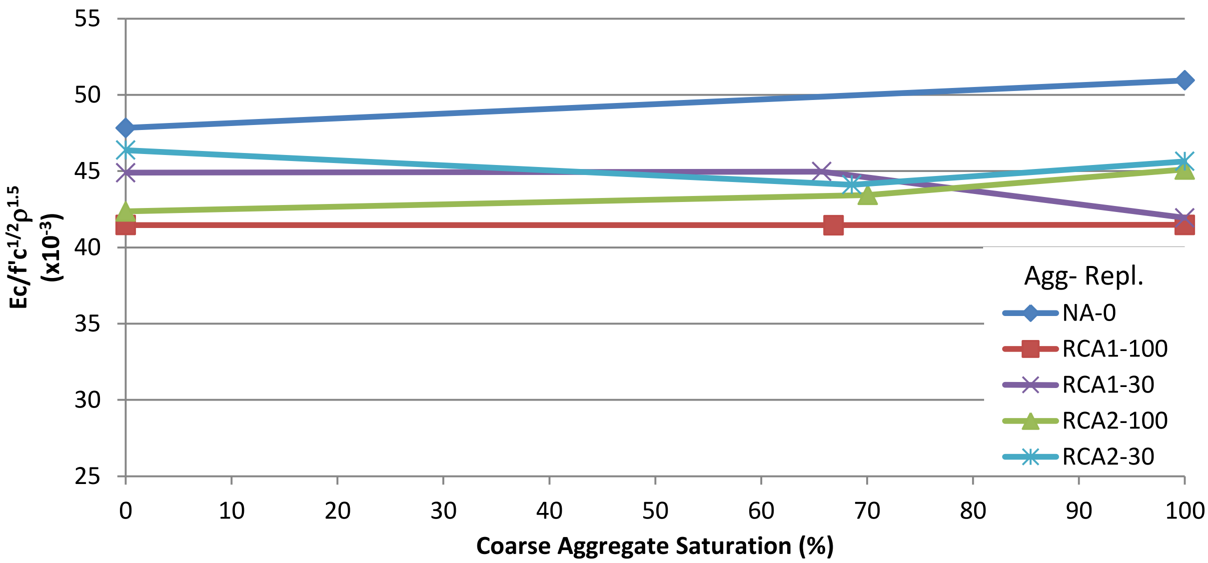


Figure 5.12: Elastic modulus normalized to $f'c^{1/2}\rho^{1.5}$ (91 day)

At 91 days all RCA mixtures appear to behave approximately independently of RCA saturation changes. This indicates that any observed changes in elastic modulus in these cases are due to the other effects associated with RCA use. When normalizing the effects of compressive strength and density, the NA mixtures still exhibit stiffer properties than all RCA mixtures.

Figure 5.13 illustrates the effects of 100% saturation of RCA on elastic modulus. The figure shows the normalized moduli compared to those of the 0% saturated mixtures and it considers the effects of compressive strength and density by removing their contributions through normalization. The horizontal line within the figure represents the level of parity between the two saturation levels.

Overall, a general trend is observed with the RCA mixtures as compared with the NA mixtures. At 28 days, the effects of aggregate saturation appear to be largely beneficial, with three of the four 100% saturated mixtures exhibiting increases of 2% - 11% over their corresponding 0% saturated mixtures. The exception to this trend is the RCA1 100% saturation-30% replacement mixture, which is approximately equal to its corresponding 0% saturated mixture in terms of normalized elastic modulus. The 100% saturated NA mixture shows an 8% decrease at 28 days age.

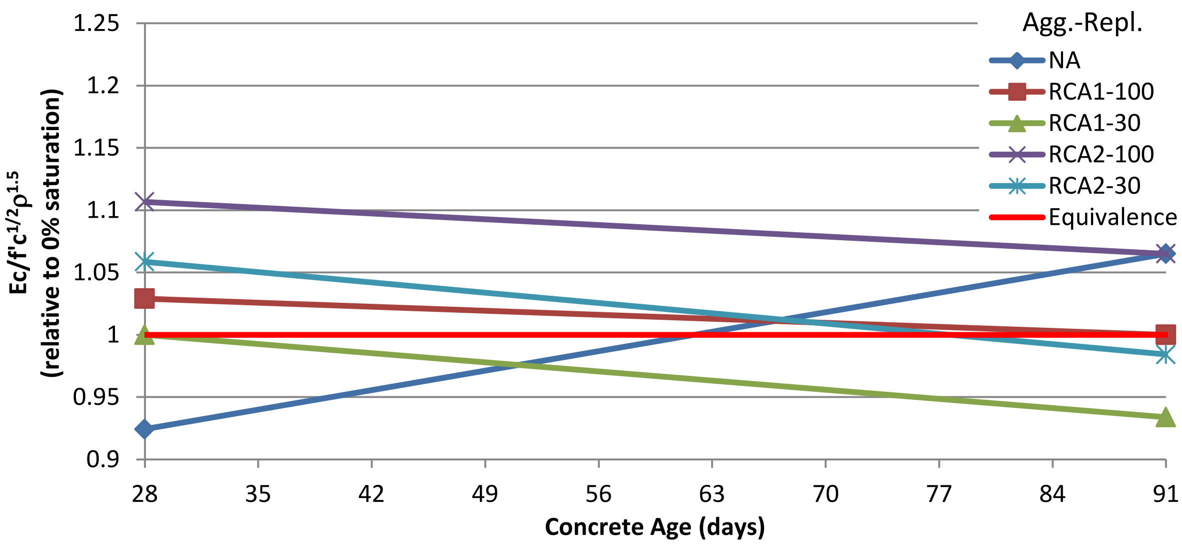


Figure 5.13: Elastic modulus of 100% saturated mixtures relative to 0% saturated mixtures

At 91 days, the relative normalized moduli for all RCA mixtures are lower. The relative NA mixture increases significantly over this time. This appears to indicate that any positive relative effect of full saturation does not extend into later ages of concrete, or is at least lessened with time. This could be correlated with to the fact that the samples had been allowed to dry over this period. It has been found that drying can reduce the secant modulus of concrete (Brooks & Neville, 1977). Due to lower levels of initially entrained water, the overall humidity levels of the 0% saturated mixtures are lower, which could reduce the moduli in comparison to the 100% saturated mixtures. At later ages the humidity level disparity between the two mixture types has lessened due to exposure, and the perceived benefit can no longer be observed.

5.1.5 Linear Coefficient of Thermal Expansion

Figure 5.14 and Figure 5.15 illustrate the effects of aggregate saturation on the LCTE of concretes at 28 days and 150 days, respectively. Table 5-5 summarizes the statistical evaluation of the variations within the mixtures due to saturation variations at 28 and 150 days.

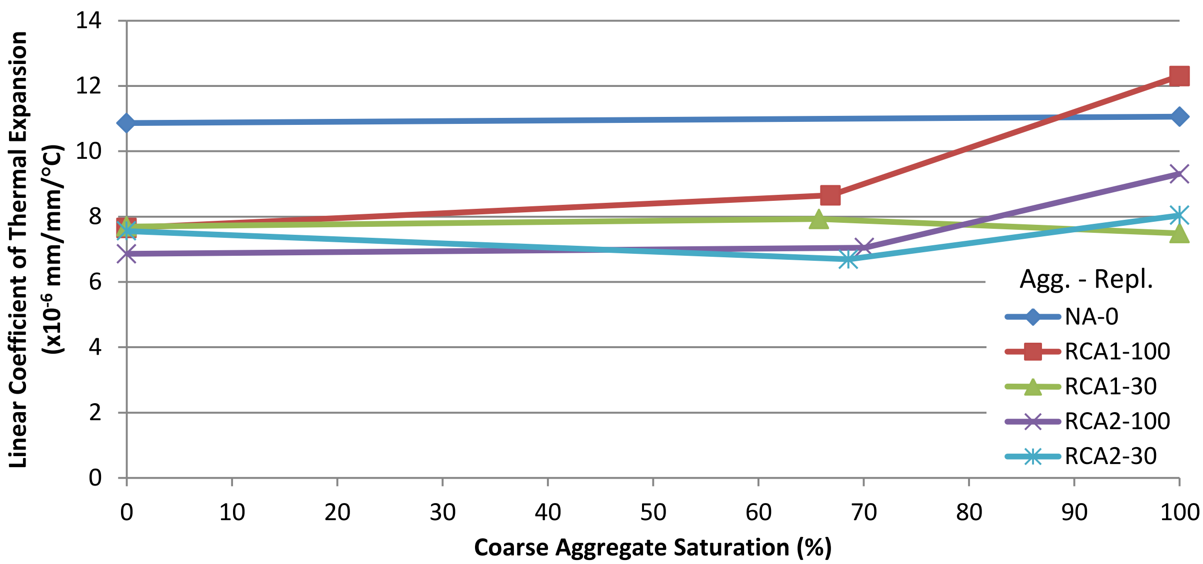


Figure 5.14: LCTE vs aggregate saturation (28 days)

Table 5-5: Statistical Comparison of LCTE Values at 28 and 150 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean LCTE ($x10^{-6}/°C$) (28 day)	11.1	10.9	12.3	8.6	7.6	7.5	7.9	7.7	9.3	7.0	6.9	8.0	6.7	7.6
STD DEV($x10^{-6}/°C$)	1.0	2.0	3.0	1.6	1.9	2.0	0.9	1.4	5.6	1.6	2.3	2.4	1.1	1.5
COV (%)	9.3	18.0	24.3	18.3	25.4	26.5	11.8	18.7	59.7	22.1	33.1	29.3	16.2	19.4
LSD ($x10^{-6}/°C$)	**1.6**		**2.7**			**1.8**			**4.3**			**2.1**		
Mean LCTE ($x10^{-6}/°C$) (150 day)	7.0	8.7	9.7	3.7	16.0	16.7	8.4	9.9	10.4	7.9	11.3	5.2	7.4	8.8
STD DEV($x10^{-6}/°C$)	2.5	2.8	0.9	2.1	3.6	3.5	1.2	1.4	2.4	1.3	6.3	2.4	1.4	1.6
COV (%)	35.1	32.0	8.9	57.5	22.7	20.8	13.9	13.9	22.9	16.5	56.0	46.5	18.7	18.4
LSD ($x10^{-6}/°C$)	**7.9**		**3.0**			**2.7**			**4.7**			**2.2**		

At the age of 28 days, the only mixture that exhibits significant changes due to changes in RCA saturation is RCA1 S100-100. All other RCA mixtures exhibit LCTEs between 7 $x10^{-6}/°C$ and 10 $x10^{-6}/°C$ regardless of aggregate saturation. At 0% and 60% saturation, the 100% replacement RCA1 mixtures exhibit this same behaviour, however at an RCA saturation of 100% the LCTE is approximately $12x10^{-6}/°C$. Both RCA2 mixture types exhibit an increase at the 100% saturation level, but the increase is not statistically significant. One possible explanation for the observed behaviour is due to the nature of thermal expansion of cement paste, which is 100% saturated. In this condition, cement paste exposed to temperatures below freezing point can exhibit CTE levels higher than at other temperatures (Neville, 1997). If pockets of fully saturated paste are present within the samples, they could exhibit increased thermal expansion. This condition could potentially be present within 100% saturated mixtures, which have been found to retain more moisture.

With the exception of the RCA1 S100-100, all RCA mixtures appear to exhibit lower LCTEs than NA concrete, regardless of saturation level. This appears to confirm previous findings (Smith & Tighe, 2009).

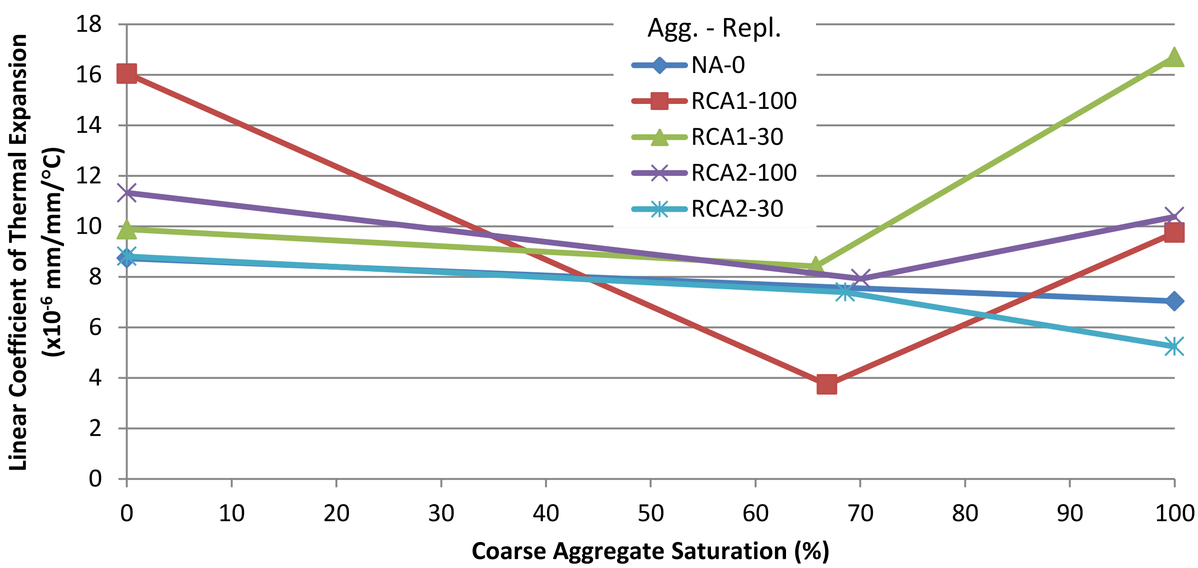


Figure 5.15: LCTE vs aggregate saturation (150 days)

The samples that were tested to gain the results shown in Figure 5.15 were the same samples as the 28 day test. These samples were left exposed to the laboratory conditions during this period and were assumed to have undergone drying.

At the age of 150 days, the thermal expansion results indicate an increase in variability as a function of saturation levels. Almost all RCA mixtures exhibit higher LCTE values, while the NA mixtures decreased. At this age, the RCA mixtures no longer exhibit lower LCTE than the NA mixtures.

The observed variations are difficult to explain. There are no clear trends when these results are considered as a group or in conjunction with the 28 day testing. It is assumed that the results in this second round may have been influenced by the non-standard testing procedure that was employed. Two significant factors are considered as potential reasons for this variation, the fluctuations in the thermal expansion behaviour of cement at low temperatures based on the moisture content of the cement and the changes in the thermal expansion coefficient of cement due to the temperature at which the thermal expansion is measured. The lack of a temperature controlled "warm" environment allowed the upper bounds of the testing temperature to fluctuate more than in the previous round of testing. Ensuring the same upper and lower bound of temperatures is reached during each cycle would minimize the effect of the latter factor. Because the samples are allowed to dry as part of this research's focus on aggregate saturation variations, the former factor is not easily controlled. Additionally, the warm portion of the test occurred in the concrete laboratory, but the second round occurred in a different laboratory with outdoor access. The RH condition of both environments was subject to change based on the external conditions. This can have a significant effect on the measured results.

Typically it is recommended that a temperature- and humidity-controlled environment be used for sample cycling in order to alleviate these effects on the testing, however this is a non-standard implementation of this test, which assess the effects of entrained moisture and the effects of drying. These research objectives make interpretation of the results challenging.

5.1.6 Total Permeable Porosity and Absorbed Water

Figure 5.16 and Figure 5.17 show the total permeable porosity of mixtures as a function of the initial RCA saturation levels. Table 5-6 tabulates the statistical analysis of the effects of coarse aggregate saturation on permeable porosity at 28 and 91 days.

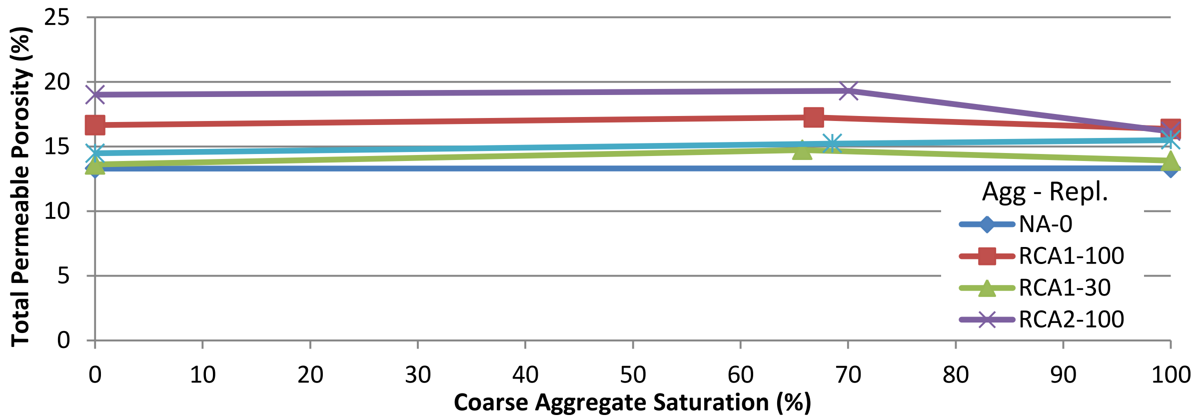


Figure 5.16: Total permeable porosity vs aggregate saturation (28 days)

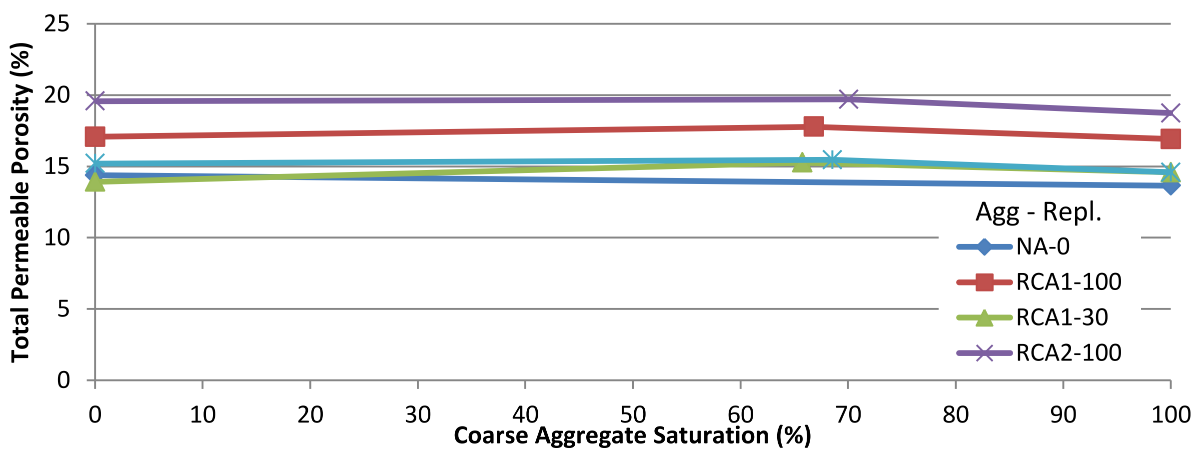


Figure 5.17: Total permeable porosity vs aggregate saturation (91 days)

Table 5-6: Statistical Comparison of Permeable Porosity Values at 28 and 91 days (Saturation)

	NA S100-0	NA S0-0	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100	RCA1 S100-30	RCA1 S60-30	RCA1 S0-30	RCA2 S100-100	RCA2 S60-100	RCA2 S0-100	RCA2 S100-30	RCA2 S60-30	RCA2 S0-30
Mean Permeable Porosity (28 day) (%)	13.7	13.6	17.0	17.6	17.1	14.3	15.1	13.9	16.7	19.7	19.7	15.9	15.6	14.8
STD DEV (%)	1.1	1.0	0.6	0.9	0.5	0.1	0.6	0.4	1.2	0.8	1.0	0.1	0.4	0.4
COV (%)	8.0	7.1	3.7	5.2	2.8	1.0	4.1	2.8	6.9	4.3	4.9	0.9	2.4	2.6
LSD (%)	**3.6**		**2.7**			**1.7**			**3.8**			**1.2**		
Mean Permeable Porosity (91 day) (%)	14.5	13.7	17.1	17.9	17.2	14.7	15.4	14.0	18.9	19.8	19.8	14.7	15.6	15.3
STD DEV (%)	0.4	0.7	0.3	0.8	0.6	0.5	0.6	0.8	0.5	0.9	0.6	0.6	0.3	0.7
COV (%)	2.9	5.4	1.6	4.4	3.5	3.7	4.0	5.9	2.8	4.7	2.8	3.9	2.0	4.3
LSD (%)	**2.1**		**2.3**			**2.6**			**2.7**			**2.1**		

Similar trends are illustrated at both testing ages. In each case, the permeable porosity of 100% RCA replacement mixtures were considerably higher than those of the 30% replacement mixtures indicating that the RCA amount had an observable influence on the transport properties of the mixtures. The RCA2 mixtures were consistently higher than their RCA1 counterparts, indicating that the quality of the RCA (specifically the absorption capacity) had an influence on the transport properties of a given concrete. Within each aggregate and replacement level, none of the saturation variations at either testing age were found to be statistically significant at 95% confidence. The permeable porosities at 0% and 100% saturation were lower than those of the 60% saturated mixtures, but not by a statistically significant margin. This may be explained by the mixing procedure, which could cause an effective water/cement ratio higher than designed. This slightly higher effective w/c would increase the porosity of the paste and thereby increase the permeable porosity of the concrete.

Figure 5.18 and Figure 5.19 illustrate the water entrained before and absorbed during the test at 28 and 91 days respectively. The absorbed water is presented as a percentage of each sample's oven dry mass. In each plot, the mixtures are grouped by replacement level to show variations across RCA saturation levels.

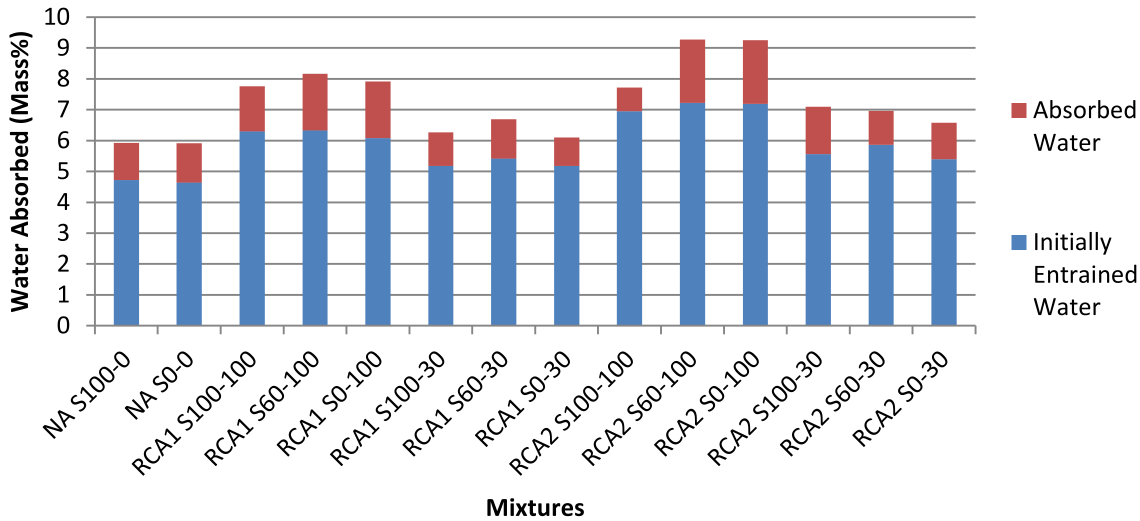


Figure 5.18: Absorbed and entrained water percentages for saturation comparison (28 days)

At 28 days the differences across the different mix types can be seen. The water absorbed by the NA mixtures appears to be unaffected by changes in the saturation of the coarse aggregate. This is expected due to the low absorption capacity of this aggregate.

In the 100% replacement mixes, the overall mass percent of water absorbed is higher than all other mix types. This is at least partially due to the lower dry density of these mixtures, which is due in turn to the relatively high RCA contents. In these mixtures, it can be seen that roughly the same amount of water was entrained within the aggregate at the beginning of the test procedure. During the course of the test, higher levels of water were absorbed by the 0% and 60% saturated mixtures in comparison to the 100% saturated mixture. In the case of RCA1 mixtures, this increase in the order of 6% while in the RCA2 mixtures, this increase is approximately 20%.

At the 30% replacement level, the magnitude of these effects is diminished although the 60% saturated RCA1 mixture still exhibits the highest absorption.

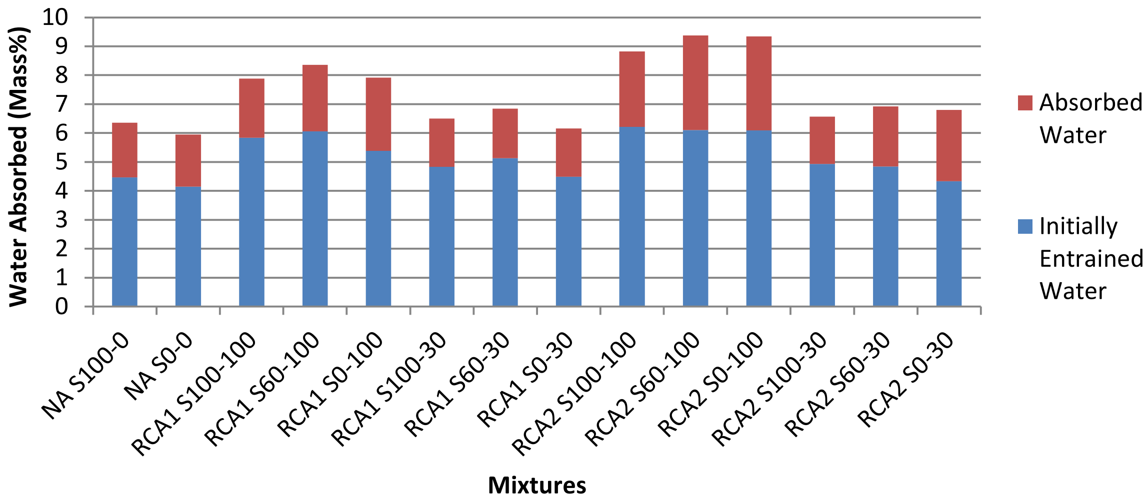


Figure 5.19: Absorbed and entrained water percentages for saturation comparison (91 days)

At 91 days, similar trends and overall absorption levels were observed. In every case, the initially entrained water levels dropped in comparison to the 28 day test, which illustrates the drying that the samples were undergoing. Despite this moisture drop in every mixture, a significant proportion of the permeable pores remain saturated prior to the test.

In the 91 day testing the same trends were observed, specifically that the 60% saturated mixture absorbed the highest percentage of water. As previously noted, this could be due to an elevated water cement ratio due to aggregate “sealing” during mixing, which could lead to higher porosity in the paste.

5.1.7 Conclusions

The following list of conclusions has been made from this portion of the study, for these mixtures under the specified curing condition:

- 100% saturated RCA1 concrete samples appear to retain more water in the form of absorbed or trapped water and hydrated cement.
- RCA1 mixtures lost less moisture than the RCA2 mixtures, which correlates well with the higher absorption of RCA2 and therefore the higher total w/c ratio.
- 100% saturated RCA mixtures appear to gain compressive strength at a higher rate for longer during early-age strength gain, as compared to the 0% and 60% saturated

mixtures. This suggests that the initial entrainment of water within the RCA is the most effective means to include extra mixing water in concrete. When RCA is considered for use in future concrete applications, this should be considered during concrete batching procedure development.

- For a given RCA type, the 60% saturated mixtures develop lower compressive strengths than the 100% or 0% saturated mixtures. While the disparity between these mixtures was not statistically significant, it may indicate that partially saturated RCA in concrete develops lower compressive strength than completely saturated or unsaturated RCA. The valuation of RCA in concrete depends on using the batching procedure, which produces the best performing RCA concrete.
- Coarse aggregate saturation was not observed to significantly influence splitting tensile strength of concrete for all aggregate types and replacement amounts. The initial saturation level of RCA can have a negative effect on the concrete's compressive strength but does not affect the tensile strength, indicating that compressive strength effects should govern the preparation procedure used when considering concrete strength.
- 100% saturated RCA mixtures exhibited significantly higher elastic moduli than the corresponding less-saturated RCA mixtures. Normalized with regard to density and compressive strength, the elastic modulus of the 100% saturated RCA mixtures appears to increase at 28 days, but this effect is lessened over time. The effects on elastic modulus appear to be governed mostly by the corresponding changes in compressive strength and density.
- In the temperature range of -15°C - +20°C at the age of 28 days, the saturation level of NA mixtures appears to have little effect on the LCTE, which remains higher than the LCTE of RCA mixtures. This indicates that RCA concretes may have significant value in concrete applications that require that concrete not contract significantly under cold weather conditions.
- In the temperature range of -15°C - +20°C at the age of 28 days, 0% and 60% saturation of RCA appears to have little influence on LCTE, however 100% saturation of RCA1 appears to result in an increase of thermal expansion. This is possibly due to areas of high moisture that are developed in the vicinity of the RCA due to the RCA's retention of

water. This could be significant to concrete producers as it may affect the recommended time before an RCA concrete can be safely exposed to low temperatures. If this moisture retention and thereby LCTE increase persists for a significant period of time, RCA concrete may not be feasible for placement late in the construction season of a cold-winter climate like Canada.

- It is recommended that future LCTE tests involve the use of temperature- and humidity-controlled environments to remove their influence from the testing results, when the testing objectives permit.
- The permeable porosity and water absorption percentage were observed to be higher in those mixtures prepared with 60% saturated aggregate, however not at a statistically significant level. This could be due to the coating effect discussed previously, whereby adhered surface moisture coming into contact with cement during batching produced a coating, which restricts the flow of mixing water into the unsaturated RCA prior to the concrete's setting. This would result in higher effective water-cement ratios in the mortar, which could increase the porosity of the sample. This indicates that partial saturation of RCA prior to inclusion in concrete may not be the ideal preparation technique.

Overall, when using RCA in concrete cured in specified conditions, 100% saturation of the recycled aggregate appears to provide benefits to the performance of the concrete in terms of compressive strength development, stiffness, and permeable porosity when compared to concrete mixtures with the same level of aggregate replacement but 0% or 60% saturation levels. In particular, mixtures with 60% saturation appear to perform worst in terms of a number of hardened concrete characteristics.

5.2 Curing Comparisons

A second objective of this study was to determine how the inclusion of saturated RCA in a concrete mixture affected concrete that was exposed to variable curing conditions. The hypothesis was that if RCA could provide some internal curing-like benefits, the RCA concrete may be less susceptible to the negative effects of spec-curing. The mixtures used for comparison were produced with 100% saturated aggregate. Each mixture was divided into two portions with half being cured in a 100% RH (moist) environment for the duration of the test and the other cured with burlap for 7 days and then exposed to drying in a 50% RH environment for the remainder of the test. Within the following discussion, mixtures use the naming convention discussed in Section 3.2.5. Mixtures denoted with an "M" or an "S" were subjected to moist curing or specified curing, respectively. Samples were tested according to the previously discussed testing schedule. Figure 5.20 outlines the key questions to be answered regarding the comparison of different curing regimes.

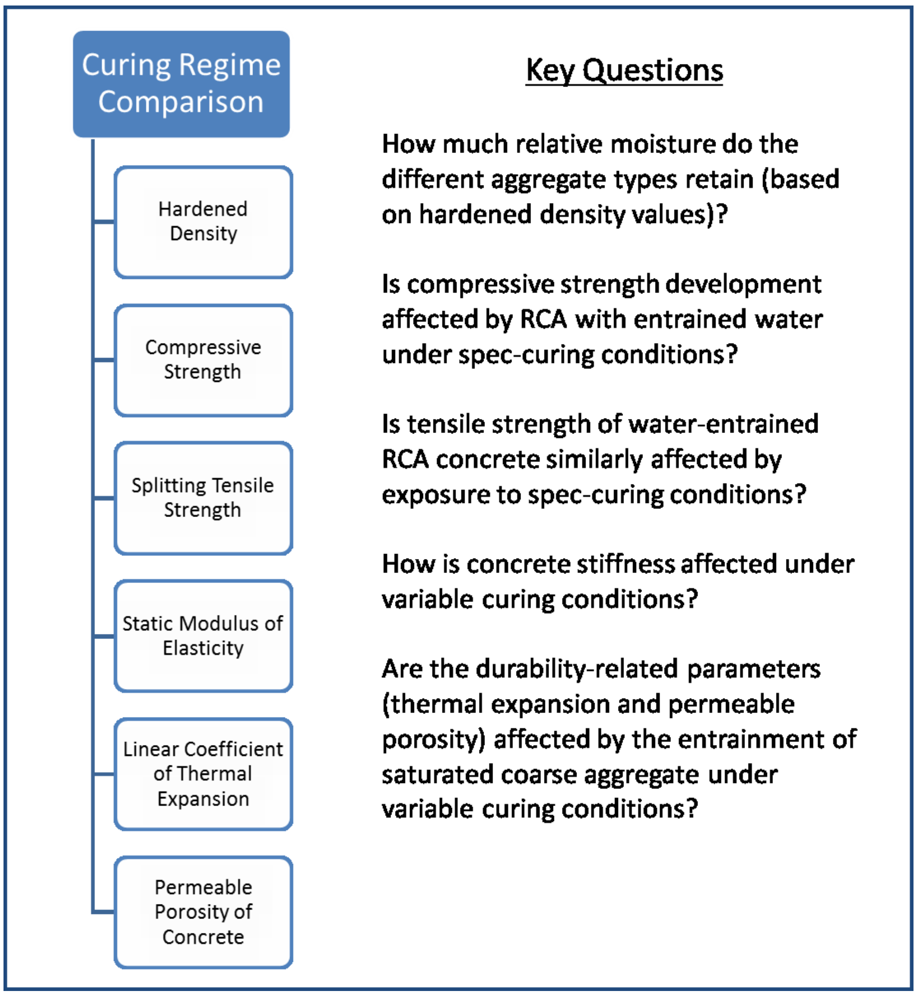


Figure 5.20: Key questions regarding the curing regime comparison

5.2.1 Hardened Density

Figure 5.21 shows the hardened densities for all comparisons. The fresh densities are also included at zero days as reference. Since "M" and "S" denoted different curing regimes for the same mixture, the fresh densities for each comparison pair are the same value. At the age of seven days, the spec-cured samples were subjected to exposed drying conditions, as denoted in the figure. According to the mixture designs and water content testing, the initial water contents for the NA, RCA1, and RCA2 mixtures were 189 kg/m^3, 211 kg/m^3, and 231 kg/m^3, respectively. Table 5-7 summarizes the statistical analysis of the hardened density values with respect to changes in curing regime.

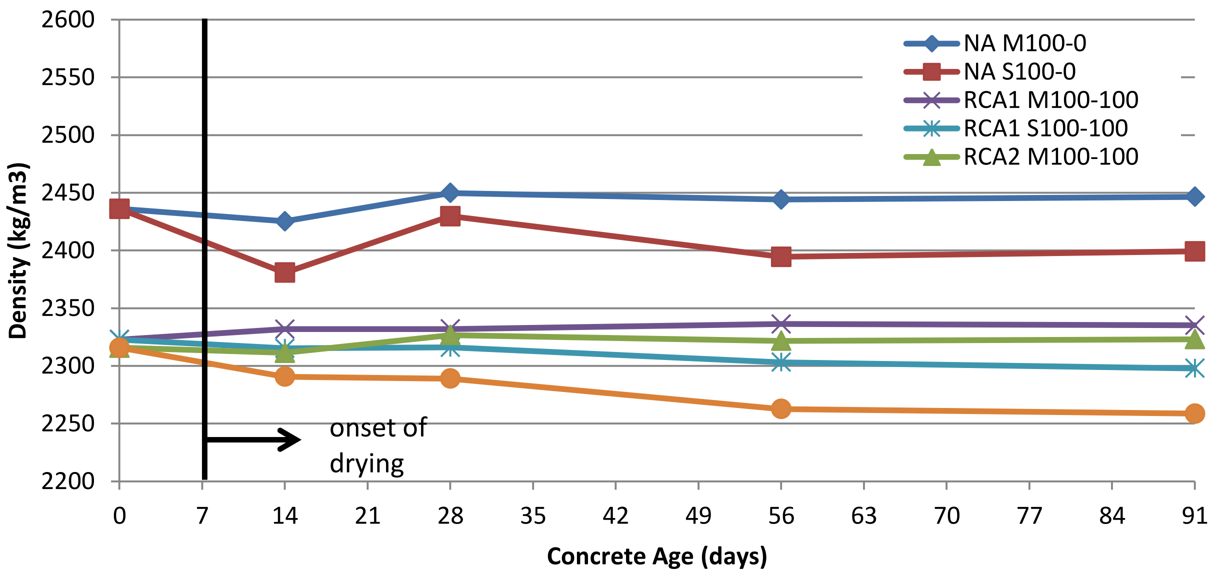


Figure 5.21: Hardened density for curing comparison

Since these values are not dry densities, but show actual density the observed disparities are assumed to be largely due to moisture loss. The drying behaviours were similar for each of the spec-cured mixtures while the moist-cured mixtures also displayed similar trends. Each moist-cured mixture displays a slight gain in density up to the 28 day age and then remains relatively constant. Each spec-cured mixture displayed a widening gap relative to its corresponding moist-cured mixture. The moisture losses are determined based on a mass loss for each mixture type. This means that any mass lost in the form of moisture is not consumed in a hydration reaction, but is lost to drying.

Table 5-7: Statistical Comparison of Hardened Density at 28 and 91 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Density (kg/m^3) (28 day)	2449.8	2429.7	2331.9	2315.9	2326.6	2289.0
STD DEV (kg/m^3)	8.2	12.3	5.7	9.0	5.7	9.1
COV (%)	0.3	0.5	0.2	0.4	0.2	0.4
LSD (kg/m^3)	**36.5**		**26.5**		**26.6**	
Mean Density (kg/m^3) (91 day)	2442.7	2399.1	2335.1	2297.9	2325.1	2259.4
STD DEV (kg/m^3)	5.9	9.3	18.9	2.7	4.0	10.2
COV (%)	0.2	0.4	0.8	0.1	0.2	0.5
LSD (kg/m^3)	**27.2**		**47.1**		**27.1**	

The RCA1 mixtures remained statistically similar until the end of the testing period, with a final disparity of 37 kg/m^3, which is less than the least significant difference at 95% confidence. The RCA2 mixture lost significantly more water, with a 91 day disparity of 66 kg/m^3, which was statistically significant. RCA2 had a higher absorption capacity and, due to the mixture design, had higher initial water content than either of the other two mixtures and more water to potentially lose. The NA mixture was observed to lose significant moisture up to the age of 56 days, but then remain relatively constant over the following 35 day period. This may indicate that all water reserves that were exposed to the external environment had been lost. The overall disparity between the two curing regimes at 91 days was 44 kg/m^3, which was statistically significant. This indicates that although the RCA1 mixture had 22 kg/m^3 more initial water than the NA mixture, the NA mixture lost 10 kg/m^3 more water over the course of 91 days. This indicates that the RCA1 mixture was better at retaining moisture than RCA2 or NA, which may be beneficial to certain mixtures, but could also present freeze thaw durability concerns under certain conditions. Due to the nature of water under freezing conditions, if the pores of a piece of aggregate are more than 91% saturated then aggregate and the concrete surrounding it could be damaged by freezing (Neville, 1997). The actual saturation levels of the RCA types are unknown beyond batching, so the actual susceptibility of each mixture to freezing damage cannot be stated based on these tests.

5.2.2 Compressive Strength

Figure 5.22 illustrates the compressive strength development for the mixtures used within the curing comparison. Table 5-8 tabulates the statistical analysis of the different curing regimes based on a 5% LSD.

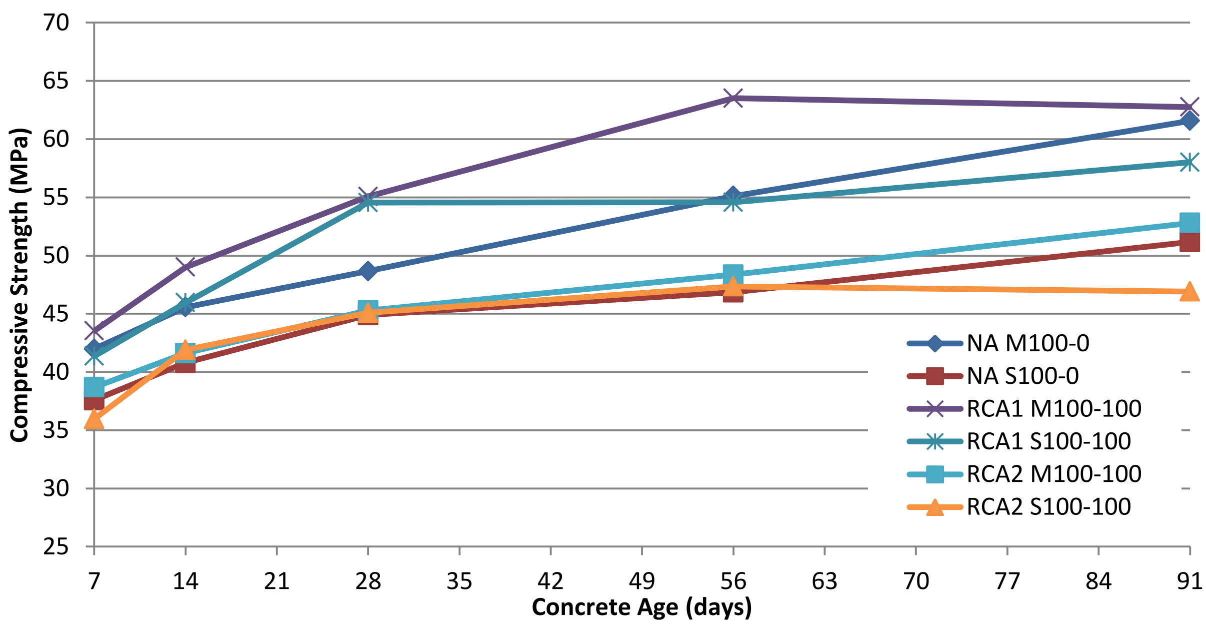


Figure 5.22: Compressive strength development for curing comparison

At the initial measurement, the difference between moist-cured and spec-cured mixtures is relatively small at approximately 5 MPa, 3 MPa, and 4 MPa for NA, RCA1, and RCA2, respectively. In all cases the moist-cured samples exhibited higher compressive strength. This indicates that the burlap-curing portion of specified curing provides comparable benefit to 100% RH conditions for these mixtures.

The three mixtures developed compressive strength in three distinct ways. The NA mixtures maintained a disparity between the compressive strength of moist and spec-cured mixtures of approximately 4 MPa until 28 days age, which was not statistically significant. After this point, the moist-cured mixture continued to develop strength at a similar rate while the spec-cured mixture's strength gain was retarded. This resulted in a significant difference in strength at 91 days.

Table 5-8: Statistical Comparison of Compressive Strength at 28 and 91 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Comp. Strength (MPa) (28 day)	48.7	44.9	55.1	54.5	45.3	45.1
STD DEV (MPa)	2.1	0.1	5.0	3.2	1.4	0.6
COV (%)	4.4	0.3	9.0	6.0	3.1	1.3
LSD (MPa)	**5.3**		**14.7**		**3.8**	
Mean Comp. Strength (MPa) (91 day)	61.6	51.2	62.8	58.0	52.8	46.9
STD DEV (MPa)	0.0	0.6	0.3	5.7	0.7	0.8
COV (%)	0.0	1.1	0.5	9.8	1.3	1.7
LSD (MPa)	**1.4**		**14.1**		**2.6**	

The moist-cured and spec-cured RCA1 mixtures also gained strength approximately equally up until the 28 day test. At this point the strength gain of the spec-cured mixture reached a plateau while the moist-cured specimen continued to gain strength. A similar plateau was reached at 56 days for the moist cured samples and by the 91 day test, the difference between the compressive strength of the two curing regimes was still statistically insignificant. The compressive strength results for the RCA1 samples had relatively high standard deviations, which resulted in high LSD values that affect the insignificant different between the "M" samples and the "S" samples. Even though the LSD is larger, the difference between the means of the compressive strength for the "M" and "S" samples is small in comparison to the differences observed in the mixtures containing the other aggregate types.

The RCA2 mixtures remained approximately at parity until the 56 day test at which point the spec-cured samples' strength gain plateaued and the moist cured samples continued to gain strength. At 91 days, the differences in compressive strength between moist cured and spec-cured RCA2 mixtures were statistically significant at 95% confidence.

The entrained moisture in both RCA mixtures had different compressive strength gain benefits under spec-curing conditions. RCA2 extended the period of initial strength gain while RCA 1 improved the later age strength of the mixtures. These benefits coincide with the previously discussed findings that RCA1 retains moisture for longer time periods than RCA2.

Relatively, the entrained moisture of RCA2 appeared to make it perform similarly to the NA mixture under spec-curing conditions, despite considerable variation between NA and RCA2 concretes observed when both are cured in ideal conditions. RCA1 mixtures exposed to spec-curing behaved similarly to moist-cured NA concrete.

Figure 5.23 illustrates the compressive strength of the spec-cured mixtures relative to their moist cured counterparts.

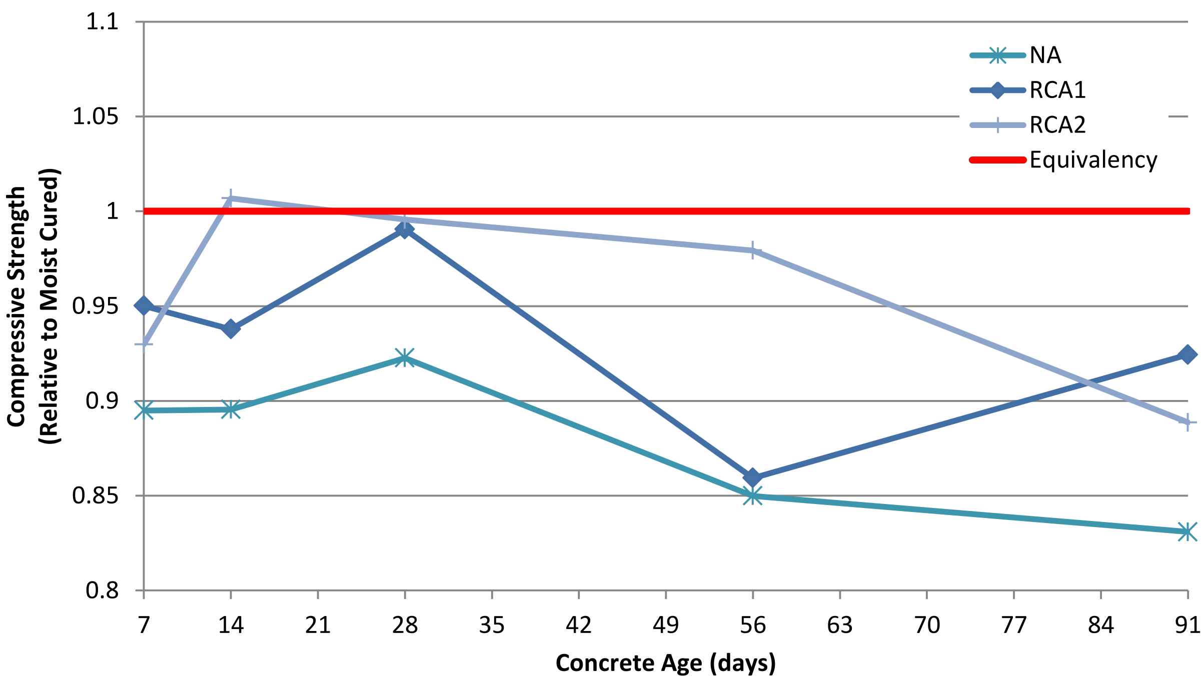


Figure 5.23: Compressive strength of spec-cured mixtures relative to moist-cured mixtures

Except for one slight increase, all compressive strengths were observed to be lower in those mixtures, which were exposed to the specified curing regime. This is intuitive as moist-curing provides a continuous source of curing moisture in addition to any entrained moisture.

At every age, the performance of spec-cured RCA mixtures performed relatively better than the NA mixtures in terms of compressive strength. This improvement is observed specifically at ages of 7 to 28 days. At later ages, the benefit relative to the NA mixtures is less pronounced, but still observable. RCA2 exhibits this relative benefit up to 56 days age.

Since all aggregates within this comparison were prepared in the same manner, the initial aggregate coating discussed in the previous section should not provide any relative benefit within these mixtures. An explanation for this improvement is that the entrained water within the aggregate provided a buffer for the concrete from the detrimental effects of spec-curing in comparison to moist curing. It was previously found that the aggregate would not perform as a traditional internal curing agent due to unfavourable desorption behaviour, however the entrained moisture could still provide some moisture to alleviate the negative effects of drying past the point of initial hydration.

5.2.3 Splitting Tensile Strength

Figure 5.23 exhibits the splitting tensile strengths measured for the mixtures being compared at ages of 28 days and 91days.

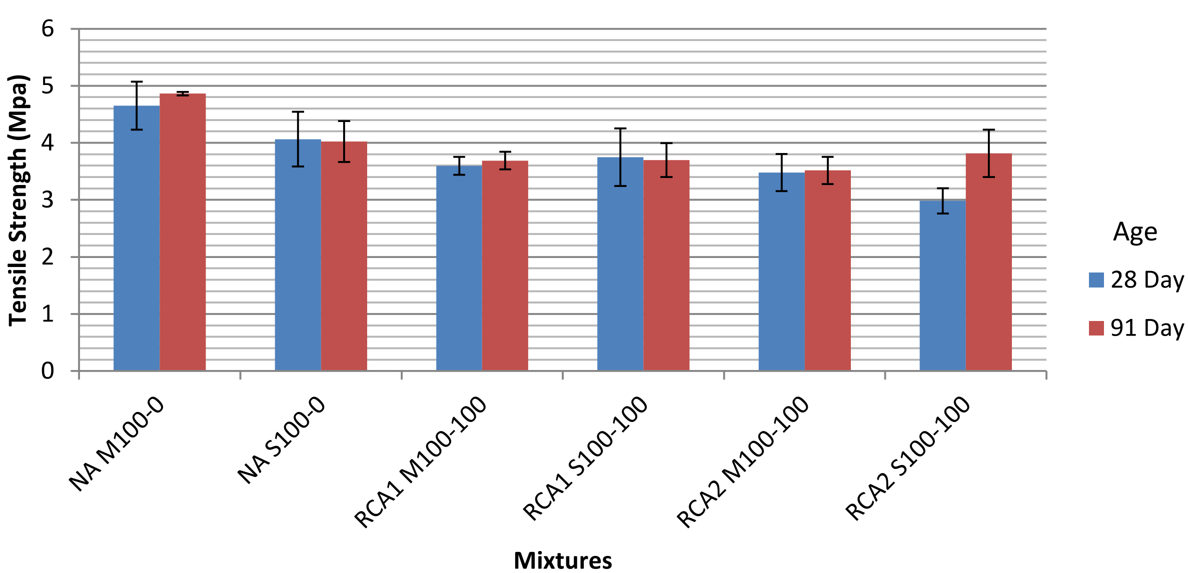


Figure 5.24: Tensile strength development for curing comparison

Table 5-9: Statistical Comparison of Tensile Strength at 28 and 91 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Tens Strength (MPa) (28 day)	4.6	4.1	3.6	3.7	3.5	3.0
STD DEV (MPa)	0.4	0.5	0.2	0.5	0.3	0.2
COV (%)	11.8	4.8	13.5	10.0	5.5	7.4
LSD (MPa)	**1.6**		**1.3**		**1.0**	
Mean Tens Strength (MPa)(91 day)	4.9	3.6	3.7	3.7	3.5	3.8
STD DEV (MPa)	0.3	0.6	0.1	0.2	0.2	0.4
COV (%)	16.8	4.7	6.6	11.1	11.1	5.5
LSD (MPa)	**1.7**		**0.7**		**1.2**	

None of the differences in tensile strength due to differences in curing regime were found to be statistically significant.

The curing conditions appear to have the greatest effect on the NA mixtures. Under the spec-curing conditions, the NA mixture exhibits an average drop of 17% in tensile strength. The spec-cured NA samples behaved similarly to the RCA samples exposed to either curing regime.

The RCA mixtures did not exhibit a similar drop in tensile strength with spec-curing, but this should not necessarily be attributed to any benefit of entrained moisture as 0% saturation RCA mixtures exhibited similar tensile strengths (Section 4.2.2.3).

It appears as though the magnitude of tensile strength loss associated with spec-curing is similar to that of RCA use. These losses do not appear to be cumulative as spec-cured RCA mixtures are not appreciably lower than moist-cured RCA mixtures.

5.2.4 Modulus of Elasticity

Figure 5.25 shows the elastic moduli associated with the mixtures being studied and Table 5-10 summarizes the statistical evaluation of the effects of curing regime on elastic modulus at 28 and 91 days.

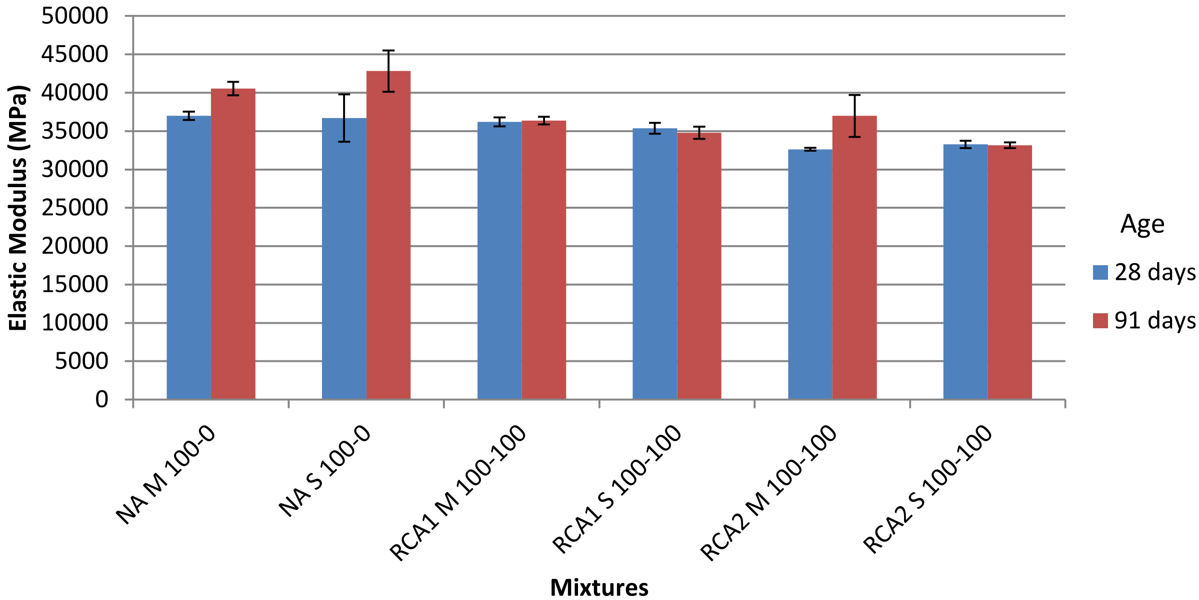


Figure 5.25: Elastic modulus development for curing comparison

Table 5-10: Statistical Comparison of Elastic Modulus at 28 and 91 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean MOE (MPa) (28 day)	37003	36707	36195	35365	32625	33261
STD DEV (MPa)	531	3082	570	722	200	467
COV (%)	1.4	8.4	1.6	2.0	0.6	1.4
LSD (MPa)	**7729**		**2275**		**1255**	
Mean MOE (MPa) (91 day)	40533	42820	36352	34793	36985	33166
STD DEV (MPa)	881	2705	498	792	2732	369
COV (%)	2.2	6.3	1.4	2.3	7.4	1.1
LSD (MPa)	**7031**		**2311**		**6813**	

The NA mixtures exhibited different behaviour than the RCA mixtures across the scope of this test. At the 28 day test, the curing regime appeared to have little influence on the elastic modulus of the samples. Within each aggregate type, the elastic moduli of each curing regime were not statistically different from one another at 95% confidence.

At 91 days of age, the elastic moduli were seen to increase for the NA mixture under both curing regimes. While this increase appeared to be more pronounced in spec-cured samples, the difference between the two was not statistically significant at 95% confidence. The moist-cured samples for both RCA types exhibited higher elastic moduli than the corresponding spec-cured samples however neither exhibited a statistically significant difference between the two.

Based on these results it does not appear as though the inclusion of saturated RCA in concrete exposed to specified curing conditions has a significant impact on the elastic modulus of said concrete as it behaves similarly to NA concrete under the same conditions.

5.2.5 Linear Coefficient of Thermal Expansion

Figure 5.26 illustrates the LCTE for the mixtures being studied at ages of 28 and 150 days. Unlike the previously discussed tests, the moist-cured samples were exposed to the same conditions as the spec-cured samples after the 28 day test. This was done in order to mitigate the effects of moisture on the samples by allowing the two types to equalize under the same conditions prior to final testing. The error bars on this plot represent one standard deviation in both the negative and positive direction in order to illustrate the spread of the data that was collected. Table 5-11 summarizes the statistical evaluation of the effects of curing regime on the RCA concretes at 28 and 150 days.

At the initial testing age of 28 days, the results of this test were variable. Generally the RCA mixtures exhibited higher variability within their results than the NA mixtures, as shown by the higher coefficients of variation. For each aggregate type, there was no statistical difference between the moist-cured and spec-cured mixtures' results.

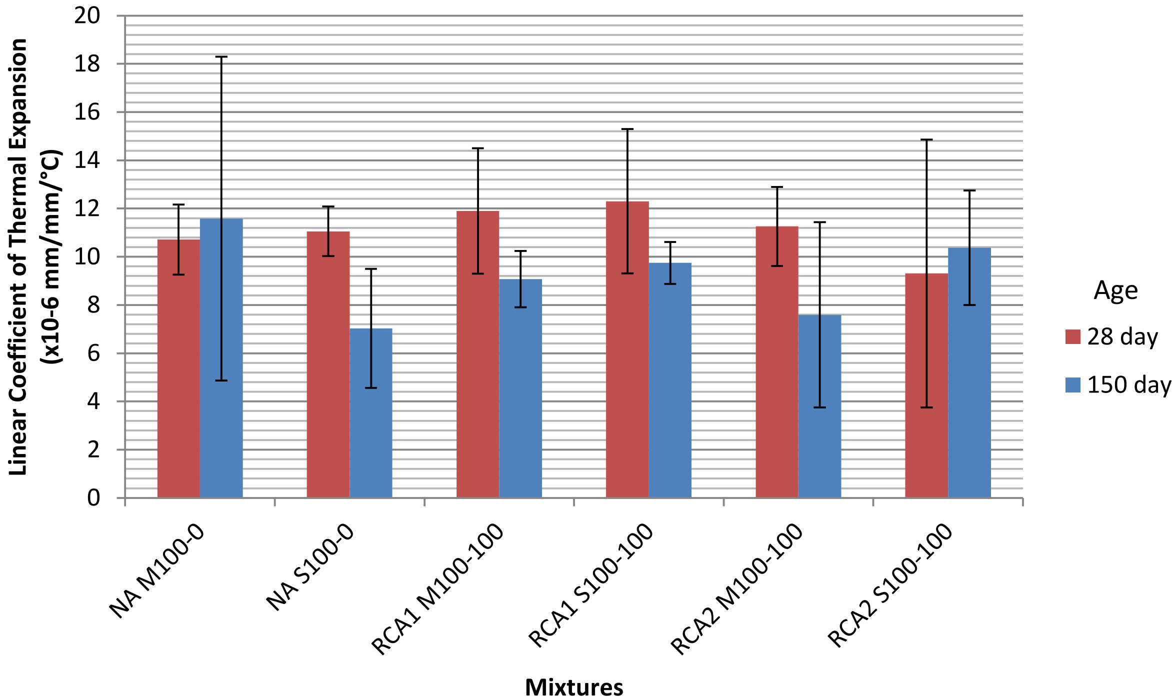


Figure 5.26: LCTE development for curing comparison

Table 5-11: Statistical Comparison of LCTE Values at 28 and 150 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean LCTE ($x10^{-6}$/°C) (28 day)	10.7	11.1	11.9	12.3	11.3	9.3
STD DEV($x10^{-6}$/°C	1.5	1.0	2.6	3.0	1.6	5.6
COV (%)	13.5	9.3	21.9	24.3	14.5	59.7
LSD ($x10^{-6}$/°C)	**1.3**		**2.9**		**4.2**	
Mean LCTE ($x10^{-6}$/°C) (150 day)	11.6	7.0	9.1	9.7	7.6	10.4
STD DEV($x10^{-6}$/°C	6.7	2.5	1.2	0.9	3.8	2.4
COV (%)	57.9	35.1	12.8	8.9	50.6	22.9
LSD ($x10^{-6}$/°C)	**5.2**		**1.1**		**3.3**	

When the effects of moisture content are accounted for in the 150 day test, the spec-cured RCA concretes appear to exhibit higher thermal expansion values than their associated moist-cured samples. Alternately, the spec-cured NA samples exhibit a lower thermal expansion. Due to the variation within the results however, these differences are not statistically significant at 95% confidence.

5.2.6 Total Permeable Porosity and Absorbed Water

Figure 5.27 shows the permeable porosities for each of the mixture types tested. The results are displayed for the tests at 28 and 91 days concrete age. Table 5-12 summarizes the statistical analysis of the effects of curing regime on permeable porosity of RCA concrete at 28 and 91 days.

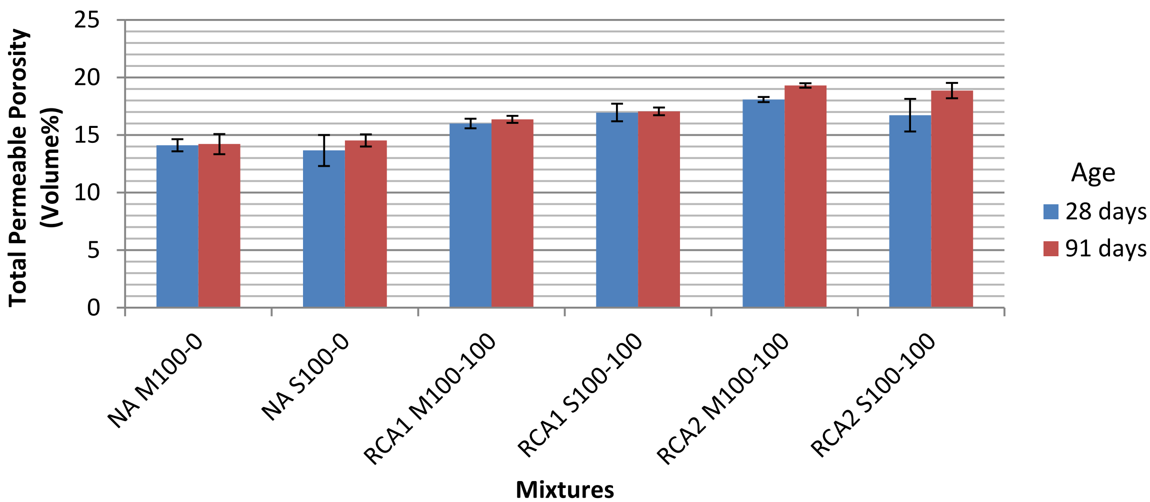


Figure 5.27: Total permeable porosity development for curing comparison

RCA2, which had a higher absorption capacity than RCA1, had reduced average permeable porosity under the spec-cured condition as compared to the moist cured condition. However, similar to the previous tests, the differences observed between the curing regimes at the same age were not statistically significant to 95% confidence. Some minor variations were observed, however the curing regime did not appear to have a large effect on the total permeable porosity on any of the concrete types.

Table 5-12: Statistical Comparison of Permeable Porosity Values at 28 and 91 days (Curing)

	NA M100-0	NA S100-0	RCA1 M100-100	RCA1 S100-100	RCA2 M100-100	RCA2 S100-100
Mean Permeable Porosity (28 day) (%)	14.1	13.7	16.0	17.0	18.1	16.7
STD DEV (%)	0.4	1.1	0.3	0.6	0.2	1.2
COV (%)	3.0	8.0	2.1	3.7	1.0	6.9
LSD (%)	**2.9**		**1.8**		**2.9**	
Mean Permeable Porosity (91 day) (%)	14.2	14.5	16.4	17.1	19.3	18.9
STD DEV (%)	0.7	0.4	0.3	0.3	0.2	0.5
COV (%)	5.1	2.9	1.5	1.6	0.8	2.8
LSD (%)	**2.1**		**0.9**		**1.4**	

Figure 5.28 and Figure 5.29 illustrate the water absorbed into the specimens, represented as a percentage of the overall dry sample mass, at ages of 28 and 91 days, respectively.

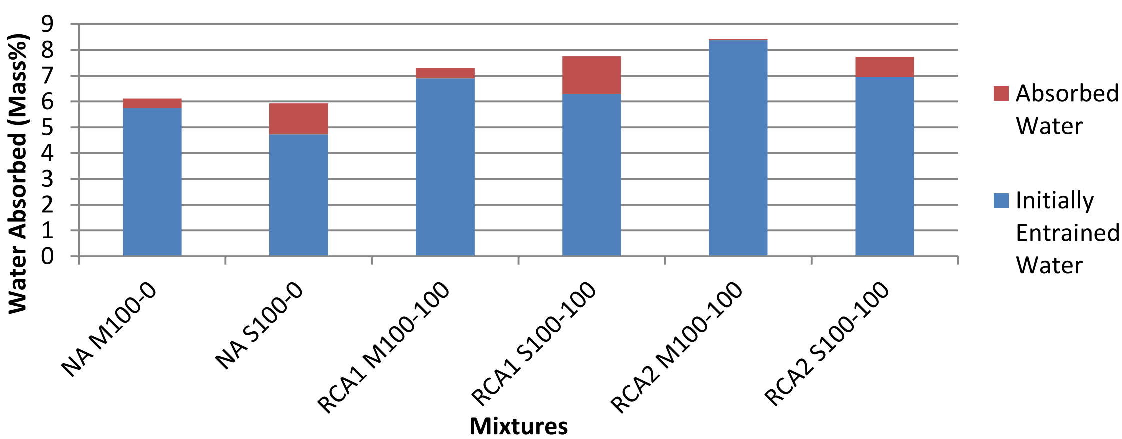


Figure 5.28: Absorbed and entrained water percentages for curing comparison (28 days)

The total absorbed water values are not statistically different, which is similar to the permeable porosity results. However, the variation in overall sample saturation can be seen when comparing the two plots. All moist-cured samples at both 28 and 91 days of age exhibit near-full saturation of the total permeable porosity while a moisture loss can be seen in the spec-cured samples. The magnitude of this moisture loss increases as the samples are left exposed for the additional 63 days between tests, which is intuitive. These results correlate with the densities shown in Figure 5.21 and confirm that observed density losses are largely due to moisture loss.

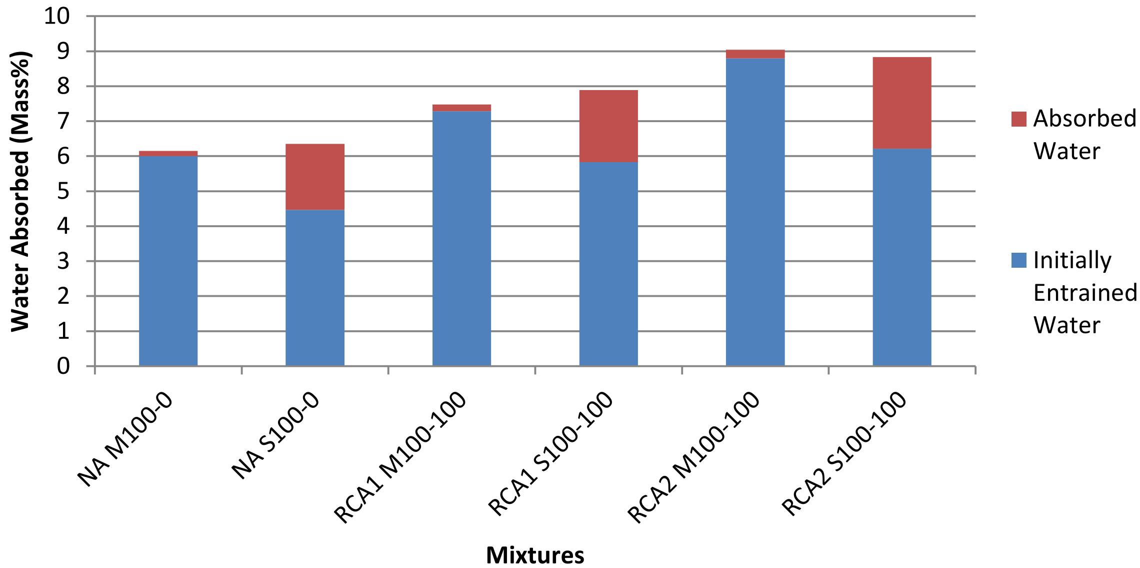


Figure 5.29: Absorbed and entrained water percentages for curing comparison (91 days)

At 28 days both RCA concrete types retain a higher moisture percentage under spec-curing conditions than the NA mixture does under moist-curing. At 91 days, the entrained water for these three types is about equal. This shows the high level of moisture present in the fully saturated RCA concrete types even at later ages of exposed curing.

Neither curing regime appears to affect the durability of concrete in terms of the permeable porosity of the mixtures.

5.2.7 Conclusions

The following list summarizes the conclusions made regarding the effects of saturated RCA in concrete subjected to spec-curing conditions:

- RCA1 was found to retain proportionately more moisture under spec-curing conditions than other two aggregate types, which could potentially provide benefit, but also may pose freeze thaw durability issues if the level of saturation is at or above 91% for a long period of time. The level of RCA saturation within concrete should be investigated as it could affect the cold weather durability of RCA concretes.
- The entrained moisture in both RCA mixtures had different compressive strength gain benefits under spec-curing conditions. RCA2 extended the period of initial strength gain

while RCA 1 improved the later age strength of the mixtures. These benefits coincide with the previously discussed findings that RCA1 retains moisture for longer time periods than RCA2. The NA samples exposed to spec-curing conditions exhibited lower compressive strength than their corresponding moist-cured samples and the difference in strength between the samples of the two curing regimes continued to grow until the end of testing. The benefits observed in the concretes produced with either RCA type were not observed in the NA samples. This indicates that concretes produced with saturated RCA have benefits in concrete applications with the potential for air drying after short periods of curing. This increases the value of RCA as a material for use in concrete production.

- Spec-curing affects the tensile strength of NA mixtures, but did not affect 100% saturated RCA mixtures significantly. The tensile strength of RCA mixtures under both curing conditions were statistically the same and were similar to the tensile strength of spec-cured NA samples. This indicates that concrete applications that typically undergo spec-curing would not have significantly worse tensile strength properties with 100% replacement of NA with saturated RCA. This is significant because tensile strength loss is often considered to be a problem associated with RCA concrete.
- 100% saturation of RCA under spec-curing conditions does not appear to provide significant benefit or detriment to the elastic moduli or thermal expansion values of concrete as compared to NA mixtures. Again, this is significant to the potential use of RCA in typically spec-cured concrete applications.
- Entrainment of fully saturated coarse RCA did not appear to affect the durability performance of poorly cured concrete in terms of total permeable porosity and absorbed water percent. At both testing ages, no statistically significant differences in permeable porosity or absorbed water were observed between curing regimes for any aggregate type. RCA concretes had higher total permeable porosity and absorbed water than NA concretes. These increases were probably largely due to the cut faces that exposed the porous RCA and thereby increased the permeable porosity of the samples. This affects the permeable porosity, but not necessarily the overall transport properties of the concrete as the exposed RCA are non-continuous pores within the concrete.

Saturated RCA concrete was found to retain moisture longer than NA concrete under specified curing conditions. This was seen to provide some buffer against the negative effects of spec-curing on compressive strength gain, but no statistically significant benefits in terms of the other tested properties. No detrimental effects of fully saturated RCA in spec-curing conditions were observed. The freeze-thaw durability of saturated RCA concrete may be compromised by the high levels of retained water, though this requires further study.

The required performance of an RCA concrete may dictate the proper RCA saturation level. While 100% saturation of aggregate appears to provide the most compressive strength benefit, it appears to have negative effects on thermal expansion initially. This may be due to the effects of the high water content that is maintained around the saturated coarse aggregate. Later age testing indicates that these negative effects are not permanent. A 60% saturation results in concrete with lower thermal expansion and lower modulus of elasticity, which could reduce thermal stresses in certain applications.

5.3 Acceptable RCA Level Comparisons

A corollary study was to gauge the effects of RCA saturation on concrete properties when the RCA replaces 30% by volume of the natural aggregate. Previous studies have found this level of replacement to have acceptably small effects on concrete properties while still replacing a significant proportion of the natural aggregate. Results of previously discussed objectives will be compared. Figure 5.30 presents the key questions to be answered based on the acceptable level testing regime.

For the purposes of comparison, NA and RCA were soaked for different lengths of time to achieve the same specified saturation levels, according to their varying absorption rates, which are discussed in Section 4.1.3. A 60% saturated NA mixture was not batched for testing, and therefore the 60% saturated mixtures are only discussed where relevant. All samples were subjected to the specified curing regime that included 7 days curing under moist burlap followed by exposure to drying in the lab environment (~50% RH).

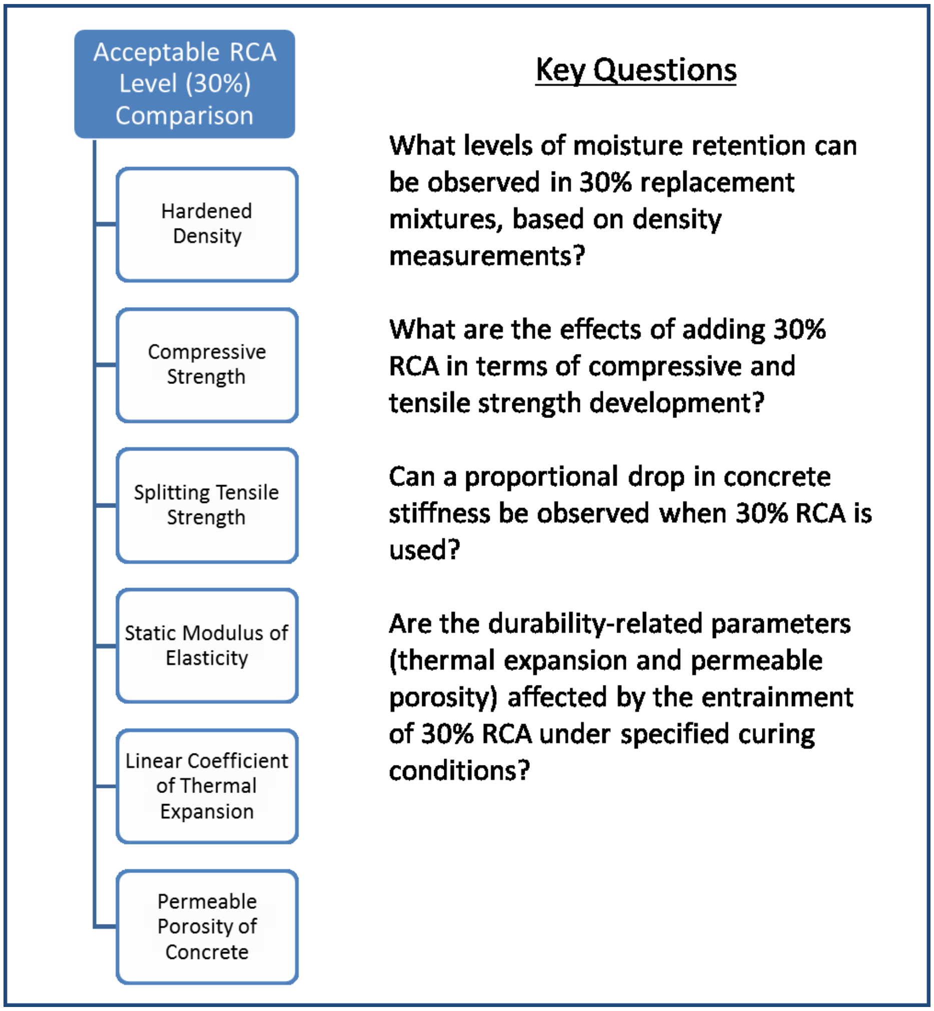


Figure 5.30: Key questions regarding 30% RCA replacement

5.3.1 Hardened Density

Figure 5.31 shows the hardened densities of all 30% replacement mixtures alongside the NA mixtures corresponding by aggregate saturation level. The initial density for each mixture at zero days is the fresh density, which is provided for reference. Table 5-13 tabulates the statistical analysis of the hardened density values as they pertain to the 30% replacement of NA with RCA.

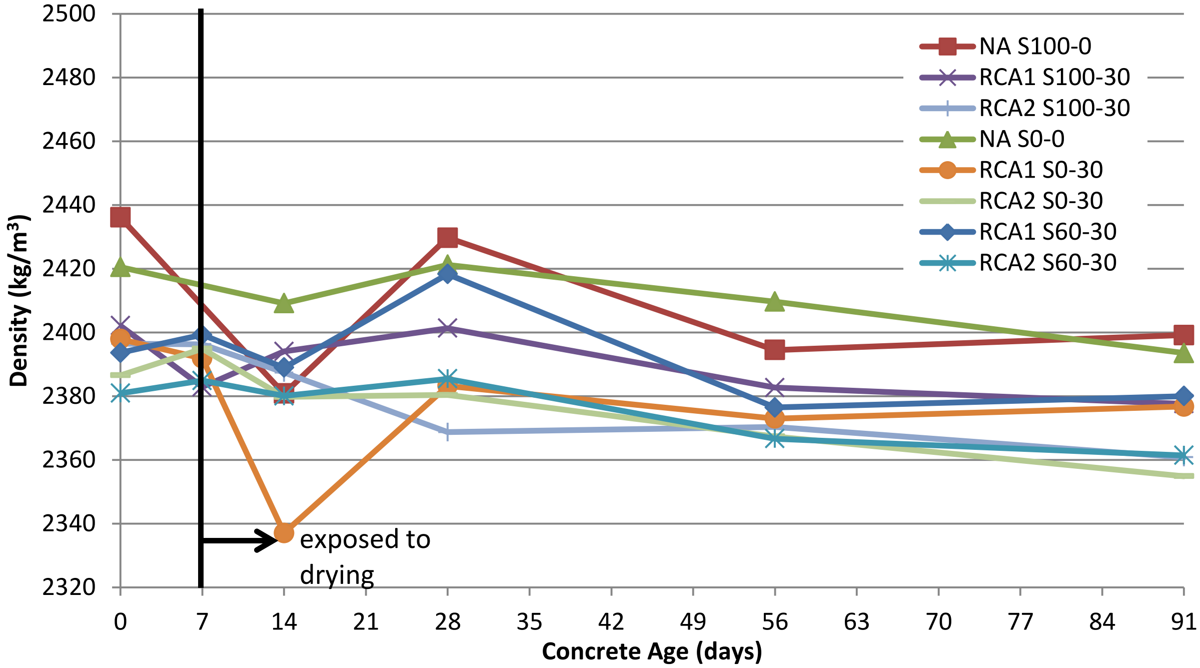


Figure 5.31: Hardened density for acceptable replacement level comparison

The figure shows that the mixtures behave as three separate groups in terms of hardened density by the 91 day age. These groups correlate to the aggregate types, which had three different densities. RCA2 had the lowest aggregate density and therefore RCA2 concretes displayed the lowest overall density. At 91 days, the overall average difference in density between NA and RCA2 mixtures is 39 kg/m^3, or about 2% of the NA concrete's density.

Table 5-13: Statistical Comparison of Hardened Density at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean Density (kg/m^3) (28 day)	2429.7	2401.3	2368.7	2421.2	2383.2	2380.4
STD DEV (kg/m^3)	12.3	9.9	15.3	10.3	14.9	9.0
COV (%)	0.5	0.4	0.6	0.4	0.6	0.4
LSD (kg/m^3)	**49.0**			**45.2**		
Mean Density (kg/m^3) (91 day)	2399.1	2377.6	2360.8	2393.5	2376.7	2354.8
STD DEV (kg/m^3)	9.3	5.3	4.4	6.4	6.8	12.3
COV (%)	0.4	0.2	0.2	0.3	0.3	0.5
LSD (kg/m^3)	**25.9**			**34.6**		

Within either aggregate saturation grouping, the hardened density of the RCA1 and NA mixtures are not statistically distinct at 28 or 91 days. At 100% saturation, the RCA2 mixture is statistically distinct from the NA mixture at both testing ages indicating that the majority of its moisture loss occurs at early ages. Between the ages of 28 and 91 days, the density of the 0% saturated RCA2 mixture becomes statistically different than that of the NA mixture. While both the 0% and 100% saturated mixtures lose approximately the same amount of moisture, full initial saturation of the RCA2 had the effect of accelerating this moisture loss.

On average, the NA mixtures lost about 32 kg/m^3 over the 91 days in comparison to 20 kg/m^3 and 29 kg/m^3 for the RCA1 and RCA2 mixtures, respectively. Considering the average initial water contents of each concrete mixture, these values correspond to 16.2%, 9.5%, and 14.2% of the initial water content, respectively. This further confirms that RCA1 concretes appear to retain more of the initially entrained water within the concrete at later ages.

5.3.2 Compressive Strength

Figure 5.32 illustrates the compressive strength development for the 30% replacement mixtures as well as for their corresponding NA mixtures, if applicable. Table 5-14 summarizes the statistical evaluation of the compressive strength for 30% replacement at 28 and 91 days.

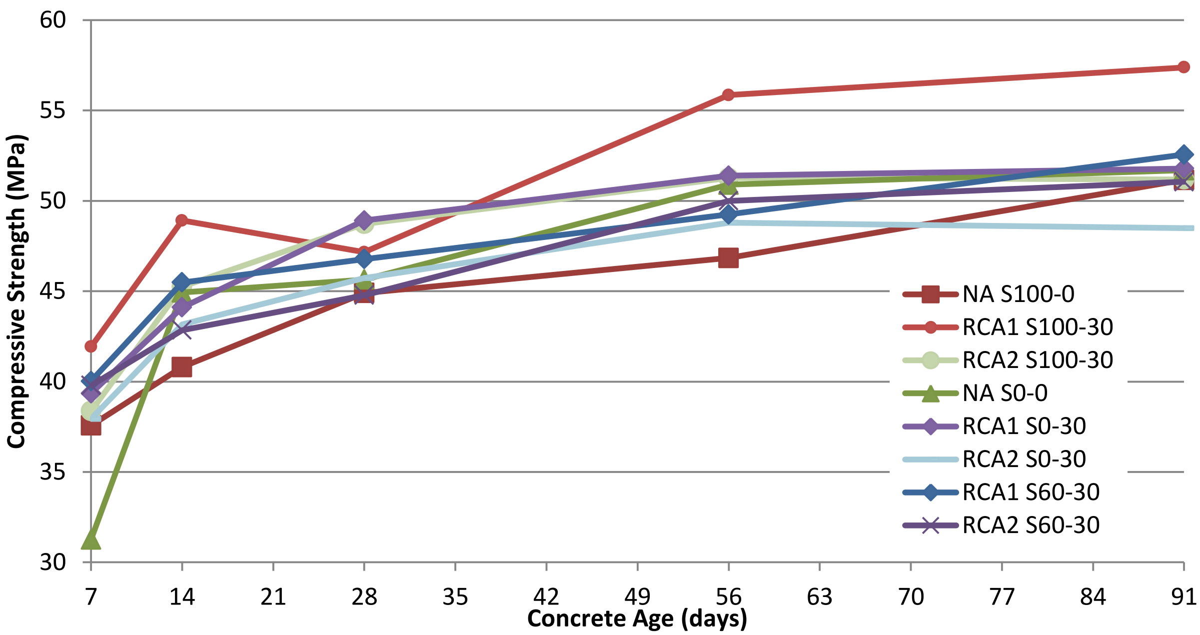


Figure 5.32: Compressive strength development for acceptable replacement level comparison

Table 5-14: Statistical Comparison of Compressive Strength at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean Comp. Strength (MPa) (28 day)	44.9	47.2	48.7	45.6	48.9	45.7
STD DEV (MPa)	0.1	0.4	0.3	1.6	1.2	1.9
COV (%)	0.3	0.9	0.6	3.4	2.5	4.2
LSD (MPa)	**1.1**			**6.1**		
Mean Comp. Strength (MPa) (91 day)	51.2	57.4	51.2	51.7	51.8	48.5
STD DEV (MPa)	0.6	0.6	0.5	1.2	1.8	1.0
COV (%)	1.1	1.0	0.9	2.4	3.4	2.0
LSD (MPa)	**2.0**			**5.3**		

Under specified curing conditions replacing 30% of the NA in a given concrete with RCA, of good or poor quality, results in only minor variations in compressive strength. At 28 days, both of the 100% saturated RCA mixtures had significantly higher compressive strength than the corresponding NA mixture. None of the 0% saturated mixtures were statistically distinct. At 91 days, the only 30% replacement mixture that was significantly different than the NA mixtures was the fully saturated RCA1. This mixture exhibited compressive strength higher than its corresponding NA mixture. These findings are similar to those previously discussed, which were that fully saturated RCA1 produced higher overall compressive strengths while fully saturated RCA2 provided early age strength gain benefits.

The 7 day results of the unsaturated NA mixture were the lowest of all mixtures, but after that test the mixtures excluding RCA1 S100-30 exhibited compressive strengths within 5 MPa of the NA control mixtures. This plot shows that the overall compressive strengths as well as the rates of compressive strength gain were similar for most mixtures.

Figure 5.33 illustrates the compressive strength of the 30% RCA mixtures relative to the compressive strength of the corresponding saturation NA mixtures. The horizontal line on the plot represents the line of equivalency between the two mixtures.

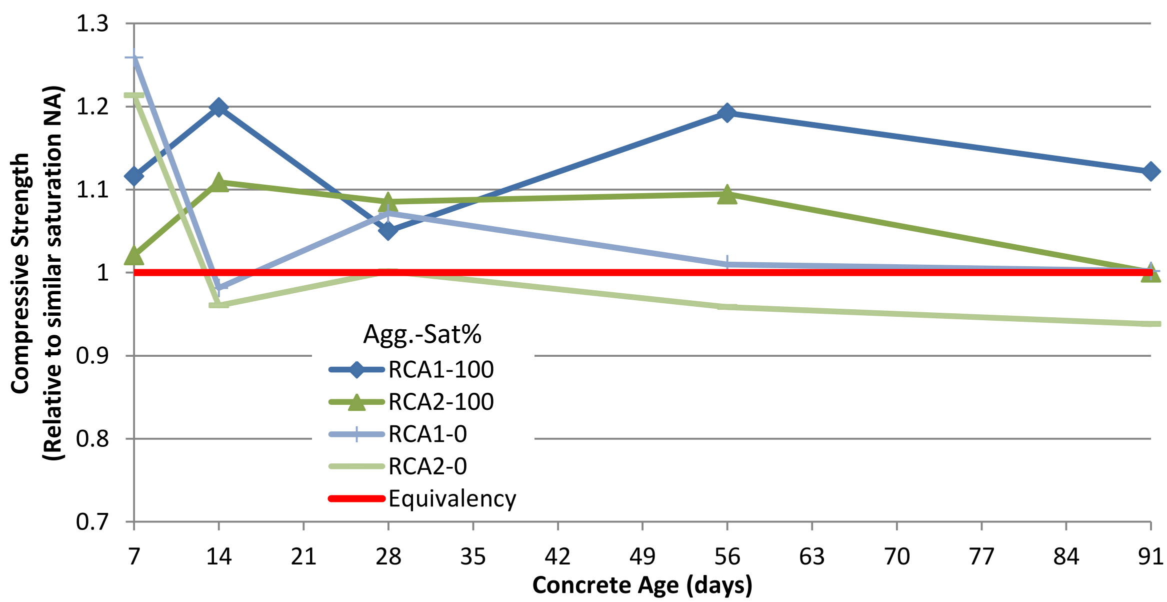


Figure 5.33: Compressive strength of 30% RCA mixtures relative to NA mixtures

This figure shows the effects of a 30% RCA replacement on the compressive strength of concrete. At most ages, the strength of RCA1 and RCA3 mixtures are higher than or approximately equal to the NA mixtures. At 91 days, the unsaturated RCA2 mixture exhibits the lowest relative point, with 6% reduction in compressive strength. This appears to indicate that the compressive strength of concrete is not unduly compromised by adding 30% RCA under these conditions. Even a poor quality RCA such as RCA2 under spec-curing conditions resulted in only a 6% loss in compressive strength, which was not statistically significant.

5.3.3 Splitting Tensile Strength

Figure 5.34 presents the splitting tensile strengths of the RCA mixtures relative to those of the NA mixtures, which were prepared to the same coarse aggregate saturation levels. Each mixture was tested at 28 and 91 days and this corresponds to the two points for each mixture type. The horizontal line on the plot represents the line of equivalency between the mixtures being compared. Table 5-15 summarizes the statistical evaluation of the tensile strengths for the 30% replacement mixtures at 28 and 91 days.

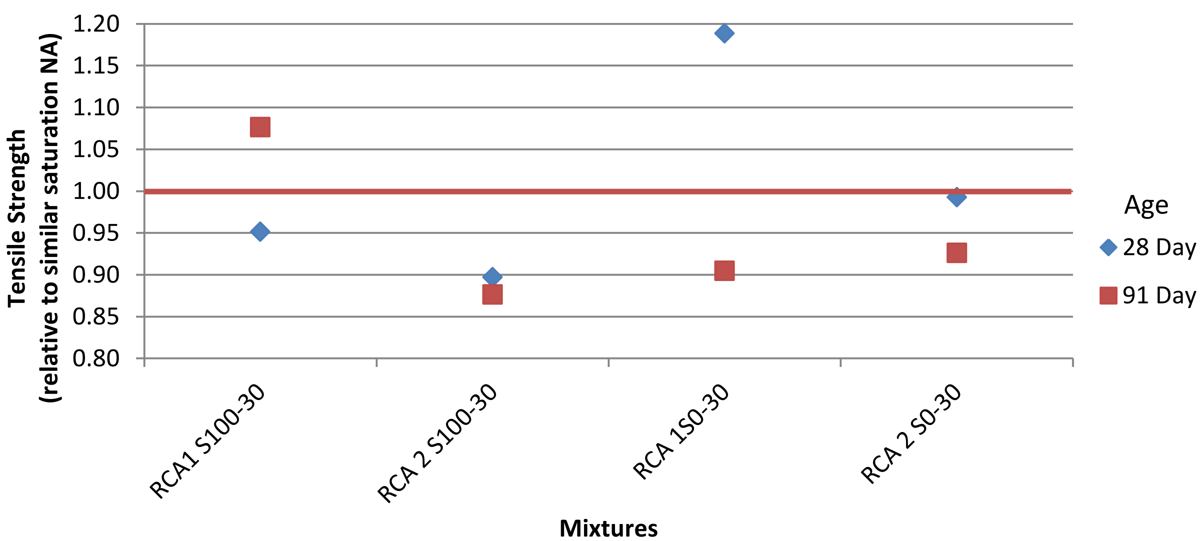


Figure 5.34: Relative tensile strength for acceptable replacement level comparison

Table 5-15: Statistical Comparison of Tensile Strength at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean Tens. Strength (MPa) (28 day)	4.1	3.9	3.6	3.6	4.3	3.6
STD DEV (MPa)	0.5	0.3	0.2	0.2	0.6	0.1
COV (%)	11.8	7.4	5.6	4.8	13.1	3.7
LSD (MPa)	**1.3**			**1.4**		
Mean Tens. Strength (MPa) (91 day)	3.6	4.3	3.5	4.3	3.9	4.0
STD DEV (MPa)	0.6	0.2	0.4	0.2	0.1	0.6
COV (%)	16.8	5.5	10.2	4.7	2.8	14.4
LSD (MPa)	**1.7**			**1.4**		

This figure shows that the effects of RCA replacement on tensile strength are more severe and less predictable than the effects on compressive strength. A wide range of results is observed in the coefficients of variation, which are not consistently high for a given aggregate type or saturation level. Generally the tensile strengths of the 30% replacement mixtures were less than those of the NA mixtures. The magnitude of this reduction varied, but went as high 12%. Based on the test results however, none of the changes in tensile strength are statistically significant at 95% confidence. This is due to the relatively high coefficients of variation, which can be seen within the results. These indicate that the splitting tensile test produces results that vary significantly. It is recommended that further testing with more samples be conducted in order to produce more statistically significant results.

The RCA1 mixtures exhibited higher tensile strength at different ages, depending on the aggregate saturation. Due to the nature of the splitting tensile strength test, which can yield high variation of results, it is assumed that these increases in tensile strength are outliers in the data. This assumption is reinforced by the lower tensile strength for the same mixture at different ages as well as the general trend of lower tensile strength in RCA mixtures.

5.3.4 Modulus of Elasticity

Figure 5.35 shows the elastic modulus of the various 30% replacement mixtures relative to those of the NA mixtures with similar coarse aggregate saturations. The horizontal line at the top of the plot indicates equivalency between the results being compared. Table 5-16 summarizes the statistical evaluation of the 30% replacement mixtures at 28 and 91 days.

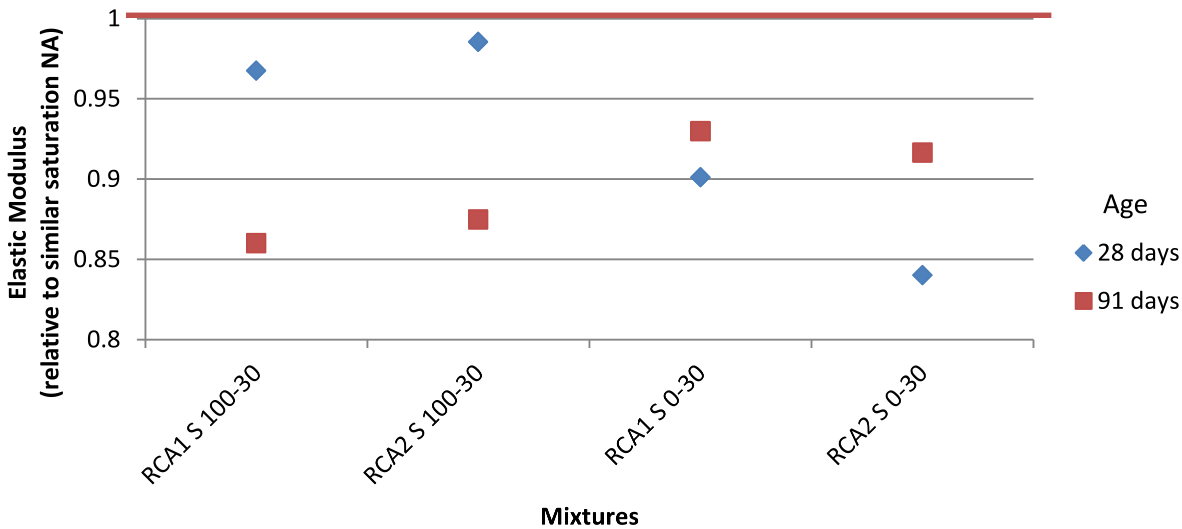


Figure 5.35: Relative elastic modulus for acceptable replacement level comparison

Table 5-16: Statistical Comparison of Elastic Modulus at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean MOE (MPa) (28 day)	36707	35513	36176	39755	35824	33401
STD DEV (MPa)	3082	870	1155	691	490	96
COV (%)	8.4	2.4	3.2	1.7	1.4	0.3
LSD (MPa)	**7593**			**1901**		
Mean MOE (MPa) (91 day)	42820	40270	36829	37850	37441	37456
STD DEV (MPa)	2705	668	524	548	416	328
COV (%)	6.3	1.7	1.4	1.4	1.1	0.9
LSD (MPa)	**6187**			**2496**		

None of the 30% RCA mixtures exhibited elastic moduli as high as their corresponding control NA mixtures. Each result exhibited a decrease in elastic modulus of between about 2% and 15%.

Opposite trends were observed between the 0% and 100% saturated concretes. The 0% saturated RCA concretes gained relative stiffness between the ages of 28 and 91 days. Over this period the stiffness of the control mixture remained relatively constant and these relative gains can be attributed to changes in the RCA mixtures. At 28 days, each 0% saturated mixture is statistically distinct however this statistical difference is no longer evident at 91 days.

Oppositely, the 100% saturated RCA mixtures displayed a drop in relative stiffness over this time period. The control concrete experienced a 33% increase in elastic modulus over this time period while the replacement mixtures experienced smaller increases. All concretes experienced increases in elastic modulus during this time period; however the fully saturated NA mixture showed the largest increase. The three aggregate types are not statistically different at either age, indicating that with saturated RCA, a 30% replacement should not significantly affect the stiffness of the concrete.

5.3.5 Linear Coefficient of Thermal Expansion

Figure 5.36 shows the results of the thermal expansion testing at 28 and 150 days. The error bars shown on each result indicate one standard deviation in either direction in order to illustrate the variability of the results.

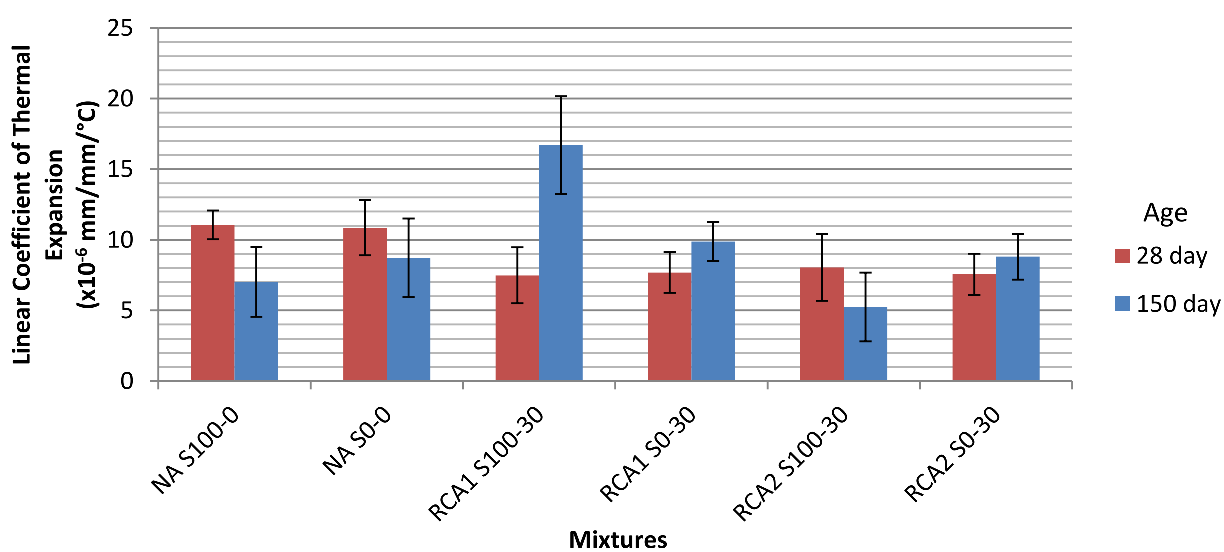


Figure 5.36: LCTE development for acceptable replacement level comparison

Table 5-17: Statistical Comparison of LCTE Values at 28 and 150 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean LCTE ($x10^{-6}/°C$) (28 day)	11.1	7.5	8.0	10.9	7.7	7.6
STD DEV($x10^{-6}/°C$)	1.0	2.0	2.4	2.0	1.4	1.5
COV (%)	9.3%	26.5%	29.3%	18.0%	18.7%	19.4%
LSD ($x10^{-6}/°C$)	**2.2**			**2.0**		
Mean LCTE ($x10^{-6}/°C$) (150 day)	7.0	16.7	5.2	8.7	9.9	8.8
STD DEV($x10^{-6}/°C$)	2.5	3.5	2.4	2.8	1.4	1.6
COV (%)	35.1%	20.8%	46.5%	32.0%	13.9%	18.4%
LSD ($x10^{-6}/°C$)	**3.4**			**2.4**		

At the initial testing at the age of 28 days, the replacement of 30% RCA appears to lower the thermal expansion of the concrete at low temperatures. Based on the gathered data, the thermal expansions of both the 100% saturated and 0% saturated RCA mixtures were significantly lower than those of their corresponding NA mixtures at 95% confidence. This appears to indicate that the inclusion of 30% RCA can have a beneficial effect on the thermal expansion of concrete at low temperatures.

The results of testing at 150 days are also included in Figure 5.36. As previously discussed the results of this round of testing are questionable due to changes in the environmental conditions of the testing laboratory. At this concrete age, the only result that was found to be statistically unique in the given comparisons was that of RCA1 S100-30, which appeared to display thermal expansion much larger than any of the other mixture types. With the exception of this mixture, it appears that the inclusion of 30% RCA in concrete does not result in significant changes to the thermal expansion properties at later ages.

5.3.6 Total Permeable Porosity and Absorbed Water

Figure 5.37 presents the total permeable porosities of the concrete mixtures being studied. The results for each mixture are shown at ages of 28 and 91 days. The error bars represent one standard deviation in either direction of the average results. Table 5-18 summarizes the statistical analysis of the effects of 30% replacement of aggregate at 28 and 91 days.

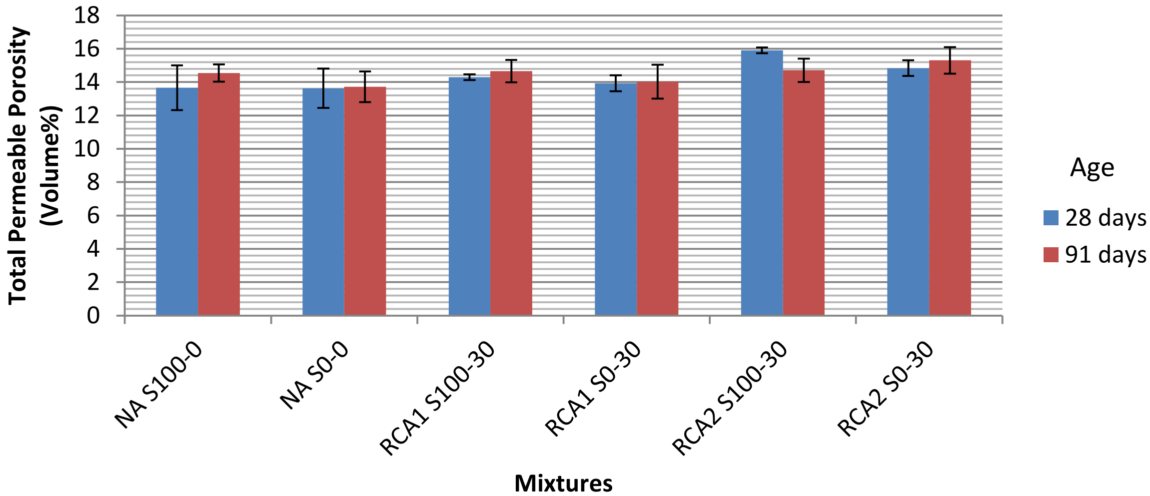


Figure 5.37: Total permeable porosity development for acceptable replacement level comparison

Table 5-18: Statistical Comparison of Permeable Porosity at 28 and 91 days (30% Replacement)

	NA S100-0	RCA1 S100-30	RCA2 S100-30	NA S0-0	RCA1 S0-30	RCA2 S0-30
Mean Permeable Porosity (28 day) (%)	13.7	14.3	15.9	13.6	13.9	14.8
STD DEV (%)	1.1	0.1	0.1	1.0	0.4	0.4
COV (%)	8.0	1.0	0.9	7.1	2.8	2.6
LSD (%)	**2.5**			**2.5**		
Mean Permeable Porosity (91 day) (%)	14.5	14.7	14.7	13.7	14.0	15.3
STD DEV (%)	0.4	0.5	0.6	0.7	0.8	0.7
COV (%)	2.9	3.7	3.9	5.4	5.9	4.3
LSD (%)	**2.0**			**2.9**		

At both ages, there was found to be no statistically significant difference at 95% confidence between the 30% RCA mixtures and their corresponding control mixture. Small increases on the order of approximately 1-2% were observed, however based on the testing procedure used these differences were not significant.

These results show that at this small level of aggregate replacement, the use of RCA is not greatly detrimental to durability properties of concrete in terms of permeable porosity.

Figure 5.38 shows the water absorptions of the concrete mixtures as measured at ages of 28 and 91 days. The figure illustrates the total water within the samples as a sum of the initially entrained water and the additional water absorbed during the testing procedure.

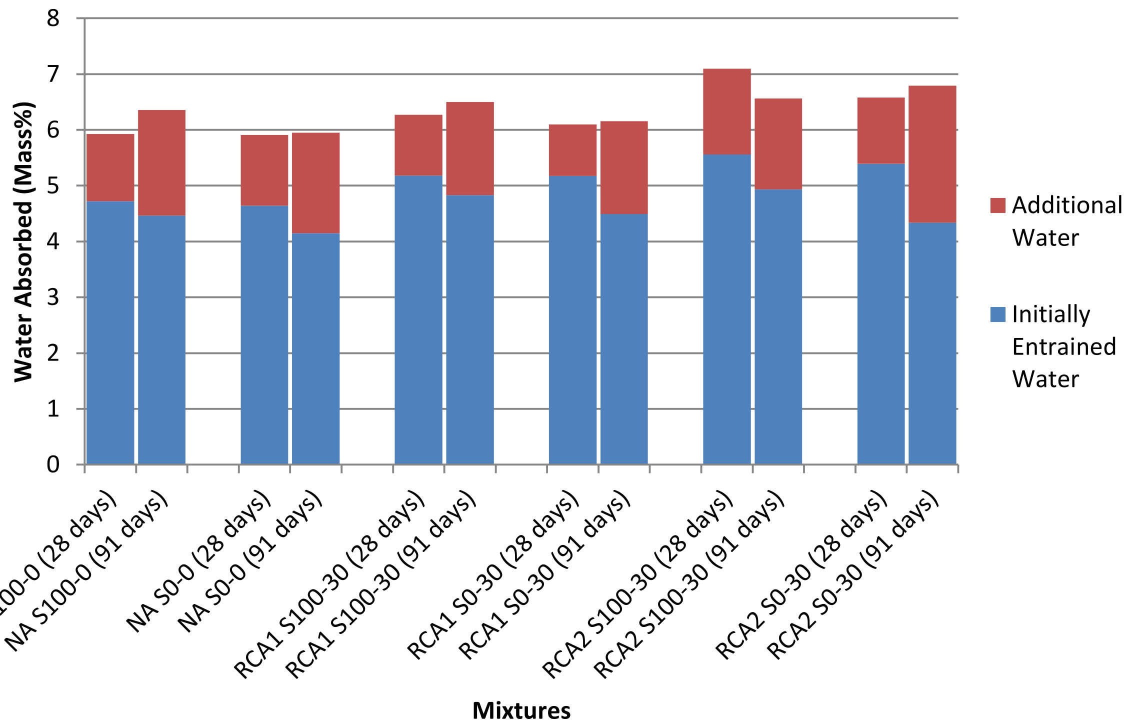


Figure 5.38: Absorbed and entrained water for acceptable replacement level comparison

The 30% replacement of NA with RCA in concrete results in increases in the water absorbed. The magnitude of this increase seems to be influenced by the absorptive capacity of the RCA. The natural aggregate was found to have an absorptive capacity of 1.53%. When RCA1, which had an absorptive capacity of 4.72%, was used in the mixtures, a small average increase in the concrete water absorption of approximately 0.25% was observed. When the more absorptive RCA2 (6.91%) was used in the mixtures, a 0.75% average increase in absorbed water was observed. This is intuitive and indicates that the use of a more absorptive coarse aggregate will result in a proportionately higher water absorption in the concrete. At the 30% replacement level the overall impact of high-absorption RCA is reduced, but could be a factor depending on the concrete application.

The entrained water within the mixtures appears to be quite similar for the replacement and control mixtures for a given aggregate saturation level at both concrete ages. All of the 0% saturated mixtures lost a higher percentage of the entrained water than their corresponding 100% saturated mixture between the ages of 28 and 91 days.

5.3.7 Conclusions

The following list summarizes the findings of the study of 30% replacement of natural aggregate with recycled concrete aggregate in concrete.

- The 91 day hardened density of concrete was not statistically affected by 30% replacement with RCA1, but was reduced through the addition of RCA2. At 28 days the difference between the hardened density of NA and RCA2 concretes was affected by the initial saturation of the RCA. 100% saturated NA and RCA2 mixtures were significantly different, but 0% saturated mixtures were not. In both saturation cases, the NA mixtures were observed to lose more water than either corresponding RCA mixture. Due to this, the effects of drying may be more severe in NA concretes than in 30% RCA concretes. This presents the same potential benefits and issues discussed previously regarding the retention of water within RCA in concrete.
- The compressive strength of concrete is not unduly compromised by adding 30% RCA under the conditions studied. The addition of poor quality RCA2 under the spec-curing conditions only resulted in a 6% loss in 91 day compressive strength, which was not statistically significant at either saturation level studied. At 28 days, both of the 100% saturated RCA mixtures had significantly higher compressive strength than the corresponding NA mixture and at 91 days, the only statistically significant mixture was the fully saturated 30% RCA1, which had higher strength than either of the NA or RCA2 concrete mixtures. These findings are similar to those previously discussed, which were that fully saturated RCA1 produced higher overall compressive strengths while fully saturated RCA2 provided early age strength gain benefits. These results indicate that concretes with 30% RCA that is fully saturated are not only statistically similar at late

ages, but provide early age benefits over NA concretes in terms of compressive strength gain. This indicates some significant value of RCA in some concrete applications that require quick concrete strength gains.

- 30% RCA inclusion resulted in tensile strength reductions of up to 12% in comparison to NA mixtures, though some increases due to 30% RCA inclusion in mixtures were observed. None of these changes were statistically significant. Concrete applications that require high tensile strengths do not preclude the use of 30% RCA concretes as tensile strength was not significantly affected by either RCA type.
- 30% RCA inclusion resulted in reductions in elastic modulus of between about 2% and 15%, both RCA types showed similar maximum reductions. The saturated RCA mixtures were not statistically distinct from the NA mixture at either testing age however the 0% saturated RCA mixtures were significantly lower at 28 days. While not statistically significant, E_c for 30% RCA concretes were consistently lower than the NA concretes. This difference may have implications for applications that require high E_c in concrete.
- At 28 days, the inclusion of 30% RCA of either type or saturation level into the mixtures had a significant beneficial effect on the thermal expansion properties of concrete. This could add considerable value to RCA in terms of concrete use. Low thermal expansion in concrete could be very useful in applications such as concrete pavements, which are subjected to significant temperature changes. These changes can result in high stresses when conventional restrained concrete pavements expand or retract. The magnitude and the damage caused by these stresses could be reduced by low LCTE RCA concrete.
- By 150 days age, this benefit is no longer evident. As previously discussed, this may be a reflection of different testing procedures as well as the differences in sample moisture conditions, which were necessitated by the objectives of the research.
- Marginal increases (<2%) in permeable porosity were observed in the 30% RCA mixtures when compared to the NA control mixtures. These increases were not a statistically significant level. Water absorption increased with 30% RCA replacement proportionally to the absorptive capacity of the RCA itself. The increase in water absorbed into concrete when replacing NA with a high-absorption RCA (6.91%) was 0.75%. As previously discussed, these increases associated with RCA replacement do not

necessarily represent increased transport properties as the porous RCA particles do not represent continuous pores throughout the concrete.

The suitability of 30% RCA replacement mixtures depends on the purpose for which the concrete will be used, and therefore no generalized conclusions about this method of concrete production can be made. Given this fact, the effect of 30% replacement of natural aggregate with RCA appears to be quite small for a number of concrete properties. For a given application, the pertinent performance indicators should be identified. If these include high tensile strength, high elastic modulus, and low permeable porosity, then the incorporation of RCA should be done carefully as these properties were found to be affected. If compressive strength and or thermal expansion properties govern the concrete's applicability then the use of 30% RCA could be a beneficial choice.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The major conclusions drawn from this research are outlined in the following sections:

6.1 Aggregate

- Both RCA types were comprised of approximately 40% mortar by mass.
- In comparison with the natural aggregate, both RCA1 and RCA2 exhibited higher absorptive capacities (1.53%, 4.72%, and 6.91% respectively) and lower bulk densities (1692, 1401, and 1353 kg/m^3 respectively). These results are due to the presence and relative quality of any adhered mortar in the aggregates.
- None of the three aggregate types desorbed significant amounts of entrained water at 93% RH and therefore could not be considered strong candidates for use as internal curing agents by the generally accepted guidelines.
- ACV results indicate that the aggregates listed in order of decreasing strength are: natural aggregate, RCA1, and RCA2. ACV results also indicate that both RCA types are considerably less stiff than the natural aggregate. This is due to the presence and relative strength of adhered mortar. The method by which RCA2 is produced creates a relatively weak mortar phase, which causes the lowest ACV results. Based on previous results, this could correlate to the relative tensile strengths of concretes produced using these aggregate.
- Based on currently existing MTO abrasion and absorption specifications, neither RCA1 nor RCA2 are suitable for use in concrete structures. Other researchers have found that low abrasion and absorption values in RCA do not necessarily correlate to lower concrete strength.

6.2 Fresh Properties

- The actual coarse aggregate saturation within the 60% saturated case exhibited considerable variation, which is a potential indicator of the impracticality of the timed soaking method of achieving a target saturation (excluding the fully saturated case).

- Effective water/cement ratios ranged between 0.32 and 0.37 while total water/cement ratios were between 0.39 and 0.52 for all mixtures. These results indicate that while the differences between the effective water/cement ratios of the concrete mixtures are relatively small, the total level of water in each mixture can vary significantly. This large difference in entrained water is what provides the potential for RCA to contribute value to certain concrete mixtures and applications.
- For each given replacement level the 60% saturated case exhibited the highest slump, possibly due to reduced moisture transport between coarse aggregate and cement matrix caused by aggregate coating. Aggregate coating could occur when the moisture adhered to the surface of soaked RCA comes into contact with cement in the batching procedure, producing a mortar that fully coats the RCA particle. This coating could restrict how well water could flow into the unsaturated pores of the RCA. In addition to the effects on workability, this could indicate that effective water-cement ratios are not fully accurate when considering partially saturated RCA.
- The entrapped air contents of all mixtures ranged between 1.1% and 2.1%. These values are acceptably close to the values predicted by the CAC concrete design handbook, and indicate that the addition of RCA does not significantly affect the entrapped air levels of concrete.

6.3 Hardened Properties

- All spec-cured concrete specimens were observed to gradually lose entrained moisture through drying over the course of the testing, as observed through decreasing density. This result is intuitive, and represents reasonable behaviour for concretes cured according the specifications of the MTO.
- The mixtures with 30% RCA lost less moisture than the NA mixtures, despite higher overall water contents, which indicates that the RCA may have helped to retain moisture normally lost from concrete due to drying.
- All moist-cured samples exhibited similar compressive strength-development behaviour that continued to the end of testing. The observable difference between these samples and the spec-cured samples indicate that exposure to drying of concrete after 7 days of moist

curing has a negative effect on compressive strength in relation to moist curing. This reinforces the idea that the typically specified method for concrete curing can have negative consequences and presents opportunities for the development of strategies for improved concrete performance.

- Spec-cured RCA2 samples generally reached a compressive strength plateau by the age of 56 days, but RCA1 samples appeared to experience later age compressive strength gains, which is a characteristic of some internally cured concretes. This indicates that although the RCAs do not desorb water like traditional internal curing agents, they may provide some benefit to spec-cured concretes.
- The inclusion of different RCA types is found to affect the compressive strength of concrete differently. In decreasing order of compressive strength at 91 days, the mixture types were RCA1, NA, and then RCA2. The opposite effects observed between RCA1 and RCA2 indicate that the inclusion of RCA is not necessarily detrimental to concrete strength, and that proper identification of RCA within the concrete industry could result in more efficient use of this construction material.
- The variations that caused a decrease in the splitting tensile strength of concrete were, in decreasing order of effect: RCA content, RCA type, curing regime used, then aggregate saturation. The inclusion of either good or poor quality RCA in concrete resulted in tensile strength losses. This could be significant to the use of RCA in the concrete industry, specifically in applications where concrete's tensile strength is an important design consideration.
- In terms of elastic modulus, the RCA1 mixtures generally behaved similarly to the NA mixtures, with the exceptions of RCA1 S60-100 and RCA1 S0-100, which were relatively lower. RCA2 mixtures all exhibited lower elastic moduli than NA and RCA1 mixtures. This indicates that the quality of RCA, specifically in terms of the absorption capacity and therefore the density, has an impact on the E_c of RCA concretes, which could have relevance to concrete applications wherein the E_c is a governing factor.
- The elastic modulus equation from ACI318-11 provides the best estimates for the E_c of the RCA concretes under the given conditions, though it was found to underestimate the

E_c of the NA mixtures. In practice, the estimation of the E_c of RCA concretes should consider the concrete density to produce accurate estimates.

- At 28 days, the LCTEs of RCA mixtures were typically lower than those of the NA mixtures although the 100% saturated, 100% replacement mixtures were not statistically unique from the control mixtures. When LCTE was measured at 150 days, changes in the testing environment and sample moisture conditions may have resulted in the noticeably different and variable results. Thermal response of concrete is an important consideration, especially in the concrete paving industry. If RCA's addition to concrete causes a reduction of the low-temperature thermal expansion of the material then this increases the material's effective value in this industry.
- Internal curing effects are not observed in the permeable porosity results.

6.4 Saturation Comparison

- 100% saturated RCA1 concrete samples appear to retain more water in the form of absorbed or trapped water and hydrated cement.
- 100% saturated RCA mixtures appear to gain compressive strength at a higher rate for longer during early-age strength gain, as compared to the 0% and 60% saturated mixtures. This suggests that the initial entrainment of water within the RCA is the most effective means to include extra mixing water in concrete. When RCA is considered for use in future concrete applications, this should be considered during concrete batching procedure development.
- For a given RCA type, the 60% saturated mixtures develop lower compressive strengths than the 100% or 0% saturated mixtures. While the disparity between these mixtures was not statistically significant, it may indicate that partially saturated RCA in concrete develops lower compressive strength than completely saturated or unsaturated RCA. The valuation of RCA in concrete depends on using the batching procedure that produces the best performing RCA concrete.
- Coarse aggregate saturation was not observed to significantly influence splitting tensile strength of concrete for all aggregate types and replacement amounts. The initial saturation level of RCA can have a negative effect on the concrete's compressive strength

but does not affect the tensile strength, indicating that compressive strength effects should govern the preparation procedure used when considering concrete strength.

- 100% saturated RCA mixtures exhibited significantly higher elastic moduli than the corresponding less-saturated RCA mixtures. Normalized with regard to density and compressive strength, the elastic modulus of the 100% saturated RCA mixtures appears to increase at 28 days, but this effect is lessened over time. The effects on elastic modulus appear to be governed mostly by the corresponding changes in compressive strength and density.
- In the temperature range of -15°C - +20°C at the age of 28 days, the saturation level of NA mixtures appears to have little effect on the LCTE, which remains higher than the LCTE of RCA mixtures. This indicates that RCA concretes may have significant value in concrete applications that require that concrete not contract significantly under cold weather conditions.
- In the temperature range of -15°C - +20°C at the age of 28 days, 0% and 60% saturation of RCA appears to have little influence on LCTE, however 100% saturation of RCA1 appears to result in an increase of thermal expansion. This is possibly due to areas of high moisture that are developed in the vicinity of the RCA due to the RCA's retention of water. This could be significant to concrete producers as it may affect the recommended time before an RCA concrete can be safely exposed to low temperatures. If this moisture retention and thereby LCTE increase persists for a significant period of time, RCA concrete may not be feasible for placement late in the construction season of a cold-winter climate like Canada.
- The permeable porosity and water absorption percentage were observed to be higher in those mixtures prepared with 60% saturated aggregate, however not at a statistically significant level. This could be due to the coating effect discussed previously, whereby adhered surface moisture coming into contact with cement during batching produced a coating that restricts the flow of mixing water into the unsaturated RCA prior to the concrete's setting. This would result in higher effective water-cement ratios in the mortar, which could increase the porosity of the sample. This indicates that partial saturation of RCA prior to inclusion in concrete may not be the ideal preparation technique.

6.5 Curing Comparison

- RCA1 was found to retain proportionately more moisture under spec-curing conditions than other two aggregate types, which could potentially provide benefit, but also may pose freeze thaw durability issues if the level of saturation is at or above 91% for a long period of time. The level of RCA saturation within concrete should be investigated as it could affect the cold weather durability of RCA concretes.
- The entrained moisture in both RCA mixtures had different compressive strength gain benefits under spec-curing conditions. RCA2 extended the period of initial strength gain while RCA 1 improved the later age strength of the mixtures. These benefits coincide with the previously discussed findings that RCA1 retains moisture for longer time periods than RCA2. The NA samples exposed to spec-curing conditions exhibited lower compressive strength than their corresponding moist-cured samples and the difference in strength between the samples of the two curing regimes continued to grow until the end of testing. The benefits observed in the concretes produced with either RCA type were not observed in the NA samples. This indicates that concretes produced with saturated RCA have benefits in concrete applications with the potential for air drying after short periods of curing. This increases the value of RCA as a material for use in concrete production.
- Spec-curing affects the tensile strength of NA mixtures, but did not affect 100% saturated RCA mixtures significantly. The tensile strength of RCA mixtures under both curing conditions were statistically the same and were similar to the tensile strength of spec-cured NA samples. This indicates that concrete applications that typically undergo spec-curing would not have significantly worse tensile strength properties with 100% replacement of NA with saturated RCA. This is significant because tensile strength loss is often considered to be a problem associated with RCA concrete.
- 100% saturation of RCA under spec-curing conditions does not appear to provide significant benefit or detriment to the elastic moduli or thermal expansion values of concrete as compared to NA mixtures. Again, this is significant to the potential use of RCA in typically spec-cured concrete applications.

- Entrainment of fully saturated coarse RCA did not appear to affect the durability performance of poorly cured concrete in terms of total permeable porosity and absorbed water percent. At both testing ages, no statistically significant differences in permeable porosity or absorbed water were observed between curing regimes for any aggregate type. RCA concretes had higher total permeable porosity and absorbed water than NA concretes. These increases were probably largely due to the cut faces that exposed the porous RCA and thereby increased the permeable porosity of the samples. This affects the permeable porosity, but not necessarily the overall transport properties of the concrete as the exposed RCA are non-continuous pores within the concrete.

6.6 Acceptable RCA Level Comparison

- The 91 day hardened density of concrete was not statistically affected by 30% replacement with RCA1, but was reduced through the addition of RCA2. At 28 days the difference between the hardened density of NA and RCA2 concretes was affected by the initial saturation of the RCA. 100% saturated NA and RCA2 mixtures were significantly different, but 0% saturated mixtures were not. In both saturation cases, the NA mixtures were observed to lose more water than either corresponding RCA mixture. Due to this, the effects of drying may be more severe in NA concretes than in 30% RCA concretes. This presents the same potential benefits and issues discussed previously regarding the retention of water within RCA in concrete.
- The compressive strength of concrete is not unduly compromised by adding 30% RCA under the conditions studied. The addition of poor quality RCA2 under the spec-curing conditions only resulted in a 6% loss in 91 day compressive strength, which was not statistically significant at either saturation level studied. At 28 days, both of the 100% saturated RCA mixtures had significantly higher compressive strength than the corresponding NA mixture and at 91 days, the only statistically significant mixture was the fully saturated 30% RCA1, which had higher strength than either of the NA or RCA2 concrete mixtures. These findings are similar to those previously discussed, which were that fully saturated RCA1 produced higher overall compressive strengths while fully saturated RCA2 provided early age strength gain benefits. These results indicate that

concretes with 30% RCA, which is fully saturated are not only statistically similar at late ages, but provide early age benefits over NA concretes in terms of compressive strength gain. This indicates some significant value of RCA in some concrete applications that require quick concrete strength gains.

- 30% RCA inclusion resulted in tensile strength reductions of up to 12% in comparison to NA mixtures, though some increases due to 30% RCA inclusion in mixtures were observed. None of these changes were statistically significant. Concrete applications that require high tensile strengths do not preclude the use of 30% RCA concretes as tensile strength was not significantly affected by either RCA type.
- 30% RCA inclusion resulted in reductions in elastic modulus of between about 2% and 15%, both RCA types showed similar maximum reductions. The saturated RCA mixtures were not statistically distinct from the NA mixture at either testing age however the 0% saturated RCA mixtures were significantly lower at 28 days. While not statistically significant, E_c for 30% RCA concretes were consistently lower than the NA concretes. This difference may have implications for applications that require high E_c in concrete.
- At 28 days, the inclusion of 30% RCA of either type or saturation level into the mixtures had a significant beneficial effect on the thermal expansion properties of concrete. This could add considerable value to RCA in terms of concrete use. Low thermal expansion in concrete could be very useful in applications such as concrete pavements that are subjected to significant temperature changes. These changes can result in high stresses when conventional restrained concrete pavements expand or retract. The magnitude and the damage caused by these stresses could be reduced by low LCTE RCA concrete.
- By 150 days age, this benefit is no longer evident. As previously discussed, this may be a reflection of different testing procedures as well as the differences in sample moisture conditions, which were necessitated by the objectives of the research.
- Marginal increases (<2%) in permeable porosity were observed in the 30% RCA mixtures when compared to the NA control mixtures. These increases were not a statistically significant level. Water absorption increased with 30% RCA replacement proportionally to the absorptive capacity of the RCA itself. The increase in water absorbed into concrete when replacing NA with a high-absorption RCA (6.91%) was

0.75%. As previously discussed, these increases associated with RCA replacement do not necessarily represent increased transport properties as the porous RCA particles do not represent continuous pores throughout the concrete.

6.7 Recommendations for Future Work

Based on this research, the following are recommended areas for future work:

1. The RCA classification framework that was previously developed at UW should be amended to include specific language pertaining to the preparation of coarse aggregate to be used in concrete, with a note regarding curing conditions. Since some variations were found to occur based on aggregate saturation, and the initial study was performed with saturated aggregate it is recommended that this condition be specified for RCA used in new concrete. This would remove some inherent variability associated with the material. A mixing procedure that produces these conditions and is also feasible for use in practice should also be specified as part of the framework.
2. The effects of the use of RCA1 and RCA2 in concrete have been studied in this and previous work. Studying concretes produced using a mixture of the two aggregate types could provide insight into cumulative effects of combining a high and a low quality aggregate source. This is applicable in practice as separate stockpiles of recycled material are not often feasible for concrete producers. Ternary blends including both RCA types and a natural aggregate could also be studied.
3. The findings indicate that entrained water may be retained within the RCA in the concretes studied. Depending on the RCA saturation levels, freezing and thawing could be detrimental to the durability of the concrete. Freeze thaw testing should be performed at various ages to determine if this poses a durability issue, and if so, if there is an age beyond which these effects are minimized.
4. This research focused on rich mixtures with high replacements in spec-curing conditions in order to magnify any potential effects of the entrained moisture (i.e. worst case scenario). Now that some conclusions have been drawn from this work, similar study should be done into “pavement” mixtures, which have lower cement content, higher w/c, 30% replacement, and flexural strength requirements.

5. The final thermal expansion test produced suspect results. It is recommended that the current low-temperature test procedure that was used within this research be modified in order to control the RH and temperature boundaries of the specimens being tested. This could potentially be done by sealing the specimens prior to testing, or closely regulating the RH of the environment under which the test is performed. The latter method presents the difficulties of maintaining a constant RH over a range of different temperatures.

6.8 Application of Findings

The previous recommendations for future work would expand upon this body of work, but some findings have the potential to be applied in the practice of producing RCA concretes. These are summarized below:

1. Full saturation of RCA prior to casting in concrete results in lower workability when compared to mixing water corrections, but avoids the variability associated with as-received moisture contents and the costs associated with aggregate drying.
2. RCA in concrete retains moisture for long periods even under exposed conditions. While this moisture could be helpful in concrete under poor curing conditions by increasing the compressive strength, it could have impacts on the freeze-thaw durability of concrete. The environmental conditions that the concrete application will be exposed to should therefore be considered when producing RCA concrete in Canadian construction.
3. Replacing 30% of the coarse aggregate with saturated RCA in concrete did not significantly negatively affect any measured concrete properties, even in the case of low-quality RCA2. This appears to be a viable level of replacement for RCA use in concrete to alleviate some negative effects. The LCTE benefits may make 30% RCA concretes particularly useful in concrete pavement applications where thermal expansion can significantly affect the durability of a pavement.

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APPENDIX A: LEAST SIGNIFICANT DIFFERENCE CALCULATION

Sample Calculation:

Consider the following compressive strength values for mixtures containing 100% RCA1 as coarse aggregate. The variable being compared is coarse aggregate saturation, which varies to include 100%, 60%, and 0%.

fc values in MPa	RCA1 S100-100	RCA1 S60-100	RCA1 S0-100
#1	58.13	46.31	46.55
#2	55.24	47.87	44.28
#3	50.27	44.31	46.97
Mean	54.55	46.16	45.93

To determine the 5% LSD value:

1. Set the significance level b = 0.05 for 5% significance (95% confidence).
2. Set k = 3as the total number of saturation levels (100%, 60%, 0%).
3. Set N = 9 as the total number of results for the three saturation levels.
4. Calculate n = 3 as the average number of results for each saturation level.
5. Calculate "α" for use in the t-test calculation:

$$\alpha = \frac{b}{k(k-1)/2} = \frac{0.05}{3(3-1)/2} = 0.01667$$

6. Calculate the t-statistic as:

$$t_{\frac{\alpha}{2},N-k} = t_{0.008,6} = 3.863$$

7. Calculate the mean square within saturation levels as the sum of squares (SS = 42.189) divided by the degrees of freedom with concrete types (i.e., N – k = 6).

   Note: a one-way or single-factor ANOVA analysis was carried out using EXCEL to calculate these values:

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
RCA1 S100-100	3	163.641	54.5469	15.823
RCA1 S60-100	3	138.49	46.1633	3.192
RCA1 S0-100	3	137.797	45.9323	2.0797

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	144.548	2	72.2739	10.279	0.0115	8.74382
Within Groups	42.1889	6	**7.03149**			
Total	186.737	8				

8. Calculate the standard error of the difference between two means:

$$SE = \sqrt{\frac{2(MS)}{N-k}} = \sqrt{\frac{2(7.03)}{6}} = 2.17$$

9. Calculate the 5% LSD:

$$5\%\ LSD = t_{stat} \times SE = (3.863)(2.17) = 8.36\ MPa$$

This 5% LSD represents the smallest significant difference between two means in the given set of values. Therefore the compressive strengths of RCA1 S100-100 and RCA1 S0-100 are significantly different since the difference of their means is 8.62 MPa, which is larger than the 5% LSD.