ABSTRACT

Title of Document:	Crushed Returned Concrete Aggregate in New Concrete: Characterization, Performance, Modeling, Specification, and Application
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Every year roughly 2% to 10% of the estimated 455 million cubic yards of ready mixed concrete produced in the USA (est. 2006) is returned to the concrete plant. The crushed returned concrete aggregate (CCA) is obtained from crushing the returned concrete that was discharged at the concrete pant and left for a period of time before crushing. It is estimated that about 60% of all returned concrete is managed with this manner by the concrete plant according to the national ready mixed concrete association report. But the reuse of the returned concrete aggregate is very much limited so that most of the returned

concrete aggregate has been diverted to the landfill. The main obstacle to limit the use of the returned concrete aggregate is the current type of prescriptive specifications by controlling the concrete composition, which limits the ability to optimize concrete mixtures for performance.

The CCA aggregate has useful aggregate properties among which it is free of any contamination. Thus, CCA aggregate is distinguished from other recycled concrete aggregate (RCA) that comes out of existing old structures with high contamination from many years of exposure during the service life. The objective of this research was to develop technical data that will support the use of the CCA aggregates from the returned concrete by the ready mixed concrete industry. Three CCA aggregates at three strength levels were characterized. Thereafter, the virgin coarse/fine aggregates and the three CCA aggregates were used with various amounts to prepare concrete mixtures so as to investigate the effect on the fresh and harden concrete properties.

The second objective of this research was to develop the performance models of harden concrete properties. The harden concrete properties of a selected number of mixtures containing CCA aggregates were used for the modeling of compressive strength, drying shrinkage, elastic modulus, and rapid chloride ion penetrability. This analysis was instrumental for a better understanding of how the CCA aggregates affect the harden concrete properties.

The fine CCA aggregates were further investigated for their potential use as internal curing agent due to their unique aggregate properties (i.e. low specific gravity and high water absorption capacity). Those two properties are crucial factors for the internal curing. The fine CCA aggregates were used with mortar mixtures to evaluate the strength

and autogenous shrinkage behavior along with the lightweight fine aggregate. This new approach can promote the use of CCA aggregate in a specialized application.

Another objective of this study was to demonstrate the advantages of using a performance based specification. An example of an experimental case study was used for both conventional and CCA based concrete for comparing performance and prescriptive specifications.

Keywords: Returned Concrete, Aggregate, Recycled Aggregate, Internal Curing, Autogenous Shrinkage, Special Application, Performance Specification.

Crushed Returned Concrete Aggregate in New Concrete: Characterization, Performance, Modeling, Specification, and Application

By

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Dedicated

To my late father Do Ha Kim

마태복음 6 장 33 절 말씀으로 나는 이 논문을 마무리할 수 있었다.

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Chapter 1. Introduction

1.1. Background

Every year roughly 2% to 10% of the estimated 455 million cubic yards of ready mixed concrete produced in the USA (est. 2006) is returned to the concrete plant. The returned concrete in the truck is typically used as one of the followings: Option 1) if it is a small quantity of returned concrete fresh concrete material can be batched on top with and/or without the hydration stabilizing admixtures, Option2) the returned concrete can also be processed through a reclaimer system to reuse or dispose the separated ingredients, including the process water with a hydration stabilizing admixture, Option 3) the returned concrete can also be used for site paving and production of other products, such as concrete blocks, either for resale or disposal, and Option 4) the returned concrete can be discharged at a location in the concrete plant for later crushed and reuse as base for pavements or fill for other construction.

Option 1 is probably done on a small scale and is not always practicable because of restrictions by concrete specifications. Option 2 is limited to larger volume plants in metropolitan areas and requires a significant capital investment, followed by attention to proper practice. Option 3 is limited by several factors – there is only so much area in a plant that can be paved and the volume of block production depends on local market conditions and opportunities. Option 4 has significant potential in US and it is estimated that about 60% of all returned concrete is managed with this manner by the concrete plant according to the National Ready Mixed Concrete Association report. But the reuse of the returned concrete aggregate is very much limited so that most of the returned concrete aggregate sitting years in the concrete plant has been diverted to the landfill with an additional cost of the owner. This research explores the use of crushed returned concrete in ready mix concrete plant, the crushed retuned concrete is referred as Crushed Concrete Aggregates (CCA) in this dissertation.

Demolishing old concrete structures, crushing the concrete and using the crushed materials as aggregates is not new and has been researched to some extent. This material is generally referred as Recycled Concrete Aggregates (RCA). However, RCA is different from CCA as construction debris tends to have a high level of contamination (rebar, oils, deicing salts etc.). CCA on the other hand is prepared from concrete that has never been in service and thus likely to contain much lower levels of contamination or none.

Since the beginning of the 21st century, the importance of the environment has been paid much attention to the deepening crisis of the global warming throughout the world. The developed countries have put the aggressive actions and efforts to help improve the global environmental health by the regulations and law enforcements but in a limited way due to the conflict interest. Yet the green movement or development has been making a significant progress in countries like US by awarding credits such as LEED (Leadership in Energy and Environmental Design) credits to industries if embracing the noble approach of saving environment for their products. The concrete industry, the foundation of the infrastructures, is also sought to participate into the green movement with sustainability.

The sustainability is very much fit for the sleeping crushed returned concrete aggregate, which can be advanced for reuse, recycle and reduce only by the research and development.

In light of the green movement, the concrete industry is gearing out to use more recycled materials such as fly ash (byproduct of coal combustion), slag cement (byproduct of the iron industry), silica fume (byproduct of silicon and ferro-silicon metal production), etc. in concrete. In recent years with the help of the researches focused on the performance evaluation of the concrete with the pozzolanic materials such as fly ash, slag cement, silica fume, etc. (mostly byproducts) the concrete technology has been advanced with an outstanding progress that helps improve the concrete's lifespan while saving the energy due to less production of the Portland cement and reducing the cost of concrete due to less use of the Portland cement. However, due to the lack of education and technology transfer the old specification written years ago based on outdated concrete technology has been used for the projects in small to larger scales. For example, one big obstacle to put sustainability in practice is the practice of the prescriptive specification in which the recipes such as mixture proportions, w/cm ratio are normally prescribed mostly based on an outdated concrete technology without allowing a space for improvement. Often the prescriptive specification makes the concrete product unhealthy with over design of the Portland cement which results the adverse effect to the concrete due to the high cement paste content causing shrinkage cracking. Most of all, the concrete producers who are considered to be an expert of the concrete cannot change the recipes written in specification as the deviation of the specification will result in the penalty. Thus, the concrete producers are avoided to improve the concrete quality and performance by utilizing their accumulated concrete technology for many years as a result of the mixture optimization with the recycled materials such as pozzolanic materials, CCA, etc. With the current specification mainly relied on the prescriptive method the concrete technology cannot move to the direction of the sustainable development. The alternative method to overcome drawbacks of the prescriptive method in specification is to develop the specification that can absorb the most updated concrete technology to improve the concrete performance as a result of the mixture optimization supported by the numerous researches. This specification which is focused on the performance of the concrete rather than the amount of the mixture ingredients is the performance based specification. The concrete industry with a lead of the National Ready Mixed Concrete Association (NRMCA) has started pushing the performance based specification forward by educating engineers and concrete producers for greater benefits, providing funding the researches related with the performance based specifications, and advocating the potential benefits to the government agencies for the sustainable development since 2004.

1.2. Problem Statement

The original problem was to solve the tremendous amount of CCA aggregates (like mountains) in the concrete plants. Because of the very limited use of the CCA aggregates most of them are eventually diverted to the landfill. Since the beginning of the ready mixed concrete industry, the CCA aggregates have been accumulated in the concrete plants. The strong economy was brought up the enormous infrastructure constructions such as high-rise buildings, road pavements, bridges, dams, etc used of the concrete sold by the ready mixed concrete industry. However the recycling (or reuse) of the returned concrete from the job site crushed into the aggregates has been less and less mainly due to the regulatory restrictions getting tighter and tighter in the project specification. In addition, the government agency, one of the biggest consumers, has not been in favor of re-use of the recycled materials as part of the new gigantic infrastructure constructions for the past years, thus the use of the recycled construction materials such as recycled concrete aggregates did not get promoted to the engineers and designers. It is partly also a lack of the government participation to legislate a green policy that has been boosted in a recent couple of years.

In the past fairly a short period of time the federal highway administration (FHWA) had funded for the researches related to the concrete performance evaluation with the re-use of the recycled concrete aggregates (RCA) but the promoting RCA was greatly discouraged due to the contamination issues whereas the crushed returned concrete aggregates (CCA) generated in the ready mixed concrete industry was free of the contamination. Even in spite of the great advantage of the contamination free, the CCA aggregates were not got attention to the engineers and researchers. One possible reason may be the isolated CCA storage in ready mix concrete plants where the access was limited from the public for years. Also the traditional conception of CCA aggregates made of the wasted concrete (returned concrete) has made the concrete producers kept from seeking for CCA aggregates as a viable green material. Thus, the relevant researches with the topic of the CCA aggregates have made none in US resulted in the absence of the technical data on CCA aggregates.

Again, the technical research for the concrete performance with the CCA aggregates has not been conducted from the characterization of the CCA aggregates into the concrete performance with the CCA aggregates in wide perspectives in US. Thus, it is important to establish the technical database and modeling for concrete performance with the CCA aggregates through the various concurrent testing methods and the performance evaluation that can be used as a foundation of the performance based specification in near future.

1.3. Objectives of This Research

The objectives of this research can be summarized in the following:

- The first objective was to develop technical data that will support the use of the CCA aggregates from the returned concrete by the ready mixed concrete industry.
- The second objective was to develop the performance models for harden concrete properties such as compressive strength, drying shrinkage, elastic modulus, and rapid chloride ion penetrability with the CCA aggregates in concrete. This was a critical component of this dissertation since a detail understanding of the mechanism and interactions between CCA aggregate and the remaining concrete ingredients is needed. Such modeling can help provide better understanding as to how the CCA aggregates affect the performance of various harden concrete properties.

- The third objective was to demonstrate advantages of using a performance based specification as compared to a prescriptive specification for both the conventional concrete and the concrete with CCA aggregates.
- The fourth objective was to apply the CCA fine aggregates as internal curing agent in mitigating the autogenous shrinkage. This new approach can promote the use of CCA aggregates in a different angle.

The research helps provide guidance on a methodology for appropriate use of the CCA aggregate material.

1.4. Research Approach

Three CCA aggregates available at three strength levels were first characterized for their aggregate properties along with the virgin coarse and fine aggregates and using the testing requirements of ASTM C33 “Standard Specification for Concrete Aggregates”. Thereafter, the virgin coarse/fine aggregates and the three CCA aggregates were used with various amounts to prepare concrete mixtures so as to investigate the effect on the fresh (plastic) and harden concrete properties. Then, the harden concrete properties of a selected number of mixtures containing CCA aggregates were selected and used for the modeling of compressive strength, drying shrinkage, static elastic modulus, and rapid chloride ion penetrability. This analysis was instrumental for a better understanding of how the CCA aggregates affect harden concrete properties. The fine CCA aggregates were further investigated for their potential use as internal curing agent due to their unique aggregate properties (i.e. low specific gravity and high water absorption capacity). Those two properties are crucial factors for the internal curing. The fine CCA aggregates were used with mortar mixtures to evaluate the strength and autogenous shrinkage behavior. The effects of high absorption properties of CCA aggregates on the effect of the slump retention in concrete were also evaluated for assessing the workability (consistency) of the fresh concrete at early ages.

1.5. Chapter Organization

The dissertation is organized in eight chapters as follows:

Chapter 1 includes the background, problem statement, research objectives, research approaches, and dissertation organization. Chapter 2 covers the literature review related to the use of CCA aggregate and/or the recycled concrete aggregate (RCA). Chapter 3 covers the material characterization of three CCA aggregates and the virgin coarse/fine aggregates. All aggregates were tested with the requirements of ASTM C33. The three strength levels of CCA aggregate are discussed along with the test results and compared to the virgin coarse/fine aggregates. Chapter 4 presents the results of using CCA aggregates in concrete mixtures at various contents. Both non air entrained concrete and air entrained concrete mixtures were prepared with various amounts and types of CCA. Both fresh and harden concrete properties were examined. Chapter 5 covers the performance analysis and modeling in using a selected number of CCA aggregates and mixtures. This chapter includes modeling related to harden concrete properties, such as compressive strength, drying shrinkage, elastic modulus, and rapid chloride ion penetrability. Chapter 6 covers comparison of prescriptive and performance based specifications. The advantages of a performance based specification as compared to the prescriptive specification are demonstrated with the conventional concrete and the CCA based concrete mixtures. Chapter 7 covers the special use of CCA fine aggregate as internal curing agent in mitigating the autogenous shrinkage. Finally, Chapter 8 includes the conclusions of this study.

Chapter 2. Literature Review

Since much of the published literature is on the use of crushed concrete from existing concrete structures, this literature review is intended as a summary of these studies, but also pertains to the use of the crushed returned concrete aggregate (CCA) as well.

2.1. Properties of Recycled Concrete Aggregates

Recycled concrete aggregates (RCA) have higher water absorption rates than virgin aggregates. Higher absorption rates are indicative of higher volume fractions of old cement mortar adhering to the virgin aggregate particles in the original concrete[1-3]. ASTM C33, *Specification for Concrete Aggregates*, includes a requirement of an abrasion loss (by ASTM C535) of less than 50% for aggregates used in concrete construction and less than 40% for crushed stone used in pavements[4]. According to the ACI 555 Committee Report[4], all RCA except that made from the poorest quality recycled concrete, can be expected to meet these abrasion loss requirements. The abrasion property of the aggregates controls the abrasion resistance of the concrete, a property that is important for warehouse floors, and concrete pavements. The relative density of RCA is 5-10% lower than that of virgin aggregates (VA)[5]. This is because of bricks in demolished construction waste[6] and/or the lower density of the cement mortar that remains adhered to the aggregates[4,6,7].

2.2. Effects of RCA on Plastic Concrete Properties

Studies have shown that as RCA content in concrete mixtures increases, their workability decreases. One study found that in order to produce similar workability as VA concrete 5% more mixing water was required when using just the coarse fraction of recycled concrete aggregates (coarse RCA) and up to 15% more mixing water when using both the coarse and fine fractions of RCA[8-11]. Issues of workability are largely tied to the inclusion of recycled fines in RCA. For that reason, it is recommended that fine recycled concrete aggregate (FRCA) levels remain at or below 30% of total fine aggregate content[12]. Entrapped air contents of non air entrained concrete containing RCA were up to 0.6% higher and varied more than air contents of non air entrained VA concrete mixtures[4]. The density (unit weight) of concrete made using RCA were found to be within 85-95% of the VA concrete[4]. Finishability of concrete containing RCA is generally adversely affected[5].

2.3. Effects of RCA on Hardened Concrete Properties

Compressive strength of concrete containing RCA is dependent upon the strength of the original concrete from which the RCA was made. Concrete's compressive strength gradually decreases as the amount of the fine recycled concrete aggregate (FRCA) increases. The reduction is reported to be between 5% and 24% when just coarse RCA was used and between 15% and 40% when the RCA (including the fine fraction) was used. Strength reduction becomes more significant when the FRCA content surpasses 60% of the total fine aggregate[13]. RCA concrete has around the same or 10% less flexural strength than concrete containing VA[4]. However, some studies have found that with the incorporation of FRCA the reduction in flexural strength can be as much as 10-40%[5]. A research program[15] that evaluated the influence of RCA on concrete durability with testing such as rapid chloride permeability, oxygen permeability and water sorptivity concluded that concrete durability became adversely affected with increases in the quantities of RCA and the durability improved with the age of curing. This phenomenon was explained by the fact that cracks and fissures created in RCA during processing render the aggregate susceptible to ease of permeation, diffusion and absorption of fluids. Interestingly the use of RCA resulted in a reduction in the leaching of calcium ions from the concrete[16].

Creep of concrete is proportional to the content of paste or mortar in it. To that end, it is understandable that RCA undergoes increased creep because it can contain about 70% more paste volume than concrete made with virgin aggregate, with the exact amount dependent upon the amount of RCA replacing the VA, and paste volume in the RCA and the new concrete[15]. Researchers have observed creep to be 30%-60% greater in concrete manufactured using RCA compared to concrete with VA[5]. Like creep, increased shrinkage rates are also related to increase in cement paste contents[17]. One study found that while RCA shrinkage rates are still dependent on the amount of recycled aggregates used, the 1 year values are comparable to that of concrete containing VA[13]. Other studies have shown more differentiation in drying shrinkage values. One study showed that concrete made with RCA resulted in 70-100% greater shrinkage. The same study also reported that concrete made using coarse RCA along with natural sand increased shrinkage by only 20-50%[4].

The measure of carbonation depth, mostly below 5 mm, increases with the amount of recycled aggregate content[13]. However, the carbonation rate when using RCA made from carbonated concrete were 65% higher than control groups[4]. One study indicated higher rate of corrosion when RCA is used in concrete. This effect can be mitigated by reducing the w/c ratio[4]. In ASTM C 1202, which tests chloride-ion penetration, concrete using RCA could be regarded as having moderate resistance if the FRCA is below 60%[13].

Concrete containing RCA can have good freeze/thaw resistance if the concrete is adequately air entrained[12]. However, in one of the studies where no air entrainment was used it was shown to be less resistant to cycles of freezing and thawing than concrete made with VA[7]. The study suggested that RCA can contribute to concrete's freeze-thaw damage by expelling water into surrounding cement paste during the freezing process. Furthermore, if it has unsound particles, they would be deteriorated by the repeated freezing/thawing action[7].

2.4. Effects on Mixture Proportioning and Production

At the mixture design stage it can be assumed that the *w/cm* for a required compressive strength will be the same for concrete containing RCA as that for conventional concrete when coarse RCA is used with natural sand[4]. The optimum ratio of fine to coarse aggregate is the same concrete containing RCA as it is for concrete made with VA. Minnesota DOT limits the allowable amount of FRCA to 25% or 30% of total fine aggregate. Many aspects of production of concrete containing RCA are similar to that of conventional concrete, however, extra care must be taken and the following differences are noted[4].

- To offset the high water absorption it is required to presoak RCA.
- Removing materials smaller than No. 8 sieve (approx. 2 mm) prior to production will improve concrete performance (some recommend eliminating the use of FRCA)
- Trial mixtures are mandatory to evaluate the effects on water demand, slump and slump loss, strength etc.

One study reported that dry mixing of RCA before adding other concrete mixture constituents resulted in higher compressive strength, tensile strength, and modulus of elasticity. It was theorized that during the dry mixing the shape of the RCA is improved; old mortar on the surface of the RCA's particles is removed; and lastly, fine particles of old cement are released, thus contributing to cement hydration[8]. However this procedure is impractical to be used in concrete plant. Another study suggested a new mixing technique which they termed as the Two Stage Mixing Approach (TSMA) which was shown to enhance compressive strength and other properties. In the first stage only half of the required water is added to the concrete mixture. By adding only half the water, a thick layer of cement slurry is created on the surface, which then permeates the porous, old cement mortar, filling cracks and voids. The mixing process is completed in the second stage by adding the remaining water to the mixture, creating a strengthened interfacial zone, which ultimately leads to improved performance[1]. The applicability of this in conventional production of ready mixed concrete is also questionable.

2.5. FHWA Experience with RCA

In the U.S. transportation agencies, including the Federal Highway Administration (FHWA), have evaluated the reuse of crushed concrete from construction demolition, such as concrete pavements that have completed their service life. Old concrete pavements are broken up the aggregates, separated as coarse and fine aggregates, and reused in the construction of new concrete pavements. The product is also crushed in place to serve as a base material. The RCA is typically reused as a pavement base layer. Very few roadway projects have used the material as an aggregate component in the concrete pavement layer due to concerns of the quality of concrete for this application. A FHWA report[10,18,19] mentions that as many as 38 state DOTs are recycling crushed concrete as aggregate base and 12 state DOTs are recycling concrete as aggregate for portland cement concrete (PCC). Even though 12 states surveyed has reported use of RCA in PCC it is not known how much it is being used. Further, the use is limited to paving, i.e. non-structural concrete.

2.6. Autogenous Shrinkage Reduction with RCA

Autogenous shrinkage is occurred as a result of both the chemical shrinkage and the self desiccation in High Performance Concrete (HPC) and High Strength Concrete (HSC). The chemical shrinkage and the self desiccation of the Portland cement is closely related to the finesse and surface area of the Portland cement. Over the decades the Portland cement is getting finer and finer in its particle size due to the advanced milling technology adopted by the cement manufacturer thus to increasing the surface area higher. The finer and higher surface area of Portland cement are enabled to generate much higher heat of hydration in a short period of time in concrete than what happened 10-20 years ago. The HPC and HSC are designed to have the high strength and durability from the early age often adapting the low *w/cm* ratio (<0.4) and high cement content in the mixture design. The low *w/cm* ratio and high cement content in HPC and HSC are left for the concrete structure vulnerable to autogenous shrinkage with the early age cracking and reducing its service life dramatically. To remedy the autogenous shrinkage cracking for the concrete structure the highly absorptive lightweight aggregate, super adsorbent polymer fiber, and the shrinkage reducing admixtures have been introduced as internal curing agents to mitigate the autogenous shrinkage while the price of these internal curing materials is soaring up[44]. Other than those high quality and expensive internal curing materials one study shows that the recycled concrete aggregate (RCA), demolished concrete aggregate from the existing structure after service life, was able to reduce the autogenous shrinkage effectively in concrete structure due to its high absorptive ability[45]. On the other hand, the use of concrete waste such as RCA was strongly encouraged to reuse, recycle, and reduce for the sustainable development.

2.7. Prescriptive to Performance based Specification

The prescriptive specification has been dominated in construction industry since the beginning of the concrete industry. The prescriptive specification was a written instruction based on the ACI building codes mostly established years ago with the outdated technology and researches. In the prescriptive specification the concrete mixture is often specified in terms of fixed w/cm ratio and fixed cementitious content. The prescriptive method tends to inhibit the most efficient use of the materials including supplementary cementitious materials, recycled materials, etc[46,47]. Also due to the prescriptive controlling of the mixture ingredients it often uses the over dose of the Portland cement that eventually leads to the early age cracking such as shrinkage cracking. On the other hand, the performance based specification defines a concrete mixture in terms of measurable plastic and hardened properties that prove the mixture with certain performance criteria such as strength, permeability, diffusion rate of chloride, etc. The performance based specification also enables concrete producer to be more innovative in the use of currently available materials such as supplementary cementitious materials, recycle materials, admixtures, polymers, and fibers depending on the specified concrete performances. Furthermore, the performance based specification helps the concrete producer to use their materials including crushed returned concrete aggregate (CCA) with sustainable approaches by the advanced optimization.

In a recent study[48,49] the advantages of the performance based specification were compared for the concrete performance results with the prescriptive specification. The result indicated the performance mixtures had equal or better performance as compared to prescriptive mixtures.

Chapter 3. Material Characterization

3.1. Crushed Returned Concrete Aggregate (CCA) Preparation

The CCA was prepared at Virginia Concrete's Edsall plant. Three different concrete mixtures with target 28 day strengths of nominal 7 MPa (1000 psi), 21 MPa (3000 psi) and 34 MPa (5000 psi) were produced at the ready mixed concrete plant. All mixtures were non air entrained; portland cement only mixtures and contained a small dosage of a Type A water reducer. A small amount of integral color was added to each concrete mixture for identification of the different grades. The concrete was discharged on the ground using a normal process for discharging returned concrete. The concrete mixtures were tested for slump, air content, temperature, density (unit weight), and compressive strengths at various ages. The compressive strength cylinders were subjected to two curing conditions: lab moist curing; field curing near the location where the concrete had been discharged. It was considered that the field cured strengths were more representative of the concrete that was crushed to make CCA aggregates.

The mixture proportions and test results are provided in Table 3.1. The volume of paste divided by the volume of total aggregate varies from 31% to 43% with increasing values obtained for the higher strength concrete mixtures due to the higher cement content. Paste volume refers to the volume of cement, water and air used in the concrete mixture. CCA aggregates produced by crushing this concrete will have high absorption, low specific gravity because it contains paste. The actual 56 day field cured strengths of the different classes were averaged at 9.1 MPa (1320 psi), 25 MPa (3630 psi), and 44.7 MPa (6480 psi). However, the different classes of CCA will continue to be referred as 7 MPa (1000 psi), 21 MPa (3000 psi), and 34 MPa (5000 psi) primarily for ease of notation. The discharged concrete was left undisturbed for 110 days, after which the concrete was processed through a crusher to produce the CCA aggregates. Figure 3.1 shows a picture of the crusher used to make the CCA. Figure 3.2 shows the CCA pigmented with different colors. The grey CCA is made from the 7 MPa concrete, the red CCA from 21 MPa concrete, and the black CCA from 34 MPa concrete.

Table 3.1 Mixture proportions and Test results of Concrete from which CCA was Prepared

	7 MPa	**21 MPa**	**34 MPa**
Material, kg/m^3			
Cement	167	251	356
Fine aggregate	964	976	862
Coarse aggregate (No. 57)	1068	1068	1098
Water	158	168	168
Type A Water Reducer (mL/100kg)	196	196	196
Fresh Concrete Properties			
Slump, mm	133	114	121
Air, %	1.7	4.2	2
Temperature, °C	24	23	24
Density, kg/m^3	2361	2348	2430
Hardened Concrete Properties			
Compressive Strength, MPa (Lab cure)			
28 days	9	22	47
56 days	11	23	51
Compressive Strength, MPa (Field cure)			
28 days	6	17	36
56 days	9	25	45
117 days	-	26	53

All strengths are average of 2 cylinders. Concrete was crushed at 110 days and CCA prepared

Figure 3.1 Crusher Used to Produce CCA at the Concrete Plant

Figure 3.2 CCA pigmented with different colors (Red=21 MPa at far back, Black=34 MPa in the middle, Gray=7 MPa in the front)

Three different strength classes of CCA aggregates were included in this study to evaluate the effects of different strength factor on the properties of the resulting concrete. It is important to study the effect of initial strength of the concrete that is crushed on the performance of new concrete containing CCA. Furthermore, it was felt that if a noticeable difference in performance existed then recommendations could be developed so that the producer can make attempts to separate CCA based on the strength levels of the returned concrete. This could help toward more efficient utilization of CCA.

In addition to the CCA prepared in a controlled manner specifically for this study, CCA aggregate generated and stockpiled at the concrete producer's yard from normal practice was also evaluated. There was no control over strength levels, cement contents, etc. on the concrete discharged to produce this CCA. This CCA is referred to as Pile 1 in this study. This evaluation provides a means of comparing the portions of the study using the controlled CCA to that made from normal practice (uncontrolled). As might be expected in typical operations, the characteristics (compositions) of the returned concrete from which the CCA in Pile 1 are unknown, which is one factor that cannot be quantified in this study. The ready mixed concrete producer is interested to know how much of this material can be used to produce concrete with acceptable performance.

Figure 3.3 Large Capacity Sieve Shaker

3.2. Materials

Using a large capacity sieve shaker shown in Figure 3.3 CCA aggregate was separated into coarse and fine fractions on the 4.75-mm (No. 4) sieve. The percentage of the coarse fraction (by volume and by mass) in each CCA aggregate is shown in Table 3.2. As indicated the coarse fraction (by volume) was 61% for the 7 MPa CCA, and about 70% for the other two CCA aggregates in this study. In comparison Pile 1 CCA aggregate gave a very low coarse fraction of 47%. Two possible reasons were summarized with the help of the concrete producer: First, it is likely that the returned concrete in the normal practice had higher water content due to retempering (introducing water to wash out the left over concrete from the drum mixer) prior to discharge. Second, it is likely that the returned concrete was disturbed and arranged in rows to make it crushable size of pieces the next day. Both of these steps can make the resulting CCA weaker and help explain the lower amount of Coarse CCA in Pile 1.

Table 3.2 Percent of plus No. 4 (4.75 mm) materials in each case

CCA Coarse Aggregate	7 MPa gray (%)	21 MPa red (%)	34 MPa black (%)	Pile1 (%)
By Mass	66.6	73.5	72.6	53.6
By Volume	61.2	70.0	68.8	46.5

Once the CCA aggregate was separated into coarse and fine CCA aggregates with the help of a large sieve shaker the coarse fraction separated into 4 different sizes was recombined in a 0.1 m^3.concrete mixer for about 15 minutes to make it homogeneous. This portion was used for all the aggregate tests for the “Coarse Fraction” whereas all the material passing the No. 4 (4.75 mm) sieve was used for the aggregate tests for the “Fine Fraction”. The following aggregate tests were conducted and the size of replicates also indicated:

- ASTM C127-04 Specific Gravity, Absorption of Coarse Aggregate, 3 samples
- ASTM C128-04a Specific Gravity, and Absorption of Fine Aggregate, 3 samples
- ASTM C136-05 Sieve Analysis of Fine and Coarse Aggregates, 3 samples
- ASTM C117-04 Materials Finer than 75-µm (No. 200) Sieve, 3 samples
- ASTM C29/C29M-97(2003) Unit Weight and Voids in Aggregate, 3 samples
- ASTM C131-03 LA Abrasion, 3 samples
- ASTM C40-04 Organic Impurities in Fine Aggregates for Concrete, 3 samples
- ASTM C1252-03 Uncompacted Void Content of Fine Aggregate, 3 samples
- ASTM C88-05 Sodium Sulfate Soundness, 2 samples

- ASTM D2419-02 Sand Equivalent Value of Soils and Fine Aggregate, 3 samples

While the control aggregates and the 7 MPa and 21 MPa CCA aggregates were tested for all properties the 34 MPa and Pile 1 CCA aggregates were tested only for those properties that are essential for concrete mixture proportions.

3.3. Coarse and Fine Aggregate Test

In this section the coarse and fine aggregate testing is summarized for lab testing procedures and relevant calculations if applicable.

3.3.1. Specific Gravity, Absorption of Coarse Aggregate

The laboratory procedures for specific gravity and absorption are conducted according to ASTM C127 and summarized in the following:

1. Dry the test sample in the oven to constant mass at a temperature of 110±5ºC
2. Cool in air at room temperature for 1 to 3h for test sample of 38 mm nominal max. size, or longer for larger sizes
3. Subsequently immerse the aggregate in water at room temperature for 24±4h
4. Remove the sample in the water and roll it in a large absorbent cloth until all visible films of water are removed
5. Wipe the large particles individually while avoiding evaporation of water from aggregate pores during the surface drying operation.
6. Determine the mass of the test sample in the saturated surface dry condition (SSD)

7. Record the mass to the nearest 0.5 g of the sample mass
8. After determining the SSD mass, immediately place the SSD test sample in the container and place it in water at 23±2ºC while removing all entrapped air by shaking the container when immersed.
9. Record the apparent mass in water
10. Dry the test sample in the oven to constant mass at 110±5ºC
11. Cool to room temperature for at least 1 to 3h and determine the dry mass

The calculation for the specific gravity and absorption of coarse aggregate is done with equations in ASTM C127. The relative density (specific gravity) on the basis of oven dry aggregate is calculated by:

$$\text{Relative density (specific gravity) (OD)} = A/(B-C) \qquad \textbf{Equation 1}$$

Where A is the mass (gram) of oven-dry test sample in air, B is the mass (gram) of saturated-surface-dry test sample in air, and C is the apparent mass (gram) of saturated test sample in water, g.

The relative density on the basis of SSD aggregate is calculated by:

$$\text{Relative density (SSD)} = B/(B-C) \qquad \textbf{Equation 2}$$

The apparent relative density (apparent specific gravity) is calculated by:

$$\text{Apparent relative density} = A/(A-C) \qquad \textbf{Equation 3}$$

The percentage of absorption is calculated by:

$$\text{Absorption, \%} = [(B-A)/A] \times 100 \qquad \textbf{Equation 4}$$

3.3.2. Specific Gravity, Absorption of Fine Aggregate

The laboratory procedures for specific gravity and absorption of fine aggregate are conducted according to ASTM C128 and summarized in the following:

1. Partially fill the pycnometer with water and introduce into the pycnometer 500±10 g of SSD fine aggregate prepared by cone testing procedures in the following:
    a. Place the test sample in a pan and dry in the oven to constant mass at 110±5ºC.
    b. Cool to room temperature followed by covering with water to stand for 24±4 h.
    c. Decant excess water with care to avoid loss of fines
    d. Spread the sample on a flat nonabsorbent surface exposed to a gently moving current of warm air generated by the heat bulb associated with a blowing fan, and stir frequently to secure homogeneous drying
    e. Continue the operation until the test sample approaches a free-flowing condition to proceed for the surface moisture test
    f. For the surface moisture test, hold the mold firmly on a smooth nonabsorbent surface with the large diameter down
    g. Place a portion of the partially dried fine aggregate loosely in the mold by filling it to overflowing and heaping additional material above the top of the mold by holding it with the cupped fingers of the hand holding the mold

    h. Lightly tamp the fine aggregate into the mold with 25 light drops of the tamper.
    i. Remove loose sand from the base and lift the mold vertically
    j. If surface moisture is still present, the fine aggregate will retain the molded shape. Slight slumping of the molded fine aggregate indicates that it has reached a surface-dry condition (SSD)
2. Fill with additional water to approximately 90% of capacity
3. Agitate the pycnometer to eliminate all air bubbles
4. After eliminating all air bubbles, adjust the temperature of the pycnometer and its contents to 23±2ºC
5. Determine the total mass of the pycnometer, specimen, and water
6. Remove the fine aggregate from the pycnometer, dry in the oven to constant mass at 110±5ºC, cool to room temperature for 1±1/2 h, and determine the mass
7. Determine the mass of the pycnometer filled to its calibrated capacity with water at 23±2ºC.

The calculation for the specific gravity and absorption of fine aggregate is done with equations in ASTM C128. The equations are summarized in the following:

The relative density (specific gravity) on the basis of oven dry aggregate is calculated by:

$$\textit{Relative density (specific gravity) (OD)} = A/(B+S-C) \qquad \textbf{Equation 5}$$

Where A is the mass (gram) of oven-dry test sample in air, B is the mass (gram) of pycnometer filled with water to calibration mark, C is the mass (gram) of pycnometer filled with sample and water to calibration mark, and S is the mass (gram) of saturated surface-dry sample.

The relative density on the basis of SSD aggregate is calculated by:

$$\text{Relative density (SSD)} = S/(B+S-C) \qquad \textbf{Equation 6}$$

The apparent relative density (apparent specific gravity) is calculated by:

$$\text{Apparent relative density} = A/(B+A-C) \qquad \textbf{Equation 7}$$

The percentage of absorption is calculated as follows:

$$\text{Absorption, \%} = [(S-A)/A] \times 100 \qquad \textbf{Equation 8}$$

3.3.3. Sieve Analysis of Fine and Coarse Aggregates

The lab procedures for the sieve analysis of fine and coarse aggregates are conducted according to ASTM C136 and summarized in the following:

1. Dry the sample to constant mass at 110±5ºC.
2. Select sieves with suitable openings to furnish the information required by the specifications covering materials to be tested
3. Nest the sieves in order of decreasing size of opening from top to bottom and place the sample on the top sieve
4. Agitate the sieves by mechanical apparatus for a sufficient period (at least 10 min)

5. Determine the mass of each size increment on a balance to the nearest 0.1% of the total original dry sample mass

The percentages passing, total percentages retained, or percentages in various size fractions are calculated to the nearest 0.1% on the basis of the total mass of the initial dry sample.

The fineness modulus (*FM*) is calculated by:

$$FM = (\sum \text{cumulative percent retained}) / 100 \qquad \textbf{Equation 9}$$

Where *FM* is the fineness modulus

3.3.4. Materials Finer than 75-µm Sieve

The lab procedures for materials finer than 75-µm (No. 200) sieve in mineral aggregates by washing are conducted according to ASTM C117 and summarized in the following:

1. Dry the test sample in the oven to constant mass at 110±5ºC.
2. Determine the mass to the nearest 0.1% of the mass of the test sample
3. Place the test sample in the container and add sufficient water to cover it
4. Agitate the sample with sufficient vigor to result in complete separation of all particles finer than the 75-µm sieve from the coarser particles, and to bring the fine material into suspension

5. Immediately pour the wash water containing the suspended and dissolved solids over the nested sieves, arranged with the coarser sieve on top while taking care to avoid the decantation of coarser particles of the sample
6. Add a second charge of water to the sample in the container, agitate, and decant as before. Repeat this operation until the wash water is clear
7. Return all material retained on the nested sieves by flushing to the washed sample
8. Dry the washed aggregate in the oven to constant mass at 110±5°C and determine the mass to the nearest 0.1% of the original mass of the sample

The calculation for the amount of material passing a 75-µm (No.200) sieve by washing is done with the equation in ASTM C117 by:

$$A = [(B-C)/B] \times 100 \qquad \textbf{Equation 10}$$

Where A is the percentage of material finer than a 75-µm (No. 200) sieve by washing, B is the original dry mass (gram) of sample, and C is the dry mass (gram) of sample after washing.

3.3.5. Unit Weight and Voids in Aggregate

The lab procedures for the unit weight and voids in aggregate with the Rodding procedure are conducted according to ASTM C29 and summarized in the following:

1. Select the size of the sample approximately 125 to 200% of the quantity required to fill the measure according to Table 1 in ASTM C29. Dry the aggregate sample to constant mass in an oven at 110±5℃.
2. If needed, calibrate the measure according to section 8, ASTM C29
3. Fill the measure on-third full and level the surface with the fingers.
4. Rod the layer of aggregate with 25 strokes of the tamping rod evenly distributed over the surface
5. Fill the measure two-thirds full and again level and rod as above
6. Finally, fill the measure to overflowing and rod again in the manner previously mentioned.
7. Level the surface of the aggregate with the fingers or a straightedge in such a way that any slight projections of the larger pieces of the coarse aggregate balance the larger voids in the surface
8. Determine the mass of the measure plus its contents, and the mass of the measure alone, and record the values to the nearest 0.05 kg.

The calculation for the bulk density is done with the equation in ASTM C29 by:

$$M = (G-T)/V \qquad \textbf{Equation 11}$$

Where M is the bulk density of the aggregate (kg/m^3), G is the mass of the aggregate plus the measure (kg), T is the mass of the measure (kg), and V is the volume of the measure (m^3)

3.3.6. LA Abrasion

The lab procedures for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine are conducted according to ASTM C131 and summarized in the following:

1. Wash the reduced sample and oven dry at 110±5ºC to constant mass
2. Separate into individual size fractions, and recombine to the grading of Table 1 of ASTM C131
3. Record the mass of the sample prior to test to the nearest 1g
4. Place the test sample and charge in the Los Angeles testing machine
5. Rote the machine at a speed of 30 to 33 r/min for 500 revolutions
6. Discharge the material from the machine
7. make a preliminary separation of the sample on a sieve coarser than the No.12 (1.7 mm) sieve
8. Sieve the finer portion on a No.12 sieve
9. Wash the material coarser than the No.12 sieve and oven-dry at 110±5ºC to constant mass
10. Determine the mass to the nearest 1 g

The loss as a percentage of the original mass of the test sample was calculated from the difference between the original mass and the final mass of the test sample.

3.3.7. Organic Impurities in Fine Aggregates for Concrete

The lab procedures for organic impurities in fine aggregates for concrete are conducted according to ASTM C40 and summarized in the following:

1. Prepare the test sample with a mass of about 450 g from the larger sample
2. Fill a glass bottle to the about 130 mL level with the sample of the fine aggregate
3. Add the sodium hydroxide solution until the volume of the fine aggregate and liquid is approximately 200 mL
4. Stopper the bottle, shake vigorously, and then allow to stand for 24 h
5. Determine the color value as compared to the glass color

3.3.8. Uncompacted Void Content of Fine Aggregate

The lab procedures for uncompacted void content of fine aggregate are conducted according to ASTM C1252 and summarized in the following:

1. Mix each test sample with the spatula until it appears to be homogeneous
2. Position the jar and funnel section in the stand and center the cylindrical measure
3. Use a finger to block the opening of the funnel
4. Pour the test sample into the funnel
5. Level the material in the funnel with the spatula
6. Remove the finger and allow the sample to fall freely into the cylindrical measure

7. After the funnel empties, strike off excess heaped fine aggregate from the cylindrical measure by a single pass of the spatula with the width of the blade
8. Brush adhering grains from the outside of the container and determine the mass of the cylindrical measure and contents to the nearest 0.1g
9. Retain all fine aggregate particles for a second test run
10. Recombine the sample from the retaining pan and cylindrical measure and repeat the procedure.
11. Average the results of two runs
12. Record the mass of the empty measure

The calculation for uncompacted voids for each determination is done with the equation in ASTM C1252 by:

$$U = 100\times[V-(F/G)]/V \qquad \textbf{Equation 12}$$

Where V is the volume of cylindrical measure (mL), F is the net mass of fine aggregate in measure (g), G is the dry relative density (specific gravity) of fine aggregate, and U is the uncompacted voids (%).

3.3.9. Sodium Sulfate Soundness

The lab procedures for soundness of aggregates by use of sodium sulfate are conducted according to ASTM C88 and summarized in the following:

1. Immerse the samples in the prepared solution of sodium sulfate for not less than 16 h nor more than 18 h in such a manner that the solution covers them to a depth of at least ½ in.
2. Cover the containers to reduce evaporation. Maintain the samples immersed in the solution at a temperature of 70±2ºF for the immersion period
3. After the immersion period, remove the aggregate sample from the solution, permit it to drain for 15±5 min, and place in the drying oven
4. Dry the sample until constant mass is achieved
5. Allow the samples to cool to room temperature
6. Repeat the process of alternate immersion and drying until 5 cycles are obtained
7. After the completion of the final cycle and after the sample is cooled, wash the sample free from the sodium sulfate by the reaction of the wash water with barium chloride
8. Wash by circulating water at 110±10ºF through the samples in their containers
9. Dry each fraction of the sample to constant mass at 110±5ºC.
10. Sieve the fine aggregate over the same sieve on which it was retained before the test
11. Sieve the coarse aggregate over the sieve described in section 9 for the appropriate size of particle
12. For fine aggregate, the method and duration of sieving shall be the same as were used in preparing the test samples

13. For coarse aggregate, sieving shall be by hand, with agitation sufficient to assure that all undersize material passes the designated sieve.
14. weigh the material retained on each sieve and record each amount

The difference between each of tested amounts and the initial weight of the fraction of the sample tested is the loss in the test and is to be expressed as a percentage of the initial weight

3.3.10. Sand Equivalent Value of Soils and Fine Aggregate

The lab procedures for sand equivalent value of fine aggregate are conducted according to ASTM D2419 and summarized in the following:

1. Siphon 4±1 in. of working calcium chloride solution into the plastic cylinder
2. Pour the test sample into the plastic cylinder using the funnel to avoid spillage
3. Tap the bottom of the cylinder sharply on the heel of the hand several times to release the air bubbles and to promote thorough wetting of the sample
4. Allow the wetted sample and cylinder to stand for 10±1 min
5. At the end of the 10 min soaking period, stopper the cylinder, loosen the material from the bottom by partially inverting the cylinder and shaking it simultaneously
6. Place the stoppered cylinder in the mechanical sand equivalent shaker, set the time, and allow the machine to shake the cylinder and the contents for 45±1 s.
7. Set the cylinder upright on the table and remove the stopper

8. Insert the irrigator tube in the top of the cylinder, remove the spring clamp from the hose, and rinse the material from the cylinder walls as the irrigator is lowered. Force the irrigator through the material to the bottom of the cylinder by applying a gentle stabbing and twisting action while the working solution flows from the irrigator tip.
9. Continue until the cylinder is filled to the 381 mm graduation.
10. Raise the irrigator tube slowly without shutting off the flow so that the liquid level is maintained at about 381 mm graduation
11. Adjust the level of the solution to the 381 mm.
12. Allow the cylinder and contents to stand for 20 min ±15 s.
13. Read and record the level of the top of the clay suspension referred to as clay reading
14. Place the weighted foot assembly over the cylinder and gently lower the assembly until it comes to rest on the sand
15. Subtract 10 in. from the level indicated by the extreme top edge of the indicator and record this value as sand reading

The calculation for sand equivalent value was done with the equation in ASTM D2419 by:

$$SE = (\text{sand reading}/\text{clay reading}) \times 100 \qquad \textbf{Equation 13}$$

Where *SE* is the sand equivalent expressed as percentage to the nearest 0.1%.

3.4. Summary and Discussion of Material Characterization Test

3.4.1. Coarse Aggregate Test Results and Discussions

Sieve Analysis

The sieve analysis of the coarse and fine fractions of the different CCAs was indicated in Table 3.3. Based on the sieve analysis, the nominal maximum size of the virgin (control) coarse aggregate and coarse CCA aggregates is 25 mm, except for the 34 MPa coarse CCA aggregate which was at 38 mm. The fineness modulus of the control coarse aggregate and all coarse CCA aggregates except the 34 MPa coarse CCA aggregate was about 7.0. The 34 MPa coarse CCA aggregate was 7.28 indicating that it had less fines. It is believed that the processing of the coarse CCA aggregates (15 minute blending in a 0.1 m^3 concrete mixer) removes a part of the mortar adhering to the coarse CCA resulting in the generation of some minus No. 4 material. This is confirmed because the greater the initial strength of the returned concrete the lower the measured amount of minus No. 4 material thus confirming that the stronger material does not break down so easily. The amounts of minus No. 4 material in each of the coarse CCA aggregate were 12% for the 7 MPa; 9% for the 21 MPa; 3% for the 34 MPa; 14% for the Pile 1.

7 MPa-gray, and 21 MPa-red sieve analysis were average of three samples whereas the rest were average of two samples.

Table 3.4 summarizes the measured properties of the different types of coarse CCA aggregate as well as the virgin coarse aggregate.

Table 3.3 Properties of Aggregate Used in Study

Sieve Size	Percent Passing									
	Coarse Aggregate					Fine Aggregate				
	Control No.57	**7 MPa Gray**	**21 MPa Red**	**34 MPa Black**	**Pile 1**	**Control Sand**	**7 MPa Gray**	**21 MPa Red**	**34 MPa Black**	**Pile 1**
64 mm	100	100	100	100	100	100	100	100	100	100
51 mm	100	100	100	100	100	100	100	100	100	100
38 mm	100	100	100	100	100	100	100	100	100	100
25 mm	99	95	90	83	88	100	100	100	100	100
19 mm	87	78	75	64	68	100	100	100	100	100
13 mm	48	45	50	36	40	100	100	100	100	100
10 mm	17	28	34	21	27	100	100	100	100	100
No. 4	2	12	9	3	14	99	100	100	100	100
No. 8	0	0	0	0	0	83	80	81	72	83
No. 16	0	0	0	0	0	69	63	63	52	67
No. 30	0	0	0	0	0	51	47	45	37	48
No. 50	0	0	0	0	0	19	25	25	22	24
No. 100	0	0	0	0	0	4	12	14	12	11
No. 200	0	0	0	0	0	2	7	9	8	7
FM	6.95	6.87	6.92	7.28	7.03	2.75	2.73	2.71	3.05	2.67

Table 3.4 Coarse Aggregate Characterization Test results

Coarse Aggregate	7 MPa Gray	21 MPa Red	34 MPa Black	Pile 1	Control No. 57
LA Abrasion	23.6	26.4			13.1
(%)	24.5	25.9			13.4
ASTM C131	23.4	25.8			
Average	**23.8**	**26.0**			**13.2**
Specific Gravity	2.56	2.54	2.57	2.56	2.91
(SSD)	2.55	2.55	2.59	2.55	2.92
ASTM C127	2.56	2.52	2.59		
Average	**2.56**	**2.54**	**2.58**	**2.56**	**2.92**
Absorption	4.43	4.30	4.45	5.61	0.86
(%)	4.45	4.19	4.20	6.13	0.86
	4.32	4.44	4.30		
Average	**4.40**	**4.31**	**4.32**	**5.87**	**0.86**
Minus 200	1.01	0.64	0.28	1.86	0.39
(%)	1.14	0.62	0.36	1.46	0.36
ASTM C117	1.22	0.70			
Average	**1.13**	**0.65**	**0.32**	**1.66**	**0.37**
Fineness Modulus	6.86	6.94	7.32	6.93	6.99
ASTM C136	6.89	6.86	7.25	7.12	6.92
	6.86	6.95			
Average	**6.87**	**6.92**	**7.28**	**7.03**	**6.95**
Dry Rodded Unit Weight	1562	1430	1501		1688
(kg/m^3)	1549	1434	1495		1695
ASTM C29	1555	1430	1501		1692
Average	**1555**	**1430**	**1499**		**1692**
Soundness	21.37	6.54			0.51
(%)	24.31	9.93			0.41
ASTM C88					
Average	**22.84**	**8.24**			**0.46**

LA abrasion

The coarse CCA aggregates had higher LA abrasion loss as compared to the virgin coarse aggregate (about 25% vs 13%). However, these values are still lower than the 50% loss limit in ASTM C33.

Specific Gravity and Absorption

The SSD specific gravity of coarse CCA aggregates was lower as compared to the virgin coarse aggregate (about 2.55 compared to 2.92). The absorption of coarse CCA aggregates was higher than the virgin coarse aggregate (4.3% to 5.9% compared to 0.9%). Pile 1 had higher absorption (5.9%) than that of the controlled coarse CCAs (about 4.3%). The higher absorption and lower specific gravity of the coarse CCA aggregate as compared to the virgin coarse aggregate is due to the lower specific gravity paste adhering to the surface of the CCA aggregate.

Materials Finer than 75-μm Sieve

The percent passing the No. 200 sieve for the coarse CCA aggregates was generally higher than that for the virgin coarse aggregate (0.32% to 1.66% compared to 0.38%) but was still lower than the 1.5% limit in ASTM C33. The lowest value (0.32%) was for the 34 MPa coarse CCA aggregate and the highest value (1.66%) was for the Pile 1 CCA aggregate.

Dry Rodded Unit Weight

The dry rodded unit weight of the coarse CCA aggregates was slightly lower as compared to the control coarse aggregate (1430 to 1555 kg/m^3 compared to 1692 kg/m^3). This is due to the lower specific gravity of the CCA.

Soundness

Sodium sulfate soundness test results indicated that the coarse CCA aggregates had higher mass loss compared to the virgin coarse aggregate (8.24% to 22.84% compared to 0.46%). The 21 MPa CCA aggregate had a lower mass loss (8.24%) than the 7 MPa CCA aggregate and met the performance requirement of ASTM C33 which is 12%. The sulfate soundness test is conducted to evaluate the weathering potential of concrete aggregate and is often correlated the durability of the aggregate under cycles of freezing and thawing. The implication of the sulfate soundness test to CCA is questionable because it is not clear whether the same mechanism is relevant or if other mechanisms such as sulfate attack might also result in a high mass loss in the test.

To summarize, a higher compressive strength of the returned concrete does lead to a coarse CCA aggregate with a lower percentage of finer particles (minus No. 4 fraction), lower amount of Minus 200 fines, and potentially improved resistance to degradation as indicated by the LA Abrasion and soundness tests.

3.4.2. Fine Aggregate Test Results and Discussions

Organic Impurities

Table 3.5 summarizes the measured properties of the different types of fine CCA aggregates as well as the virgin fine aggregate. There was no indication of organic impurities for the fine CCAs and the virgin fine aggregate.

Specific Gravity and Absorption

The SSD specific gravity of fine CCA aggregates was lower compared to the virgin fine aggregate (2.11 to 2.27 compared to 2.61). The specific gravity of the fine CCA aggregate increased with increasing strength of the returned concrete. The absorption of fine CCA aggregates was much higher compared to the virgin fine aggregate (10.0% to 16.3% compared to 0.95%). The absorption of the fine fraction from Pile 1 was 16.3%. The absorption of the fine CCA aggregate decreased with increasing strength of the returned concrete. The higher absorption and lower specific gravity of the fine CCA as compared to the virgin fine aggregate is due to the lower specific gravity paste adhering to the surface of the CCA.

Materials Finer than 75-μm Sieve

The percent passing the No. 200 sieve for the fine CCA aggregates was higher than that for the virgin fine aggregate (7.3% to 9.5% compared to 1.3%). These are above the 5 or 7% limit in ASTM C33 for manufactured sand. The fineness modulus of the fine CCAs was about the same as compared to the virgin fine aggregate (about 2.75) except that the 34 MPa fine CCA aggregate had a much higher fineness modulus (3.05).

Sand Equivalency

The sand equivalency of the fine CCA aggregates was lower compared to the virgin fine aggregate (56% to 63% compared to 87%). Sand equivalency is an indication of the relative proportions of detrimental fine dust or clay-like materials in fine aggregate thus indicating that the fine CCA aggregates had a higher percentage of fines.

Table 3.5 Fine Aggregate Characterization Test results

Fine Aggregate	**7 MPa Gray**	**21 MPa Red**	**34 MPa Black**	**NA Pile1**	**Control Sand**
Organic Impurity	1	1			1
ASTM C40	1	1			1
	1	1			
Average	**1**	**1**			**1**
Specific Gravity	2.15	2.23	2.26	2.09	2.61
(SSD)	2.16	2.27	2.26	2.14	2.61
ASTM C128	2.21	2.26	2.29		
Average	**2.17**	**2.25**	**2.27**	**2.11**	**2.61**
Absorption	11.52	10.44	9.94	17.03	0.98
(%)	12.06	10.06	10.33	15.56	0.92
	12.13	10.24	9.81		
Average	**11.90**	**10.25**	**10.03**	**16.30**	**0.95**
Minus 200	7.04	9.31	7.73		1.51
(%)	7.33	9.67	7.56		1.29
ASTM C117	7.57	9.52			
Average	**7.31**	**9.50**	**7.64**		**1.40**
Fineness Modulus	2.74	2.74	3.03	2.69	2.74
ASTM C136	2.73	2.69	3.07	2.65	2.76
	2.72	2.69			
Average	**2.73**	**2.71**	**3.05**	**2.67**	**2.75**
Sand Equivalency	54.8	61.4			85.4
(%)	53.2	62.1			87.0
ASTM D2419	57.6	61.8			
Average	**56.0**	**63.0**			**87.0**
Uncompacted Void	37.0	40.1			41.7
Contents (%)	36.9	40.4			41.7
ASTM C1252	37.1	40.3			
Average	**37.0**	**40.3**			**41.7**
Soundness	32.23	16.46			2.72
(%)	30.15	16.09			2.71
ASTM C88					
Average	**31.19**	**16.28**			**2.72**

Uncompacted Void Content

The uncompacted voids content of the fine CCA aggregates as measured by the ASTM C1252, standard graded sample (Test Method A) was slightly lower as compared to the virgin fine aggregate (37% to 40% vs 42%). Generally lower voids contents indicate a more rounded and/or smooth-textured aggregate particles. The difference between the CCA fine aggregates and virgin fine aggregate in this case was not very significant.

Soundness

Soundness test results indicated that the fine CCA aggregates had higher mass loss compared to the virgin fine aggregate. The fine CCAs tested exceeded the 10% limit for sodium sulfate soundness in ASTM C33.

To summarize, a higher compressive strength of the returned concrete does lead to a fine CCA aggregate with higher fineness modulus, higher specific gravity, lower absorption, and potentially improved resistance to degradation as indicated by the soundness test.

Chapter 4. CCA in New Concrete

4.1. Introduction

The seventeen non air entraining concrete and four air entraining concrete mixtures were prepared with different grade (strength) CCA aggregates and tested on the following parameters: i) Control mixture using virgin coarse and fine aggregates, ii) Use CCA in "as received" state at different replacement levels for virgin aggregate, iii) Use coarse fraction of CCA (to replace virgin coarse aggregate) and a portion of the fine fraction of the CCA to replace virgin fine aggregate at different replacement levels.

The following materials were used in the study.

- Type I Portland Cement
- Air entraining admixture
- Type F naphthalene sulfonate high range water reducing admixture
- Virgin natural sand
- Virgin crushed trap rock sand (used only for ASR tests)
- No. 57 Virgin crushed trap rock coarse aggregate
- Crushed returned concrete aggregate (7 MPa, gray color pigmented)
- Crushed returned concrete aggregate (21 MPa, red color pigmented)
- Crushed returned concrete aggregate (34 MPa, black color pigmented)
- Crushed returned concrete aggregate (Pile 1)

The material characterization details for both virgin and CCA aggregates are provided in Chapter 3.

4.2. Experimental Program Phase I: Non Air Entraining Concrete

4.2.1. Mixing Concrete

A revolving drum mixer with a 0.07 m^3 mixing capacity was used to mix the concrete batches. Concrete batch size was kept at 0.04 m^3. All concrete mixtures except Mixture 16 were mixed in accordance with ASTM C192 with the CCA being batched along with virgin coarse aggregate.

Mixture 16 was mixed similar to the “Two Stage Mixing” approach discussed in literature [1, 32] to evaluate the claim in that study of improved concrete performance. For Mixture 16, the coarse aggregate, CCA, and the fine aggregate were placed with 60% of mix water. This was mixed for about 60 seconds. The mixer was stopped and cement added and then mixed for 2 minutes. This was followed by a rest period of 3 minutes after which the rest of the water was added and concrete mixed for another 2 minutes.

4.2.2. Concrete Testing

Concrete tests were, for the most part, conducted in accordance with ASTM standards.

4.2.3. Fresh Concrete Tests

All concrete batches were tested for slump, air content, density, and temperature. Setting time was measured by the thermal method, currently being by considered by ASTM.

Setting time test by penetration resistance as per ASTM C403 was also performed for some mixtures for comparisons. For the setting time of concrete by the thermal method a representative sample of fresh concrete was filled in a container approximately to the depth of 152 mm. After consolidating the concrete by rodding, the sides of the container was tapped gently to level the surface of the concrete. The container was then placed into an insulating cavity in which a thermocouple was installed at the bottom to monitor the heat (temperature) change of the concrete specimen as a function of time. For selected mixtures the sieved mortar for the setting time test (ASTM C403) was transferred to a 70ºF, 50% relative humidity room for the penetration resistance testing until the concrete attained final set.

4.2.4. Harden Concrete Tests

Compressive Strength Test:

Compressive strength testing for concrete mixtures was conducted at 7, 28, and 90 days with 100 mm x 200 mm (4 x 8 inch) cylindrical specimens according to ASTM C39. The specimens were transferred to the moist room as soon as they were made and cured until the test age. The neoprene caps of 70 durometer hardness were used to cap the test specimens in accordance with ASTM C1231. The strength test result was the average of 2 cylinders tested at the same age.

Length Change (Drying Shrinkage):

Length change of concrete due to the drying shrinkage was conducted in accordance with ASTM C157. Prismatic specimens 76 x 76 x 280 mm (3 x 3 x 11 inches) with embedded studs were used to measure the length change, using a gage length of 254 mm (10 inches) between the insides of the studs. The specimens were moist cured for 7 days and then stored in a controlled room at 70ºF, 50% RH. Length change measurements were obtained at various intervals of air drying period as indicated in the reported results. The length change result was the average of 2 specimens.

Elastic Modulus Test:

The elastic modulus of concrete was tested at 28 days in accordance with ASTM C469. Two 100 mm x 200 mm cylindrical specimens were prepared. The specimens were transferred to the moist room as soon as they were made and cured until the test age. The result reported for modulus of elasticity was the average of 2 cylinders tested at the same age.

Rapid Chloride Permeability Test:

The rapid indication of chloride ion penetrability, also referred to as the Rapid Chloride Permeability (RCP) test, was conducted in accordance with ASTM C1202. The two 100 mm x 200 mm cylindrical specimens were prepared for RCP testing. One specimen was cured in a moist room at 70ºF until the test age while the other specimen was cured in a moist room at 70ºF for a certain period of time and then stored in a controlled room at 70ºF, 50% RH until the test age to examine the curing effect. The top 50 mm portion of the specimen was cut and used for the test. The charge passed result was the average of two specimens tested at the same age of 90 days.

ASR Test:

The alkali silica reactivity (ASR) testing was conducted on four concrete mixtures to evaluate the ASR potential with CCA according to ASTM C1293. The three prismatic specimens were prepared and tested for 1 year according to ASTM C1293 requirements. The result was the average of 3 specimens.

4.2.5. Mixture Design

Seventeen concrete mixtures were prepared. The experimental variables, mixture proportions adjusted for yield, and test results are provided in Table 4.1. All mixtures were non-air entrained and the water content was adjusted to achieve a target slump of 125-180 mm. The cement content was maintained at 297 kg/m^3 for all mixtures. Mixture 1 was the control mixture in which the mixture proportions were determined by ACI 211 design method using virgin coarse and fine aggregate. Mixtures 2-6 used CCA in “as received” state at different replacement levels for virgin aggregate. “As received” condition signifies that the CCA was not separated and recombined. Representative samples of CCA were obtained from the CCA stockpile. The CCA aggregate replaced a portion of virgin aggregate in the concrete mixture. The replacement was done by weight on the coarse virgin aggregate based on the mass fractions of the CCA determined in the preliminary separation. CCA was treated as a third aggregate and its absolute volume was calculated from the measured specific gravity. Finally the quantity of virgin fine aggregate was adjusted to achieve the target yield of 0.76 m^3 (1 yd^3).

Table 4.1 Details of Phase I Mixtures

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
CCA Type	0	7	7	21	Pile1	21	7	7	21	34	21	Pile1	0	21	21	21	Pile1
CCA, kg/m^3	0	178	356	356	356	534	NA	NA	NA	NA	NA	NA	0	356	NA	356	NA
CCA, coarse, %	0	NA	NA	NA	NA	NA	50	100	100	100	100	100	0	NA	100	NA	100
CCA, fine, %	0	NA	NA	NA	NA	NA	0	0	0	0	25	0	0	NA	0	NA	0
Calculated Batch Quantities, kg/m^3																	
Cement	294	298	294	295	293	294	295	295	292	291	295	279	291	294	298	295	285
Virgin Coarse	1140	1038	904	885	949	751	572	0	0	0	0	0	1127	881	0	889	0
CCA (as recd.)	0	179	352	354	352	529	-	-	-	-	-	-	0	353	0	356	-
Coarse CCA	-	-	-	-	-	-	485	971	955	966	965	907	0	0	971	0	926
Virgin Fine	815	707	624	658	563	575	818	819	834	828	615	781	813	664	828	669	790
Fine CCA	0	0	0	0	0	0	0	0	0	0	162	0	0	0	0	0	0
Mixing Water	170	166	173	171	170	173	163	153	171	164	174	190	168	170	174	172	195
Fresh Concrete Properties																	
Slump, mm	152	152	165*	152	127	152*	159	152	152	152	178	95	159	165	127	178	159
Air, %	2.5	2.1	2.4	2.1	2.3	2.7	2.8	3.1	2.8	3	3.5	3.8	3.2	2.5	2.2	1.8	3
Density, kg/m^3	2436	2417	2385	2398	2379	2366	2366	2289	2302	2299	2276	2219	2417	2398	2321	2417	2257
Temperature, ^{o}C	24	24	24	25	24	24	24	23	24	23	23	23	25	26	22	23	20
Initial Set Time**	4:14	4:03	4:04	3:52	3:48	3:44	3:42	4:01	3:00	-	4:11	4:00	4:02	3:52	-	-	-
Final Set Time**	7:00	6:44	5:54	6:30	4:41	5:52	6:32	6:16	6:24	-	5:42	4:51	6:46	6:25	-	-	-
Initial Set Time***	-	-	-	-	3:09	-	4:34	3:54	3:58	-	3:45	3:16	4:43	4:05	-	-	-
Final Set Time***	-	-	-	-	4:41	-	6:19	5:40	5:45	-	5:29	4:37	6:32	5:44	-	-	-
Hardened Concrete Properties																	
Compressive Strength, MPa																	
7 days	21.2	20.1	16.6	19.3	17.9	19.3	18.2	17.0	18.8	18.9	17.4	14.8	20.5	18.0	-	-	-
28 days	28.3	27.5	25.0	25.4	23.5	26.8	23.9	21.9	27.1	26.1	24.2	18.5	27.1	25.9	-	26.9	19.6
90 days	32.7	32.2	26.1	30.7	31.2	32.5	29.9	25.0	29.4	33.2	28.3	22.0	36.9	31.5	29.1	30.3	23.2
28 d, % control	100	97.3	88.5	90	83.2	94.9	84.6	77.6	95.9	92.4	85.6	65.6	95.9	91.7	85.1	95.1	67.4
Elastic Modulus (E_c), GPa																	
28 days	32.3	30.5	27.0	28.2	29.0	29.6	30.5	26.7	24.1	26.7	23.2	22.6	32.3	30.3	-	-	-
28 d, % control	100	94.2	83.4	87.2	89.6	91.5	94.2	82.5	74.6	82.5	71.6	69.9	100	93.6	-	-	-
Length Change (Drying Shrinkage), %																	
28 days	0.012	0.013	0.021	0.022	0.022	0.026	0.017	0.020	0.029	0.021	0.029	0.044	0.025	0.026	0.028	0.021	0.019
90 days	0.031	0.035	0.042	0.043	0.040	0.048	0.033	0.040	0.049	0.041	0.051	0.072	0.042	0.049	0.047	0.036	0.051
6 months	0.036	0.040	0.049	0.053	0.047	0.057	0.040	0.046	0.055	0.048	0.058	0.083	0.045	0.051	0.051	0.041	0.061
180 d, % control	88.9	98.8	121.0	130.9	116.0	140.7	98.8	113.6	135.8	118.5	143.2	204.9	111.1	125.9	125.9	101.2	150.6
RCP, Coulombs																	
90 days	3618	2970	2984	3936	3232	4276	5402	5187	6248	4729	7231	6201	3424	3316	5036	3683	6033

* slump sheared slightly, ** Thermal Method, *** ASTM C 403

Mixtures 7-10, and Mixture 12 used coarse fraction of CCA (replaced 50%-100% of the coarse virgin aggregate by mass) with virgin fine aggregate. Mixture 11 used coarse fraction of CCA (replaced 100% of the coarse virgin aggregate) and a portion of the fine fraction of CCA to replace virgin fine aggregate. For these mixtures the replacement of virgin aggregates by CCA was based on a volume basis.

Mixtures 7–11 and Mixture 12 differed in preparation of the coarse CCA. For Mixtures 7-11 the coarse CCA was prepared exactly as discussed earlier. Since the coarse CCA contained some material passing No. 4 sieve as shown in Table 3.3 the material was again sieved over a No. 4 sieve and only the material retained on No. 4 sieve was used as coarse CCA. For Mixture 12 the CCA in an "as received" state was first sieved with the mechanical sieve shaker over various sizes. Each size fraction retained over the No. 4 sieve was placed on the floor and re-combined with a shovel to prepare a homogenous coarse CCA fraction. This hand processing with a shovel did not generate the fines (minus No.4) from the CCA as was observed in the other form of processing.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture 1 was control mixture with virgin aggregates. This mixture proportions were established to achieve an average strength of 28 MPa.
- Mixture 2 and 3 used 7 MPa CCA (CCA7) in "as received" state at replacement levels of 178 kg/m^3 and 356 kg/m^3 for virgin aggregate, respectively.

- Mixture 4 and 6 used 21 MPa CCA (CCA21) in “as received” state at replacement levels of 356 kg/m^3 and 534 kg/m^3 for virgin aggregate, respectively.
- Mixture 5 used Pile1 CCA in “as received” state at replacement level of 356 kg/m^3 for virgin aggregate.
- Mixture 7 and 8 used the coarse fraction of CCA7 to replace virgin coarse aggregate at different replacement of 50%, and 100%, respectively.
- Mixture 9 and 10 used the coarse fraction of CCA21, CCA34, respectively to replace virgin coarse aggregate at 100% replacement.
- Mixture 11 used the coarse fraction of CCA21 and the fine fraction of CCA21 to replace virgin coarse and fine aggregates at replacement of 100% and 25%, respectively.
- Mixture 12 used the coarse fraction of Pile1 CCA to replace virgin coarse aggregate at 100% replacement.
- Mixture 13, 14, and 17 were replicates of Mixture 1, 4, and 12 conducted on a different day to establish the batch to batch repeatability of the study.
- Mixture 15 is a repetition of Mixture 9 except that preparation of the coarse fraction of the CCA was similar to that of Mixture 12 in order to study how processing of the CCA prior to its use can affect its performance in concrete.
- Mixture 16 is a repetition of Mixture 4 except using a modified batching sequence for the CCA as discussed in the Mixing Concrete section.

For alkali silica reactivity (ASR) testing four conditions were evaluated:

- Mixture A was control mixture containing virgin aggregates. The aggregates were virgin crushed trap rock stone and virgin crushed trap rock sand that have been previously determined to be non-reactive in ASR.
- Mixture B used Pile1 CCA in “as received” state at replacement of 356 kg/m^3 for virgin aggregate.
- Mixture C used the coarse fraction of CCA21 to replace virgin coarse aggregate at 100% replacement.
- Mixture D used the fine fraction of CCA21 to replace virgin fine aggregate at 100% replacement.

The other material and mixture proportion were followed by ASTM C1293. The four mixtures were made, cured and tested separately according to ASTM C1293.

4.2.6. Results and Discussions

Fresh Concrete Properties

Slump and Temperature:

The slump for all the mixtures ranged between 125 to 180 mm. Only Mixture 12 had a lower slump of 95 mm. The temperature of the concrete mixture was maintained between 23°C and 26°C. The resultant mixing water content of these mixes is reported in Table 4.1.

Mixing water content:

The mixing water content for the control mixture was 170 kg/m^3. When CCA was used in as received condition (Mixtures 2-6) the mixing water content did not change very much from that of the control mixture. For mixtures 7-11 in which mixtures used different proportions of coarse and fine fraction of CCA to replace the virgin coarse and fine aggregate the water content appears to be lower. For Mixture 12 (Pile1 CCA) the mixing water content was about 20 kg/m^3 higher when 100% coarse CCA was used. When this mixture was repeated (Mixture 17) it still yielded a high water content suggesting that it was not a batching error. The high mixing water content for this mixture could be due to the increased fines in the Pile1 CCA.

Air content and Density:

The air content, measured by ASTM C231, of the control mixture was 2.5%. Most of the CCA mixtures had similar air contents however it was noticeable that as the CCA amount, more particularly the fine CCA amount, increased the entrapped air contents tended to be higher. This effect was most noticeable in Mixtures 11, and 12. This may possibly due to the high absorption capacity of the fine CCA. The high absorption capacity of the fine CCA is another indication of the high voids content if it's not fully saturated. That could result in contributing higher air content in the mixtures. The density of the control mixture was 2436 kg/m^3. Concrete containing CCA is expected to have lower concrete density due to the lower density of the CCA aggregates. The greater the amount of CCA the more these effects matter and therefore the density will decrease. When small amounts of CCA were used in "as received" state (Mixtures 2-6) then the concrete density was not compromised (only 1%-2% lower than control) similar to control concrete. However when CCA was used in larger quantities (Mixtures 7-11) the decrease in density was higher about 6%. Mixture 12 had about 9% lower density which is mainly due to its much higher water content, higher entrapped air and the lower density of the Pile1 coarse CCA.

Setting time:

The initial and final setting times of the control mixture as determined by the thermal method were 4:14 hrs and 7 hrs respectively. The setting times of the CCA mixtures mostly were similar to the control within the range of 30 minutes. However, for Mixture 9 the setting times were accelerated by more than 1 hour. The initial setting times measured by ASTM C403 for the control had initial and final setting times of 4:43 hrs and 6:32 hrs, respectively. The ASTM C403 setting times of the CCA mixtures generally tend to be shorter than that of the control concrete by about 45 minutes to 1 hour. However the mixtures containing the Pile1 aggregates had much lower initial setting times – about 1.5 hours lower. The accelerated initial setting of CCA mixtures may be responsible for the cement paste coated aggregate characteristic that could be used as an activator of the cement hydration resulted in higher heat of cement hydration.

Harden Concrete Properties

Compressive Strength:

Compressive strength of the control mixture was 21.2 MPa at 7 days, and 28.3 MPa at 28 days. Compressive strength of mixtures containing CCA was generally lower than the control, between 3% and 22% lower, at 28 days. In general, as the quantity of CCA in the mixture was reduced, the reduction in strength was less. Further the higher the strength of the returned concrete from which the CCA aggregate was prepared the lower the strength reduction. It was anticipated that when the strength of the returned concrete when crushed and used was equal to or higher than the strength of the new concrete then the CCA is unlikely to adversely affect the strength of the new concrete. In this study the returned concrete used to make the 21 MPa CCA had a 56 day strength of about 24 MPa which is in the range of the design strength for the series of mixtures in this study. Therefore, it was anticipated that the 21 MPa and 34 MPa CCA are unlikely to impact the strength very much as opposed to the 7 MPa CCA. In the discussions below the 28 day compressive strengths of the mixtures containing CCA have been compared to that of the control mixture.

- For the mixtures containing 7 MPa CCA the strength was 3% (0.7 MPa) lower when 178 kg/m^3 was used (Mix2) while it was 11% (3.2 MPa) lower when 356 kg/m^3 was used (Mix3).
- For the mixtures containing 21 MPa CCA the strength was 10% (2.8 MPa) lower when 356 kg/m^3 was used (Mix4) while it was 5% (1.4 MPa) lower when 534 kg/m^3 was used (Mix6). Interestingly the higher amount of 21 MPa CCA actually yielded slightly higher strengths. This is possibly explained by the discussions earlier that if the strength of the returned concrete was higher than the strength of

the new concrete then the use of that CCA is unlikely to adversely affect the strength very much.

- For the mixture containing Pile1 CCA the strength was 17% (4.8 MPa) lower when 356 kg/m^3 was used (Mix5).
- For the mixtures containing 7 MPa CCA the strength was 15% (4.3 MPa) lower when 50% coarse CCA was used (Mix7) while it was 22% (6.3 MPa) lower when 100% coarse CCA was used (Mix8).
- For the mixtures containing 21 MPa CCA the strength was 4% (1.2 MPa) lower when 100% coarse CCA was used (Mix9) while it was 14% (4.1 MPa) lower when 100% coarse CCA and 25% fine CCA were used (Mix11).
- For the mixture containing 34 MPa CCA the strength was 8% (2.1 MPa) lower when 100% coarse CCA was used (Mix 10).
- For the mixture containing Pile1 CCA the strength was 34% (9.7 MPa) lower when 100% coarse CCA was used (Mix12). The low strength for this mixture could be due to high water demand and high *w/c* of this mixture.

When 90 day compressive strength results are analyzed the following additional conclusions can be drawn:

1. As compared to the control mixture compressive strength of mixtures containing CCA was between 2% higher and 23% lower.

2. The higher the strength of the concrete from which the CCA was made the higher the resulting concrete strength. This was evident when 100% coarse CCA test results were compared.
3. The higher amount of 21 MPa CCA aggregate mixtures (Mix6 vs Mix4) yielded higher strengths at 90 days thus confirming the observations made based on the 28 day strength test results.
4. Mixture containing Pile1 CCA at 356 kg/m^3 had comparable strengths to the mixture containing 21 MPa CCA at 356 kg/m^3. However, when 100% coarse Pile1 CCA was used the strengths were 33% lower than that of the control mixture.

Static Modulus of Elasticity:

The static modulus of elasticity of the control mixture was 32 GPa (4.7 x 10^6 psi) at 28 days. The modulus of elasticity of mixtures containing CCA was generally lower than the control, between 6% and 28% lower at 28 days. Generally mixtures containing lower quantities of CCA in the mixture had smaller reductions in the modulus of elasticity. Strength of the returned concrete from which the CCA was prepared did not seem to influence the modulus. However, Mixture 9 (100% coarse 21 MPa CCA) had lower modulus as compared to Mixture 8 (100% coarse 7 MPa CCA). Mixture 11 (100% coarse 21 MPa CCA plus 25% fine 21 MPa CCA) had lower modulus than Mixture 8 even though it had higher strengths. The explanation is probably as follows: Table 4.1 suggests that even though the strength of the returned concrete mixtures varied a great deal it is probably unlikely that the modulus of elasticity varied very much. This is because of the much higher paste contents (8% to 12% more paste volume) of the higher strength mixtures as compared to the lower strength mixture. It is well known that a coarse aggregate such as trap rock has a much higher elastic modulus as compared to the paste.

Drying Shrinkage:

Drying shrinkage test results following 180 days of air drying indicate that increasing amounts of any CCA leads to increasing length change as compared to the control mixture. However, the 7 MPa CCA led to smaller increase in length change as compared to the 21 MPa CCA. This could be because of the lower amount of paste present in the 7 MPa CCA aggregate as compared to the 21 MPa CCA aggregate (Table 4.1). For example 356 kg of 7 MPa CCA is expected to contribute 19% more paste than the Control mixture. In contrast 534 kg of 21 MPa CCA is expected to contribute 36% more paste than the Control mixture. The 34 MPa CCA led to lower increase in length change (similar to the 7 MPa CCA mixture) in spite of its higher total paste content. This could be due to the lower fine material larger than the No. 200 sieve present in the 34 MPa CCA. However, it should be noted that even the 21 MPa CCA led only to about 40% increase in length change over the control mixture. Pile1 CCA when used at 356 kg/m^3 led to a very slight increase in length change. However, when it was used at 100% coarse CCA the length change levels doubled!

Chloride Ion Penetrability:

The use of small amounts of CCA (178 kg, 356 kg) does not change the RCP values as compared to the control mixture. The use of the 7 MPa CCA at 178 kg, and 356 kg and Pile1 CCA at 356 kg led to slightly lower RCP values where as the use of 21 MPa CCA led to slightly higher RCP values. However, the use of 100% coarse CCA led to an all around increase in the RCP values with the chloride ion penetrability going from moderate to high. The 7 MPa CCA, and the 34 MPa CCA had lower increases in RCP values as compared to the 21 MPa CCA and Pile1 CCA mixtures.

Alkali Silica Reactivity:

Alkali silica reactivity (ASR) test results in accordance with ASTM C1293 are summarized in Table 4.2. The expansions of the 4 concrete mixtures are in the range of 0.022% to 0.032% after 1 year. While the three CCA mixtures had higher expansions than the control mixture the values were still below 0.04% limit. By ASTM C1293 1 year expansions below 0.04% are indicative of aggregate that can be classified as non-reactive due to alkali-silica reaction. These results are not surprising because the concrete from which the CCA was made contained aggregates that were not susceptible to ASR. So, addition of CCA might be increasing the alkali level in the system due to the additional cementitious paste. So a virgin aggregate that may be on the borderline in terms of ASTM C1293 expansion may lead to a CCA that fails the C1293 expansion limit if used to make new concrete in combination with the virgin aggregate. However, if the virgin aggregate expansions are significantly low as in this case (0.022%) then the CCA clearly can be tested to be non-reactive. Since the use of fly ash or slag is common in most ready mixed concrete operations, this will provide additional protection against deleterious ASR and can be tested if critical to the proposed application.

Table 4.2 ASTM C1293 ASR Test Result

Mix No.	Description	ASTM C1293 Expansion %, Age – 12 months
A	No.57 Virgin Coarse + Virgin Crushed Fine	0.022
B	No.57 Virgin Coarse + 356 kg/m^3 Pile1 CCA + Virgin Crushed Fine	0.027
C	Coarse fraction of 21 MPa CCA + Virgin Crushed Fine	0.032
D	No.57 Virgin Coarse + Fine fraction of 21 MPa CCA	0.028

4.2.7. Repeatability

Mixtures 13, 14, and 17 were replicates of Mixture 1, 4 and 12 conducted on a different day to establish the batch to batch repeatability of the study. A quick look at the water content, air content, density, strength (28, 90 days), elastic modulus (28 days), shrinkage (180 days), and RCP (90 days) shows that the mixtures are repeatable as the properties did not vary by more than the standard precision levels associated with the different test methods.

4.2.8. Effect of Processing Variations

Mixture 15 was conducted to evaluate how difference in preparation of the coarse CCA affected concrete performance. In order to draw conclusions it is best to compare the performance of Mixture 15 with that of Mixture 9 both of which are identical but for the difference in preparation of the coarse CCA. It can be observed that the water demand for this mixture was slightly higher (by 3 kg/m^3) and the slump was lower by 25 mm. No significant difference was observed in air content, density, compressive strength (90 days), and shrinkage (180 days). RCP (90 days) test results were about 15% lower.

Mixture 16 was conducted to see how the effect of concrete mixing sequence would affect the concrete performance. In order to draw conclusions it is best to compare the performance of Mixture 16 with that of Mixture 4 both of which are identical but for the difference in concrete mixing. No significant difference was observed in water content, air content, density, strength (28, 90 days), and RCP (90 days). Length change (180 days) values were about 20% lower. It appears that the modified mixing sequence did not provide any benefit relative to concrete properties.

4.3. Experimental Program Phase II: Air Entraining Concrete

4.3.1. Materials, Mixing, Mixture Proportions, and Testing

The same materials were used as in Phase I. In addition a Type F high range water reducer (HRWR) and an air entraining admixture were used. Mixing was similar to Phase I with the following changes. Air entraining admixture was added on top of the fine aggregate followed by the addition of the mixing water. HRWR was added only after the concrete had been mixed for about 2 minutes and a slump of about 13 mm had been ascertained visually. The use of HRWR meant that the concrete was mixed for an additional 2 minutes over the 3-3-2 standard mixing cycles in ASTM C192. A total of four concrete mixtures were made. The experimental variables, yield adjusted mixture proportions, and test results are provided in Table 4.3. The cement content was maintained at 335 kg/m^3 for all mixtures. All mixtures were air entrained to achieve a design air content of 6% ± 1.5%. HRWR dosage was adjusted to achieve a target slump of 150 to 200 mm.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture II-1 was control mixture with virgin aggregates.
- Mixture II-2 used 7 MPa CCA in "as received" state at a replacement of 356 kg/m^3 for virgin aggregate.
- Mixture II-3 used 21 MPa CCA in "as received" state at a replacement of 356 kg/m^3 for virgin aggregate.
- Mixture II-4 used the coarse fraction of 21 MPa CCA to replace virgin coarse aggregate at 100% replacement.

All concrete batches were tested for slump, air content, density, and temperature. The compressive strength, drying shrinkage, and rapid chloride permeability tests for concrete mixtures were conducted in accordance with ASTM standards. Other details such as specimen size, curing conditions are similar to Phase I.

Freeze thaw durability testing was conducted according to ASTM C666 Procedure A – Rapid Freezing and Thawing in Water. Specimen dimensions were identical to that of the drying shrinkage test specimens. Specimens were introduced into the freeze thaw chamber after 56 days of moist curing. Two specimens were tested for each mixture. Dynamic modulus of elasticity, length change, and mass change were measured periodically until the specimens had been subjected to 300 freeze thaw cycles.

Table 4.3 Details of Stage II Mixtures

	II-1	**II-2**	**II-3**	**II-4**
CCA Type	0	7	21	21
CCA, kg/m^3	0	356	356	NA
CCA, coarse, %	0	NA	NA	100
Calculated Batch Quantities, kg/m^3				
Cement	336	341	338	326
Virgin Coarse Agg. (No. 57)	1154	931	898	0
CCA (as received)	0	363	360	-
Coarse fraction of CCA	-	-	-	944
Virgin Fine Aggregate	727	538	568	706
Mixing Water	151	154	154	147
AE admixture – mL/100 kg	26	26	26	33
Type F admixture – mL/100 kg	652	763	1030	652
Fresh Concrete Properties				
Slump, mm	191	178	159	152
Air, %	6.4	4.8	5.6	8.5
Density, kg/m^3	2385	2366	2353	2171
Temperature, ^{0}C	21	21	21	21
Hardened Concrete Properties				
Compressive Strength, MPa				
7 days	27	25	28	24
28 days	35	31	35	30
90 days	42	36	42	35
28 d, % of control	100	88.4	98.6	84.1
Length Change (Drying Shrinkage), %				
28 days	0.020	0.028	0.025	0.038
90 days	0.034	0.046	0.043	0.058
6 months	0.041	0.050	0.047	0.062
180 d, % of control	100	122.0	114.6	151.2
RCP, Coulombs				
90 d @ moist cure	2261	3044	2510	3821
Freeze and Thaw after 300 cycles				
Durability Factor, %	92	13*	9	89
Length Change, %	-0.01	0.14	0.03	-0.01
Mass Loss, %	0.52	0.18	0.73	1.23

* Test was terminated at 226 F/T cycles due to the specimen failure.

4.3.2. Results and Discussions

Fresh Concrete Properties

Slump and Temperature:

The slump for all the mixtures ranged between 152 to 191 mm. The temperature of the concrete mixture was maintained between 20.5°C and 21.1°C. HRWR dosages for the control mixture (II-1) and coarse CCA mixture (II-4) are similar. HRWR dosages for the mixtures which used CCA in the "as received" condition was 17% and 58% higher with the higher dosage required for the 21 MPa CCA.

Air content and Density:

The air content varied between 4.8% and 8.5%. For similar air contents as the control mixture it was estimated that slightly higher air entraining admixture dosages (20% to 30%) will be required when the CCA is used in the "as received" condition (Mixtures II-2, II-3). However, when coarse CCA was used (Mixture II-4) no increase in air entraining admixture dosage was required. The density of the control mixture was 2385 kg/m^3. Concrete containing CCA is expected to have lower density due to the lower density of the CCA aggregate. When small amounts of CCA was used in "as received" condition (Mixtures II-2, II-3) concrete density decreased by about 1% to 2% as compared to the control mixture. However when CCA was used in larger quantities (Mixtures II-4) the decrease in density was higher – about 9%. A portion of that lower density was attributed to the higher air content of Mixture II-4.

Harden Concrete Properties

Compressive Strength:

Compared to the control mixture the use of 21 MPa CCA at 356 kg/m^3 did not lead to any strength reductions while the use of 7 MPa CCA at 356 kg/m^3 led to about 10% strength reduction. The use of coarse 21 MPa CCA (Mixture II-4) led to about 16% strength reductions although half of that could be attributed to the much higher air content.

Drying Shrinkage:

The use of CCA led to increased length change due to drying shrinkage. After 180 days of drying the average length change values increased by 15% to 51% with the higher values obtained when 100% Coarse CCA was used.

Rapid Chloride Permeability:

The 90 day RCP values suggested that all four concrete mixtures had moderate chloride ion penetrability with the 100% Coarse CCA mixture having the highest RCP values.

Freeze and Thaw Resistance:

Observations on the ASTM C 666 test results after freeze thaw cycles:

1. Control Mixture – Both specimens had a durability factor in excess of 90% (average 92%), average mass loss of 0.52% and negligible length change. No

visible signs of deterioration could be noted apart from some minor surface scaling (Figure 4.1).

Figure 4.1 Control Mixture after 300 Freeze Thaw Cycles

2. 7 MPa CCA at 356 kg/m^3 – Both specimens failed, i.e. their relative dynamic modulus of elasticity went below 60% in less than 300 cycles. Specimen 1 failed in 107 cycles whereas Specimen 2 failed in 190 cycles. Average mass loss was only 0.18% and average length change was 0.14%. It was obvious that the specimens had cracked up significantly particularly near the ends (Figure 4.2).

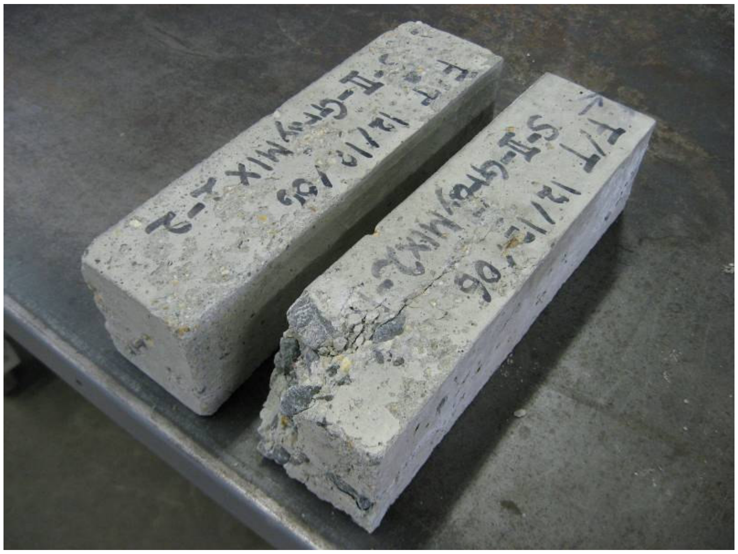


Figure 4.2 7 MPa CCA at 356 kg/m3 Mixture after 300 Freeze Thaw Cycles

3. 21 MPa CCA at 356 kg/m^3 – Both specimens failed, i.e. their relative dynamic modulus of elasticity went below 60% in less than 300 cycles. Specimen 1 failed in 243 cycles where as Specimen 2 failed in 300 cycles. Average mass loss was only 0.73% and average length change was 0.03%. No visible signs of deterioration however could be noted (Figure 4.3).

Figure 4.3 21 MPa CCA at 356 kg/m3 Mixture After 300 Freeze Thaw Cycles

4. 21 MPa CCA at 100% Coarse CCA – Both specimens had a durability factor in excess of 88% (average 89%), average mass loss of 1.23% and negligible length change. The higher mass loss was due to noticeable amount of surface scaling that was observed (Figure 4.4).

Figure 4.4 21 MPa CCA at 100% Coarse Mixture After 300 Freeze Thaw Cycles

Both concrete mixtures containing 356 kg/m^3 of CCA in the “as received” condition had poorer freeze thaw durability. The mixture containing 21 MPa 100% coarse CCA had good freeze thaw durability. These results seem to be consistent with the aggregate sulfate soundness (ASTM C 88) test results, which is normally an indicator test for freeze thaw durability of aggregate. In that test 21 MPa coarse CCA passed the sulfate soundness test where as both the 7 MPa and 21 MPa fine CCA failed the sulfate soundness test. This suggests that the inclusion of fine CCA which occurs in the “as received” condition may lead to poorer freeze thaw performance. However, it should be noted that both the concrete mixtures containing CCA in the "as received" condition had lower measured air contents (about 1 to 2%) where as the mixture containing 21 MPa 100% coarse CCA had higher air content (about 2%) as compared to the control mixture. This was not done on purpose but this may be suggesting that CCA mixture need to have higher air contents to have similar freeze thaw performance as control mixture. A different but related point is that the original concrete from which the CCA was prepared was non-air entrained. Most likely in a freeze thaw environment the original concrete is likely to have air entrainment and it is possible that CCA made from such returned concrete may have better freeze thaw resistance.

Based on the freeze thaw test results it would appear that the use of 21 MPa 100% coarse CCA should be acceptable even in concrete applications that are exposed to freeze thaw environment. However concrete containing CCA in the "as received" condition must be further evaluated for its freeze thaw resistance if that is critical to the application. Evaluation might be based on determination of service records of test sections (if such exist), or freeze thaw testing in accordance with ASTM C666. ASTM C666, Procedure A, used in this study is a very severe test and appropriate for concrete flatwork that will be continuously moist in service with anticipated use of deicing chemicals. Exterior members that are not continuously moist in service, such as vertical members, will not be subject to this very severe exposure and may not require the level of caution expressed in this study.

Chapter 5. Performance Analysis and Modeling

5.1. Introduction

In this chapter the performance results and modeling are presented using the experimental data of Chapter 3, and 4. The non air entrained concrete mixtures with 7 MPa CCA (CCA7) and 21 MPa CCA (CCA21) were used. The Pile1 CCA concrete mixtures were also examined and compared to other CCA concrete mixtures for their mechanical and non-mechanical behavior. The Pile1 CCA was a representative CCA that was "uncontrolled" meaning no proper separation with respect to the strength quality. The Pile1 CCA is normally available in a ready mixed concrete plant. Due to the uncontrolled characteristic of the Pile1 CCA, the concrete mixtures prepared with Pile1 CCA were not included in the analysis and modeling.

The mixture identifications used in this chapter are summarized in Table 5.1. For example Mix No.2 (Mix 2) had 7 MPa CCA with 178 kg/m^3 "as-received condition" from which the volumes of coarse and fine fractions were 7.9% in 0.76 m^3 (1 yd^3) concrete. The CCA "as-received condition" (or simply "as-received") was a mixture of coarse and fine aggregate directly from the crushing the returned concrete. Mix No.9 (Mix 9) had 21 MPa CCA with 100% CCA coarse fraction in which its volume was 39% in 0.76 m^3 (1 yd^3) concrete. In another example, Mix No.11 had 21 MPa CCA with 100%/25% CCA coarse/fine fractions in which their volumes were 46.8% in 0.76 m^3 (1 yd^3) concrete.

Table 5.1 Mixture Identifications

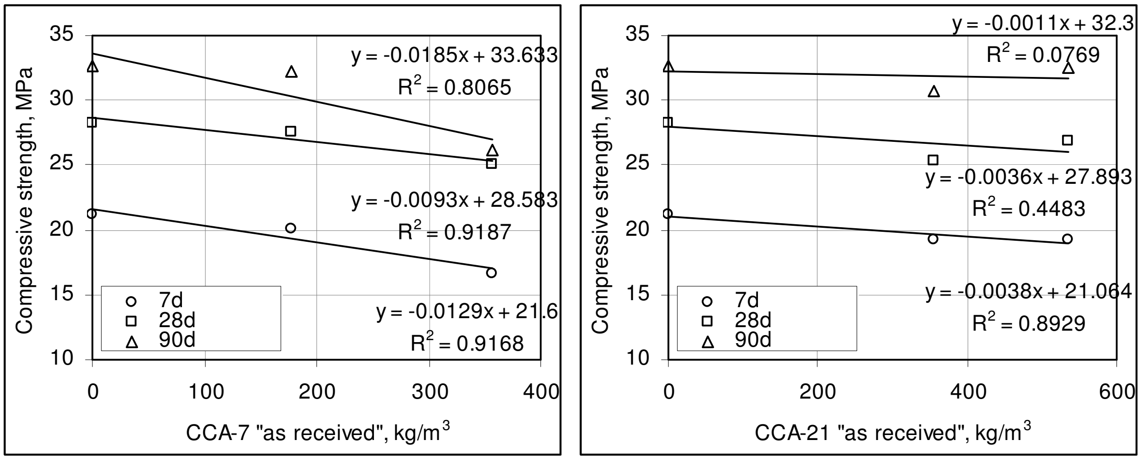
Mix No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**11**	**17**
CCA Type	0	7MPa	7MPa	21Mpa	Pile1	21MPa	7MPa	7MPa	21Mpa	21MPa	Pile1
CCA, kg/m^3	0	178	356	356	356	534	-	-	-	-	-
CCA, coarse, %	0	-	-	-	-	-	50	100	100	100	100
CCA, fine, %	0	-	-	-	-	-	0	0	0	25	0
CCA volume, %	0	7.9	15.5	15.2	16.8	22.6	19.9	40.0	39.0	46.8	38.1

5.2. Analysis and Modeling on Harden Concrete Property

The various harden concrete properties such as compressive strength, elastic modulus, drying shrinkage, and rapid chloride permeability will be discussed for the CCA concrete mixtures with various amounts of CCA as compared to the control concrete mixture which contained no CCA.

5.2.1. Compressive Strength

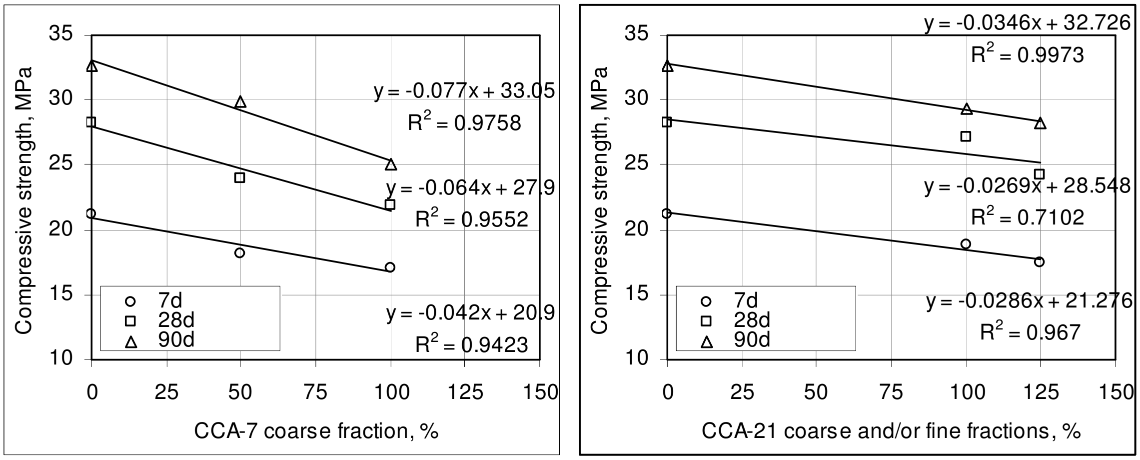
The compressive strength is the most common harden concrete property as a basic indicator of the concrete quality. The compressive strength result was illustrated with various CCA replacements "as-received condition" in concrete as shown in Figure 5.1 (a), (b). In Figure 5.1 (a) the compressive strength for Mix 1, 2, and 3 with 0 kg/m^3, 178 kg/m^3, and 356 kg/m^3 of CCA7 as-received condition, respectively, was shown at ages of seven, 28, and 90 days whereas in Figure 5.1 (b) the compressive strength for Mix 1, 4, and 6 with 0 kg/m^3, 356 kg/m^3, and 534 kg/m^3 of CCA21 as-received condition, respectively, was plotted at the same ages. The linear trend lines with the determination of coefficients (R^2) were also made in the plots. For the CCA7 and the control mixtures the R^2 values at various ages were ranged in 0.81-0.92 indicating a good correlation. Mix 2 had a strength reduction by 0.5-1.2 MPa (1.5-5.5%) and Mix 3 by 3.2-6.6 MPa (11.5-21.8%) at various ages as compared to Mix 1 (control). For the CCA21 and the control mixtures the 0.44 R^2 was obtained at 28, 90 days whereas the 0.89 R^2 was obtained at seven days. Mix 4 had a strength reduction by 1.9-2.8 MPa (6.1-10%) and Mix 6 by 0.1-1.9 MPa (0.4-9.1%) at various ages as compared to Mix 1 (Control) as shown in Figure 5.1 (b). In general the concrete mixtures with CCA7 as-received condition had a lower compressive strength than the concrete mixtures with CCA21 as-received condition consistently over various ages. The strength reduction can be explained by the strength (or quality) of CCA used in concrete. The lower strength CCA such as CCA7 led to a higher strength reduction in concrete. The strength reduction was also affected by the amount of CCA used in concrete. However, it must be noted that the strength reduction can be minimized in CCA concrete mixtures if the strength of CCA is equal or greater than the design concrete strength.



(a) (b)

Figure 5.1 Compressive Strength at Various CCA Replacements with As-Received Condition

Figure 5.2 (a) illustrates the compressive strength result for Mix 1, 7, and 8 with 0%, 50%, and 100% of CCA7 coarse fraction, respectively, in concrete mixtures at ages of 7, 28, and 90 days; whereas, Figure 5.2 (b) shows the compressive strength result for Mix 1, 9, and 11 with 0/0%, 100/0 %, and 100/25% of CCA21 coarse/fine fraction, respectively, in concrete mixtures at same ages. The linear trend lines are indicated with a good correlation with the 0.94-0.98 R^2 at various ages. Mix 7 had a strength reduction by 2.8-4.3 MPa (8.6-15.4%) and Mix 8 by 4.3-7.7 MPa (20.1-23.4%) as compared to Mix 1 (control). The strength reduction was also observed in concrete mixtures with CCA21 coarse/fine fraction, but the reduction was lower than that of CCA7 mixtures. The linear trend lines are indicated with a good correlation with the 0.71-0.99 R^2 at various ages as shown in Figure 5.2 (b). Mix 9 had a strength reduction by 1.2-3.2 MPa (4.1-11.4%) and Mix 11 by 3.9-4.3 MPa (13.3-18.2%) as compared to Mix 1 (control). As observed previously the concrete mixtures with CCA7 indicated generally higher strength reduction than the concrete mixtures with CCA21.



(a) CCA-7 (b) CCA-21

Figure 5.2 Compressive Strength at Various CCA Replacements with Coarse and/or Fine fraction(s)

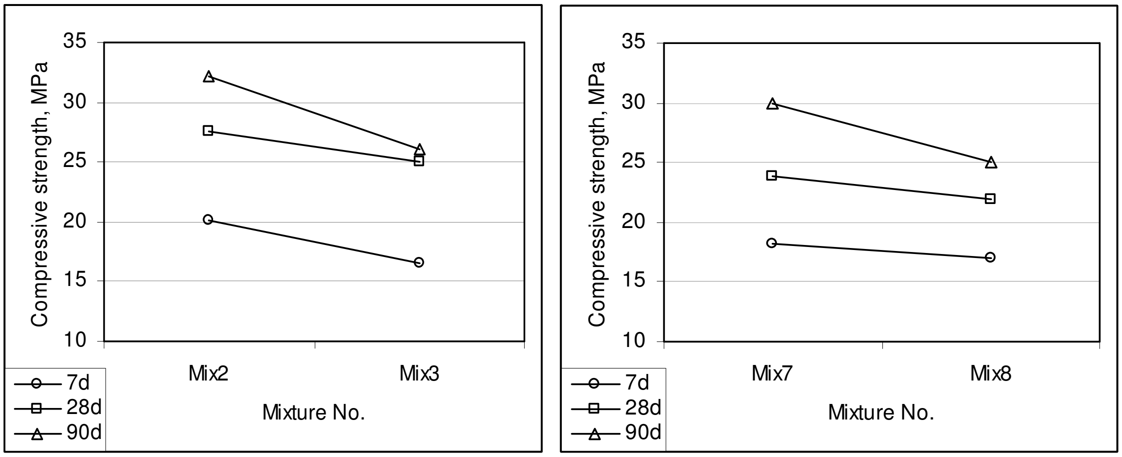
As illustrated in Figure 5.1, Figure 5.2 the strength of concrete mixtures was generally decreased as the amount of CCA either 7 MPa or 21 MPa was increased in concrete mixtures. It was also illustrated that the strength reduction of CCA mixtures was minimized if the strength of CCA was increased. In this study, all concrete mixtures were designed with a constant cement content (297 kg/m^3), but varying amounts of the mixing water in order to meet the target slump range between 125mm and 180 mm at various CCA amounts and types. The varying mixing water content was led to a change of *w/c* ratio. Was the *w/c* ratio change responsible for the strength reduction of the CCA concrete mixtures? In order to answer this question the *w/c* ratio was examined for the CCA mixtures:

- Mix 2, 3 had *w/c* ratios of 0.56, 0.59, respectively, with various amounts of CCA7 as-received condition in concrete mixtures whereas Mix 7, 8 had *w/c* ratios of 0.55, 0.52, respectively, with various amounts of CCA7 coarse fraction in concrete mixtures.
- Mix 4, 6 had *w/c* ratios of 0.58, 0.59, respectively, with various amounts of CCA21 as-received condition in concrete mixtures whereas Mix 9, 11 had a *w/c* ratio of 0.59 both with various amounts of CCA21 coarse and/or fine fraction in concrete mixtures.

For all concrete mixtures the *w/c* ratio, slump, and aggregate absorption are also summarized in Table 5.2. As can be seen from the *w/c* ratio and the corresponding slump the change of *w/c* ratio was well reflected to the change of slump. For example, the *w/c* ratio of Mix 3 was 0.03 higher than that of Mix 2. Thus, the higher *w/c* ratio was increased with the slump by 38 mm but still within the target slump range. Namely, the 0.03 *w/c* ratio change was acceptable to meet the target slump range without significantly affecting the strength change. It is generally accepted that the *w/c* ratio change is allowed within the target slump range in which the strength gain/reduction is minimal. Therefore it is clear that the minimal *w/c* ratio change wasn't a major contributor for the strength reduction. Then what else would be the major contributor(s) to cause the strength loss for the CCA mixtures? They are different CCA amounts and different types (strength levels). For example, Mix 2, 3 had 178 kg/m^3, 356 kg/m^3, respectively, of CCA7 as-received condition in concrete mixtures. As shown in Figure 5.3 (a) the strength result was plotted against the amount of CCA7 in concrete mixtures. Mix 2 had a half amount of CCA7 as-received in concrete mixture and had a slightly lower *w/c* ratio as compared to Mix 3. Due to both the half reduced amount of CCA7 as-received and the slightly lower *w/c* ratio Mix 2 showed a significantly higher strength (on average 15% higher) than Mix 3. In another example, Mix 7, 8 had 50%, 100%, respectively, of CCA7 coarse fraction in concrete mixtures. The strength result for both mixtures was plotted against the amount of CCA7 fraction as shown in Figure 5.3 (b). Mix 7 had 50% less CCA7 coarse fraction but, a slightly higher w/c ratio than Mix 8. Due to the 50% reduced CCA7 coarse fraction in concrete mixture Mix 7 had a higher strength (on average 10%) in spite of an increased *w/c* ratio than Mix 8. From this observation it makes clear that the CCA amounts and types had a significant influence over the strength effect rather than the *w/c* ratio change within the target slump range.

Table 5.2 Summary of Absorption, *w/c* ratio, and Slump for CCA mixtures

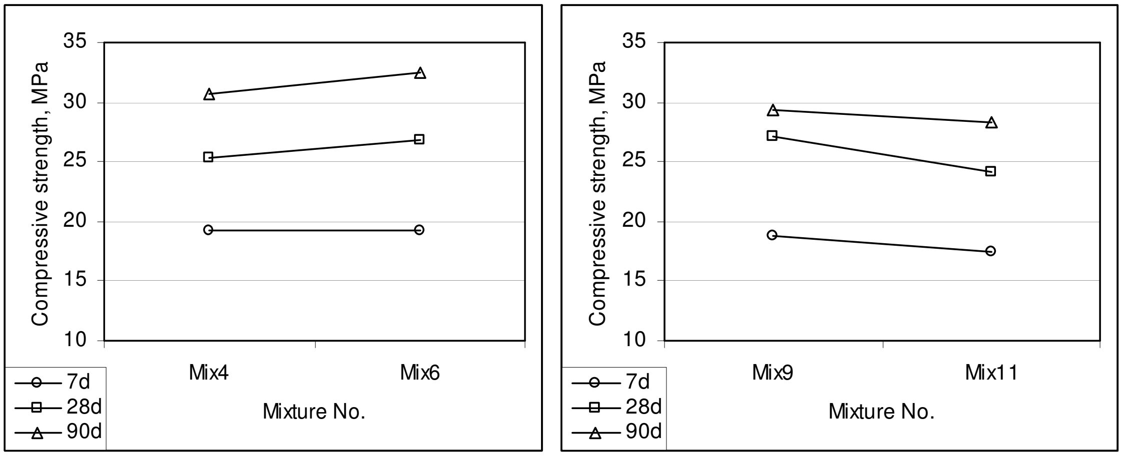
Mix No.	CCA Type	CCA, kg/m^3 "as received"	CCA coarse, %	CCA fine, %	Absorption %	*w/c*	Slump mm
Mix2	7 MPa	178	-	-	6.91	0.56	125
Mix3	7 MPa	356	-	-	6.91	0.59	165
Mix7	7 MPa	-	50	-	4.4	0.55	160
Mix8	7 MPa	-	100	-	4.4	0.52	152
Mix4	21 MPa	356	-	-	5.88	0.58	152
Mix6	21 MPa	534	-	-	5.88	0.59	152
Mix9	21 MPa	-	100	-	4.31	0.59	152
Mix11	21 MPa	-	100	25	4.31(ca), 10.25(fa)	0.59	178



(a) CCA7 replaced with "as received" (b) CCA7 replaced with coarse fraction of CCA

Figure 5.3 CCA7 Compressive Strength Result

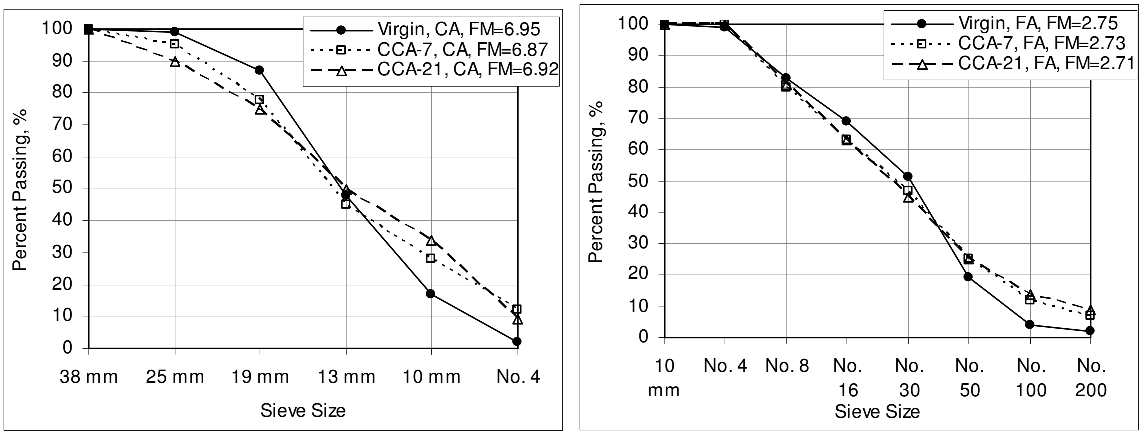
The CCA21 concrete mixtures were also examined as shown in Figure 5.4. Mix 4, 6 had 356 kg/m^3, 534 kg/m^3, respectively, of CCA21 as-received in concrete mixtures. Both mixtures had similar *w/c* ratios. Mix 4 had 170 kg/m^3 (33%) less CCA21 as-received in concrete than Mix 6. As compared to Mix 6, Mix 4 had the same compressive strength at seven days, but had a reduced strength at 28, 90 days as shown in Figure 5.4 (a). Mix 6 had an improved strength without compromising it due to an increased amount of CCA21 as-received in concrete as compared to Mix 4. The strength improvement, due to an increased CCA in concrete, was not observed for the CCA7 concrete mixtures in which the compressive strength was always reduced with increasing CCA7 in concrete mixtures. As it was discussed in Chapter 3 (CCA characterization), the higher strength CCA (such as CCA21) indicated a higher resistance to the toughness and soundness than the lower strength CCA (such as CCA7). The higher resistance due to an improved strength CCA can minimize the strength reduction and potentially can improve the strength of concrete. This was illustrated by Mix 3, 4 with similar mixture ingredients only except different strength CCAs (*ex*. CCA7, CCA21) in concrete mixtures. Mix 4 with CCA21 as-received was improved with the strength by 2.8 MPa higher at seven days compared to Mix 3 with CCA7 as-received. The strength improvement with an increased CCA21 (Mix 6) can be explained by the higher quality CCA and possibly more fines (< 75 μm) in CCA21 as-received contributing dense packing of the paste structure. It is clear the compressive strength of CCA concrete can be minimized with a higher quality CCA. In Figure 5.4 (b) Mix 9, 11 were illustrated for the strength effect of CCA21 fine aggregate in concrete mixtures. Mix 9, 11 had 100/0%, 100/25%, respectively, of CCA coarse/fine fraction in concrete mixtures. Mix 9 with 25% CCA21 fine fraction led to a strength reduction by 7% on average at various ages as compared to Mix 11 with no CCA21 fine fraction in concrete mixture.



(a) CCA21 "as-received" condition (b) CCA21 coarse and/or fine fraction(s)

Figure 5.4 CCA21 Compressive Strength Result

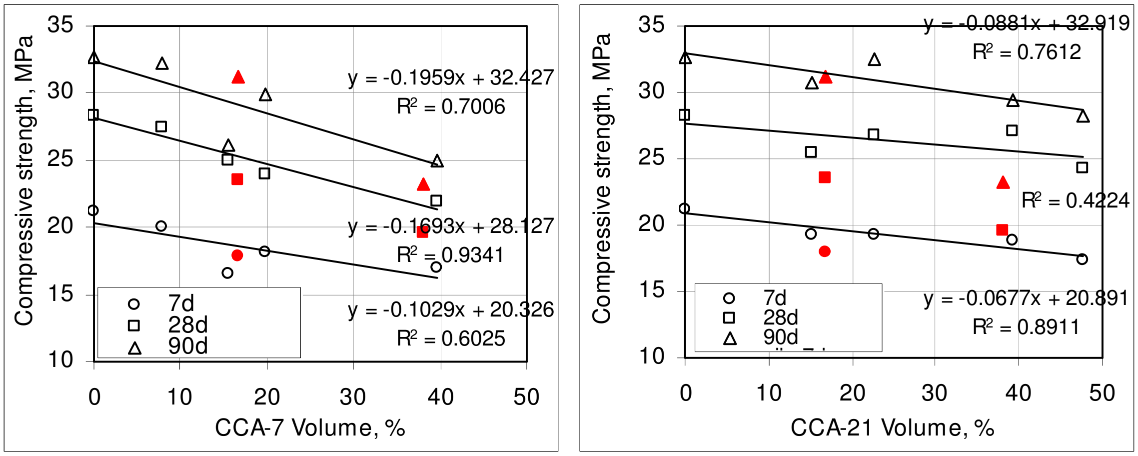
The aggregate particle size distributions (PSD) of the virgin, CCA7, and CCA21 aggregates were also examined for any potential impact to the compressive strength as shown in Figure 5.5. Figure 5.5 (a) illustrated the coarse aggregate particle size distributions. Both CCA7 and CCA21 had slightly less passing (more retained) on 25 mm and 19 mm sieve sizes, but had slightly more passing (less retained) on 10 mm and No.4 sieve sizes than the virgin coarse aggregate. The difference of the particle size distributions between the virgin coarse aggregate and both CCA coarse aggregates was about 10% or less. Figure 5.5 (b) illustrated the fine aggregate particle size distributions. Both CCA7 and CCA21 showed slightly less passing (more retained) on No.16 sieve size but had more passing (less retained) on No.100, No.200 sieve sizes than that of the virgin fine aggregate. The difference of the particle size distributions between the virgin fine aggregate and both CCA fine aggregates was about 5% or less. The fineness modulus (FM) of virgin aggregate and both CCA aggregates was similar. From this observation, the aggregate packing characteristic for both the virgin aggregates and the CCA aggregates was fairly similar. Therefore, it is reasonable to say that the PSD of the virgin and CCA aggregates had less or no influence over the compressive strength of concrete mixtures.



(a) Coarse Aggregate (b) Fine Aggregate

Figure 5.5 Aggregate Particle Size Distributions

The CCA mass with both as-received condition and coarse/fine fraction was converted into the CCA volume in 0.76 m^3 (1 yd^3) concrete. For example the CCA as-received condition was first divided into the coarse and fine fraction by the ca/fa ratio obtained from CCA separation over 4.7 mm (No.4) sieve size (refer Table 3.2 in Chapter 3). After the coarse and fine fraction divided from CCA as-received the specific gravity of CCA coarse and fine fraction was used to calculate the volumes of CCA coarse and fine fraction. Lastly CCA volume was divided by 0.76 m^3 (1 yd^3) concrete volume. For example, 20% CCA volume in Figure 5.6 indicates 20% CCA in 0.76 m^3 (1 yd^3) concrete volume.



(a) CCA7 (b) CCA21

* The red points in the chart are the result of the Pile1 CCA that was obtained from one of many CCA stock piles (mixed with any source of returned concrete regardless strength, air entrainment, etc.) in the ready mixed concrete plants. The Pile1 CCA data are plotted in the chart for the reference purpose not for the analysis purpose.

Figure 5.6 Compressive Strength vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

In Figure 5.6 (a), (b) the compressive strength result was illustrated with the corresponding CCA volume at ages of 7d, 28d, and 90d for the CCA and the control mixtures. The linear trend lines were the best. The R^2 values were ranged in 0.61-0.93 for the CCA7 and the control mixtures at three ages as shown in Figure 5.6 (a). The 0.61 R^2 was observed at 7d whereas the 0.93 R^2 was found at 28d. For the CCA21 and the control mixtures the R^2 values were ranged in 0.42-0.89 at three ages as shown in Figure 5.6 (b). The 0.42 R^2 was observed at 28d whereas the 0.89 R^2 was found at 7d. The Pile1 CCA (red color) was also plotted on the charts to examine the strength behavior of the uncontrolled CCA mixtures. Due to uncertain material compositions of Pile1 CCA they were not used in the analysis and modeling purpose. Mix 5 had 356 kg/m^3 of Pile1 CCA as-received (16.8%) in concrete with 0.58 *w/c* ratio whereas Mix 17 had 100% of Pile1 CCA coarse fraction (38.1%) in concrete with 0.69 *w/c* ratio. Mix 5 showed a similar strength to Mix 3 with 356 kg/m^3 CCA7 as-received whereas Mix 17 had a similar strength to Mix 8 with 100% CCA7 coarse fraction.

For the practical application in the ready mix concrete plants the proper separation of the returned concrete mixtures with various strength levels will be associated with the spaces and the management cost. However, in most ready mix concrete plants the spaces and management cost are normally restrained. Thus, the most practical approach for the proper separation of the returned concretes is to use broader strength ranges such as low strength, medium strength, and high strength. The low strength may be ranged in less than 7 MPa, the medium strength may be ranged in 7-21 MPa, and the high strength may be ranged in greater than 21 MPa.

So, CCA7 and CCA21 mixtures were put together representing as medium strength range and evaluated with the control mixture. The compressive strength result for the CCAs and the control mixtures was illustrated in Figure 5.7. The linear trend lines were the best. The R^2 values were ranged in 0.34-0.42 indicating a poor correlation between the compressive strength and CCA volume. Due to a poor correlation the simple linear model as a function of the CCA volume cannot be established for the compressive strength.

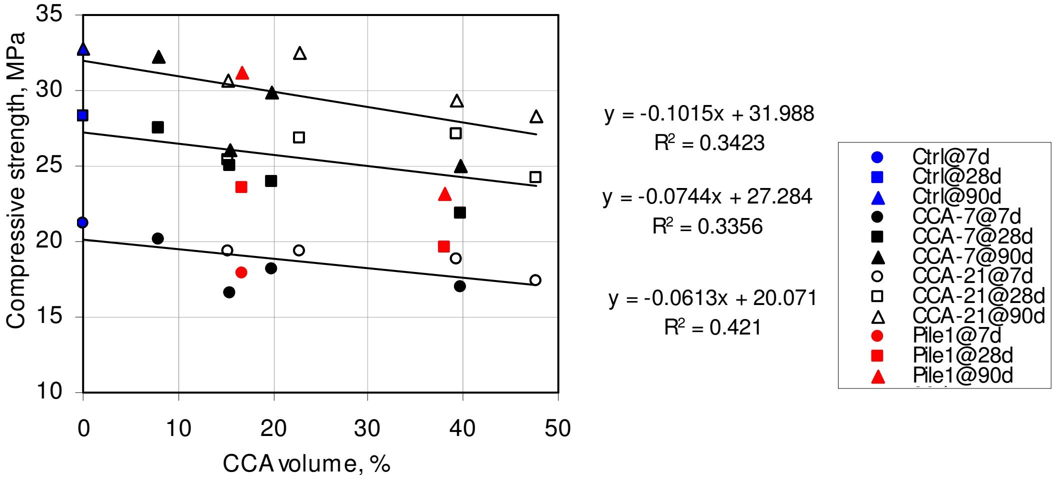


Figure 5.7 Compressive Strength vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

Step-Wise Multiple Regression Analysis

Since one dimensional linear regression model as a function of CCA volume (independent variable) could not be established the multiple regression model with multiple variables was attempted for the compressive strength of CCAs and the control mixtures. The compressive strength result was analyzed with the mixture ingredients using the multiple regression analysis in which the compressive strength was used as a dependent variable and the mixture ingredients were used as independent variables.

The linear form of the model for multiple regressions is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon$$

Equation 14

Where y is a dependent variable, $x_1, \ldots x_i$ are independent variables and $\beta_0 .... \beta_i$ are experimental coefficients of regression model. F test and T test were used to test the validity of the models and testing the coefficients of the multiple regression models with 95% significance. The step wise multiple regression analysis was conducted to the mixture ingredients for independent variables and corresponding compressive strength result for the dependent variable. The F test was used to test the validity of the model while the T test was used for testing the coefficients of the multiple regression model. In the stepwise regression analysis, non significant variables (independent variables) were first examined and removed one by one until the F and T tests were satisfied.

For example, in Table 5.3 an acceptable F test (Significance $F < 0.05$; f theoretical equal to 7.28, $f > F_{0.05,2,9} = 4.26$) for the CCAs and the control mixtures was obtained with two independent variables remained (Significance $T < 0.05$; t theoretical equal to $t > t_{0.025,10} = 2.228$ or $t < -2.228$) whereas the rest independent variables such as volumes of air content, virgin coarse aggregate, virgin fine aggregate, and cement were removed as they were found to be insignificant during the step wise regression analysis. In the analysis, the most significant variables (independent variables) for the compressive strength result were found to be the volumes of CCA and mixing water. As previously discussed, the CCA amounts and types were the main influencing factors to affect the compressive strength while the *w/c* ratio change within acceptable slump range was a minor factor to influence the strength. On the other hand, the rest of the mixture ingredients (independent variables) such as the volumes of cement, air content, and virgin aggregates were found to be insignificant and removed in the analysis because:

- the volume of cement was constant for all mixtures

- The volume of air content stayed relatively low as all mixtures used in the analysis were non air concrete mixtures. The entrapped air in concrete was in many cases known to be less influencing for the compressive strength than the entrained air in concrete.
- the volume of virgin fine aggregate in CCAs mixtures was varied at -2%~25% (13% on average) as compared to the control mixture whereas the volume of virgin coarse aggregate in CCAs mixtures was varied at 9%~100% as compared to the control mixture. Both virgin fine and coarse aggregates were also found to be insignificant to influence the compressive strength.

The multiple regression analysis result with 0.79 R^2 is shown in Table 5.3

Table 5.3 Step Wise Regression Analysis Result for CCAs and Control Mixtures

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.79
R Square	0.62
Adjusted R Square	0.53
Standard Error	1.26
Observations	12

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	2	23.024	11.512	7.2836	0.0131
Residual	9	14.225	1.58054		
Total	11	37.249			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	49.79	9.787	5.088	7E-04	27.65	71.94
x_1 *(vol. of water)*	-3632	1582	-2.295	0.047	-7212	-52.21
x_2 *(vol. of CCA)*	-9.589	3.334	-2.876	0.018	-17.13	-2.046

Thus, the proposed model is,

$$y = 49.8 - 3632 \cdot \left(x_1^{-1}\right) - 9.6 \cdot \left(x_2\right)$$ **Equation 15**

Where,

y = compressive strength at 28 days (MPa)

x_1 = volume of water (m^3) in 0.76 m^3 (1 yd^3) concrete volume

x_2 = volume of CCA (m^3) in 0.76 m^3 (1 yd^3) concrete volume

In Table 5.4 an acceptable F test (Significance $F < 0.05$; f theoretical equal to 6.47, $f > F_{0.05,2,8} = 4.46$) for the CCA7 and CCA21 mixtures was also obtained with the same two variables remained (Significance $T < 0.05$; t theoretical equal to $t > t_{0.025,9} = 2.262$ or $t < -2.262$) whereas the remaining independent variables such as the volumes of air content, virgin coarse aggregate, virgin fine aggregate, and cement were found to be insignificant in the analysis. These insignificant variables were removed due to partly constant (cement) in the mixtures, partly staying low (air content), and partly less influencing (virgin aggregates) to the strength as previously explained. The multiple regression analysis result with 0.79 R^2 is shown in Table 5.4.

Table 5.4 Step Wise Regression Analysis Result for CCA Mixtures

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.79
R Square	0.62
Adjusted R Square	0.52
Standard Error	1.19
Observations	11

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	18.182	9.0911	6.467	0.0213
Residual	8	11.246	1.4058		
Total	10	29.428			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	47.245	9.2705	5.0963	0.0009	25.868	68.623
x_1 *(vol. of water)*	-3797	1491.6	-2.545	0.0344	-7236	-357
x_2 *(vol. of CCA)*	296.9	115.63	2.5677	0.0332	30.264	563.53

Thus, the proposed model is,

$$y = 47.3 - 3797 \cdot \left(x_1^{-1}\right) + 296.9 \cdot \left(x_2\right) \qquad \textbf{Equation 16}$$

Where,

y = compressive strength at 28 days (MPa)

x_1 = volume of water (m^3) in 0.76 m^3 (1 yd^3) concrete volume

x_2 = volume of CCA (m^3) in 0.76 m^3 (1 yd^3) concrete volume

Strength-Porosity Model

With the highly porous characteristic of CCA due to the paste attached/coated over the virgin particle, the porosity of CCA can affect the compressive strength of the concrete mixtures significantly. Thus, the CCA concrete strength can depend on the pore volume in CCA.

Popovics (1987) presented a mathematical model to describe the quantitative effect of macro porosity (air content and/or larger pores) on the reduction of concrete strength. The mathematical model (Equation 17) demonstrates that the compressive stress concentrations at the boundary of a void (pore) cause an additional reduction in strength. It also demonstrates that the rate of strength reduction increases with the magnitude of the stress applied in the specimen. The mathematical model is expressed as follows:

$$f_{rel} = \left(1 - \frac{a}{a_{cr}}\right) 1.0 \exp\left[-\delta\left(\frac{a}{a_{cr}}\right)\right]$$

Equation 17

Where,

f_{rel} = relative value of strength as a fraction of the strength of pore free concrete

a = volume of macroporosity in the concrete

a_{cr} = critical volume of macroporosity that is the macroporosity at which the strength becomes zero

δ = experimental parameter which depends on the stress level in the specimen

The first term of equation, $(1-a/a_{cr})$ reflects the reduction in the quantity of solid load-carrying material in the specimen (independent of the magnitude of the stress field produced by the externally applied loads). The second term represents the effect of macro porosity, primarily, for the effect of compressive stress concentrations at the boundary of pores/weak inclusions. Popovics (1987) reported a value of a_{cr} of about 60% for plain concrete under tensile and compressive loading. The effect of stress concentration on the strength reduction is defined by the experimental parameter.

The Popovics model also accounts for the stress concentrations at the tip of the pores surrounded by the homogeneous paste matrix while transferring the external loading. The model is considered with two products among which one of them is the volume reduction and the other is the stress concentrations at the tip of pores when externally loaded. Adding CCA in concrete the underlying assumption of the homogeneous paste matrix through which the gradual stress concentrations are made at the tip of pores cannot be made. Because the old paste coated on CCA particle adds another paste layer within the new paste matrix in concrete. Also, adjusting the strength of CCAs, such as CCA7, CCA21, have different paste stiffness which will interact differently with the new paste matrix in concrete when externally loaded. Due to the intricacy of the old paste on CCA situated within the new paste matrix, and their two different levels of stress concentrations, the Popovics model was found to be inappropriate to establish the CCA concrete strength model.

The CCA concrete is a two paste system with the main portion of the new paste matrix and the minor portion of the old paste matrix from CCA. As indicated earlier in the Popovics model, the porosity is used to determine concrete strength. Thus, a model is attempted to be developed for the concrete strength considering the porosity and associated influencing factors using the following form:

$$\begin{aligned} y = \beta_0 + \beta_1 \cdot (Porosity.New.Paste) + \beta_2 \cdot (Porosity.Old.Paste) \\ + \beta_3 \cdot (Porosity.Asso.Factor)x_3 + \varepsilon \end{aligned}$$

Equation 18

The porosity of the new and old paste is of importance in this model. Also, the porosity of associated factor(s), such as *w/c* ratio, interfacial transitional zone (ITZ) between paste and aggregate, air content, etc., have to be analyzed in conjunction with the porosity of the paste matrixes. The porosity of the old paste from CCA was quantified by the absorption test accounting for the permeable pores whereas the porosity of the new paste was quantified using Power's model (1958) [55,56]. The virtue of using Power's model should be its age and reputation by which the model has been verified, re-visited, and simplified by many other researchers. Also, it provides the quantitative volume proportions of cement paste as a function of the degree of hydration. The volume proportions of cement paste are composed of the chemical shrinkage, capillary water, gel water, hydrated products, and cement. From this volume proportions the porosity of cement paste can be quantified as a function of the degree of hydration. Power classified the water in the hardened cement paste into evaporable and non evaporable water. The evaporable water includes water contained in the capillaries (capillary pores) and water adsorbed held close to the solid surface. Since the porosity that affects concrete strength is relatively larger size pores, the capillary and macro pores (> 50 nm) are therefore considered to the effect of concrete strength. In this study, the porosity of the new cement paste was calculated at 80% degree of hydration as the concrete strength was taken at an age of 28 days at which it was considered to be about 80-90% of the infinite strength at an infinite age. The details of the porosity calculation using Power's model is provided in Appendix B.

The stepwise multiple regression analysis was conducted using the porosity of the cement paste and the associated influencing factor(s) as independent variables and the compressive strength as the dependent variable. As shown in Table 5.5 an acceptable F test (significance $F < 0.05$; f theoretical equal to 6.47, $f > F_{0.05,4,4} = 9.84$) was obtained for the CCAs and the control mixtures. The four independent variables remained significant (Significance $T < 0.05$; t theoretical equal to $t > t_{0.025,7} = 2.365$ or $t < -2.365$). These variables such as the porosity of the new paste, porosity of the old paste, *w/c* ratio, and volume of virgin aggregates were found to be significant to the CCA and the control concrete strength model. The *w/c* ratio, one of the four significant variables, is found to be important since it is associated with the degree of the cement hydration. Also, the volume of the virgin aggregates is believed to be associated with the ITZ zone between the paste and the aggregate. The air content was also considered as one of the dependent variables; however, it was found to be insignificant and was removed from the model. As indicated earlier, the entrapped air in concrete is less significant to the concrete strength than the entrained air.

The multiple regression analysis result with 0.95 R^2 is shown in Table 5.5.

Table 5.5 Multiple Regression Analysis Result for CCAs and Control Mixtures

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.95
R Square	0.91
Adjusted R Square	0.81
Standard Error	0.88
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	30.00	7.501	9.640	0.025
Residual	4	3.11	0.778		
Total	8	33.11			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	834	284	2.943	0.042	47	1622
Porosity.N.Paste	44277	15041	2.944	0.042	2516	86038
Porosity.O.Paste	-2408	702	-3.431	0.027	-4356	-459
w/c	-1848	648	-2.850	0.046	-3648	-48
Vir.Agg.Vol.	-104	33	-3.135	0.035	-195	-12

Thus, the proposed model is,

$$f_c^{28d} = 834 + 44277 \cdot (x_1)^{1.72} - 2408 \cdot (x_2) - 1848 \cdot (x_3) - 104 \cdot (x_4)^{1.3} \quad \textbf{Equation 19}$$

Where

x_1 = Porosity of new cement paste (m^3)

x_2 = Porosity of old cement paste (m^3)

x_3 = w/c ratio

x_4 = Virgin coarse and fine aggregate volume (m^3)

The data used in the strength-porosity model are summarized in Table 5.6.

Table 5.6 Input Data Used in Strength-Porosity Model

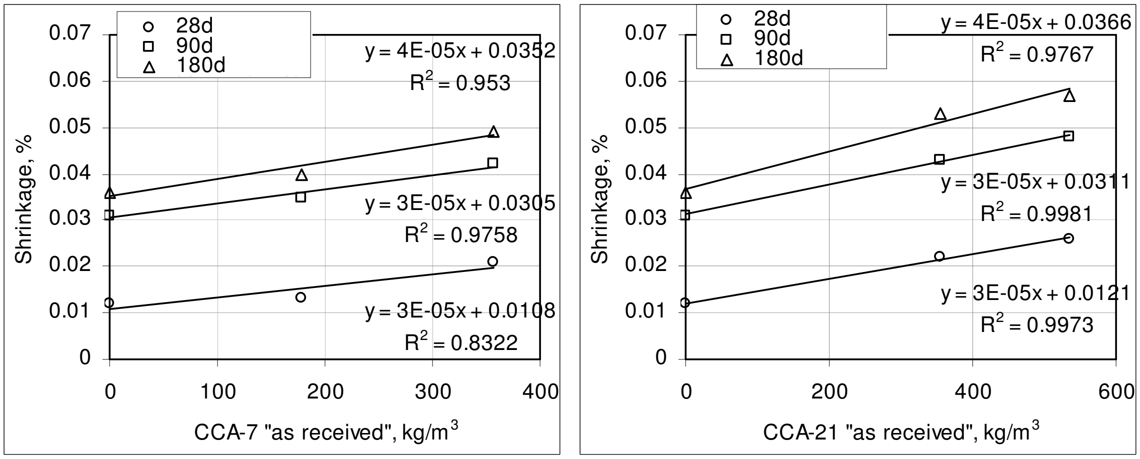
Mix #	CCA Type	Strength(28d) MPa	Por.N.C.* m^3	Por.O.C.$^+$ m^3	*w/c*	Vir.Agg.Vol. m^3
1	control	28.3	0.056	0.000	0.58	0.542
2	7 MPa	27.5	0.052	0.004	0.56	0.484
3	7 MPa	25.0	0.058	0.008	0.59	0.423
7	7 MPa	23.9	0.050	0.007	0.55	0.393
8	7 MPa	21.9	0.042	0.013	0.52	0.242
4	21 MPa	25.4	0.056	0.007	0.58	0.428
6	21 MPa	26.8	0.058	0.010	0.59	0.369
9	21 MPa	27.1	0.057	0.013	0.59	0.246
11	21 MPa	24.2	0.059	0.019	0.59	0.182

* Por.N.C. = Porosity of New Cement Paste (Degree of Hydration at 80%)

$^+$ Por.O.C. = Porosity of Old Cement Paste

5.2.2. Drying Shrinkage

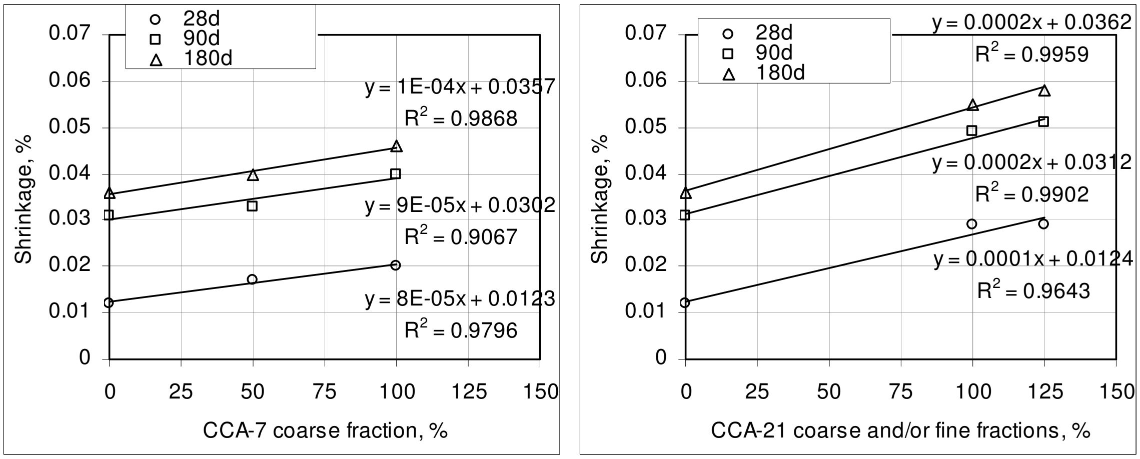
The drying shrinkage of CCA and the control mixtures was examined by considering various amounts of CCA and shrinkage data at 28d, 90d, and 180d. Figure 5.8 (a) illustrates the drying shrinkage result for Mix 1, 2, and 3 with 0 kg/m^3, 178 kg/m^3, 356 kg/m^3, respectively, of CCA7 as-received in concrete mixtures whereas Figure 5.8 (b) shows the drying shrinkage result for Mix 1, 4, and 6 with 0 kg/m^3, 356 kg/m^3, 534 kg/m^3, respectively, of CCA21 as-received in concrete mixtures. The linear trend line was the best. For the CCA7 and the control mixtures the R^2 values were ranged in 0.83-0.98 indicating a good correlation between drying shrinkage and the amount of CCA7 as-received condition at various ages. Mix 2, 3 had on average 10.7%, 46.6%, respectively, higher shrinkage than Mix 1 (control) at various ages. For the CCA21 and the control mixtures the R^2 values were ranged in 0.98-0.99 indicating a good correlation at various ages. Mix 4, and 6 had on average 52.6%, and 72.6%, respectively, higher shrinkage than Mix 1 (control) at various ages. From this observation, CCA21 mixtures showed much higher shrinkage than CCA7 mixtures as compared to the control mixture. The higher shrinkage result can be explained by the paste content attached on CCAs. CCA7 was originally made from 7 MPa strength returned concrete; whereas, CCA21 was originally made from 21 MPa strength returned concrete. The 21 MPa strength returned concrete had more cement content than the 7 MPa strength returned concrete because the higher strength returned concrete was designed with more cement content. Therefore, CCA21 had more cement paste attached than CCA7. The higher the amount of cement paste attached/coated on CCA21 resulted in higher drying shrinkage in concrete.



(a) (b)

Figure 5.8 Shrinkage vs CCA Replacements with As Received Condition

Figure 5.9 (a) illustrates the drying shrinkage result for Mix 1, 7, and 8 with 0%, 50%, and 100% of CCA7 coarse fraction, respectively, in concrete mixtures whereas Figure 5.9 (b) shows the drying shrinkage result for Mix 1, 9, and 11 with 0/0%, 100/0%, 100/25% CCA21 coarse/fine fractions, respectively, in concrete mixtures. The R^2 values for both CCAs and the control mixtures were greater than 0.9 indicating a good correlation at various ages. Mix 7, 8 had on average 10.1%, 33.1%, respectively, higher shrinkage than Mix 1 whereas Mix 9, 11 had on average 83.2%, 92.5%, respectively, higher shrinkage than Mix1 at various ages. As observed previously CCA21 mixtures had much higher drying shrinkage than CCA7 mixtures as compared to the control mixture.



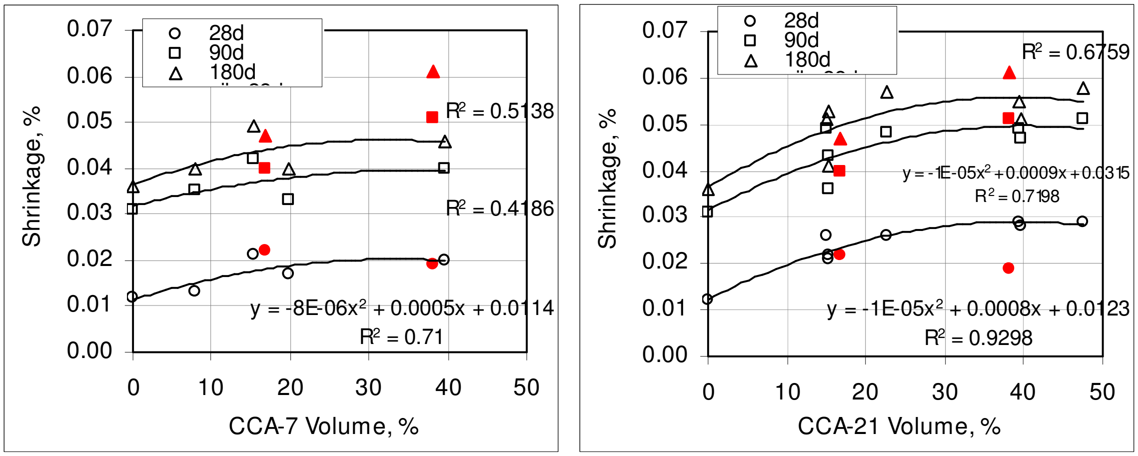
(a) (b)

Figure 5.9 Shrinkage vs CCA Replacements with Coarse and/or Fine fraction(s)

It must be noted the drying shrinkage rate was slowing down significantly during the later 3 month periods from 90 days to 180 days as opposed to the first 3 month periods at which the drying shrinkage rate was fast significantly as illustrated in Figure 5.8, Figure 5.9. The drying shrinkage rate for the first 3 month periods (0d-90d) was at least 3 times faster than that for the later 3 month periods (90d-180d). In other words, most of drying shrinkage was happened during the first 3 month periods. It must also be noted that the overall drying shrinkage behavior over time for the CCA7, CCA21 mixtures was similar to the control mixture. This similar drying shrinkage can indicate that the hyperbolic equation shrinkage model in ACI 209 for the Portland cement concrete is applicable for the CCA concrete mixtures as well. The drying shrinkage model for the CCA concrete mixtures will be discussed in the modeling section.

Figure 5.10 illustrates the drying shrinkage result against the corresponding CCA volume in 0.76 m^3 (1 yd^3) concrete along with Pile1 CCA mixtures (red color). Generally Pile1 CCA mixtures showed inconsistent shrinkage behavior over time with various amounts of Pile1 CCA as a result of uncontrolled separation and uncertain material compositions such as air content, chemical admixtures, mineral admixtures, cement content, etc. whereas CCA7, CCA21 mixtures had consistent shrinkage behavior over time because of the controlled separation and traceable material compositions. The best trend line was found to be a second degree quadratic line as shown in Figure 5.10. For the CCA7 and the control mixtures the R^2 values were ranged in 0.42-0.71 indicating a poor to moderate correlation at various ages. The 0.71 higher R^2 was observed at 28d whereas the 0.41 lowest R^2 was obtained at 90d. For the CCA21 and the control mixtures the R^2 values were ranged in 0.68 – 0.93 indicating a moderate to good correlation at various ages. The 0.93 highest R^2 was obtained at 28d whereas the lowest 0.68 R^2 was observed at 180d.

In the observation the drying shrinkage impact was minimal when CCA7 was used with less than 10% volume whereas the drying shrinkage impact was relatively high when CCA21 was used with the same 10% volume as compared to the control mixture. The drying shrinkage was significantly increased with 15% volume of CCA21 in concrete as compared to the control mixture. Therefore, CCA with various amounts and types (strength levels) can affect the drying shrinkage significantly.



(a) (b)

Figure 5.10 Shrinkage vs CCA Replacement by Volume in 0.76 m^3 (27 ft^3) Concrete

The drying shrinkage result was also put together with CCA7, CCA21 as representing medium strength range as shown in Figure 5.11 with the control mixture. The second degree quadratic trend line was best to achieve the highest correlation (R^2). The R^2 values were ranged in 0.52 – 0.68 indicating a moderate correlation at various ages. Due to low correlation, the analysis model to predict the drying shrinkage as a function of the CCA volume was not proposed.

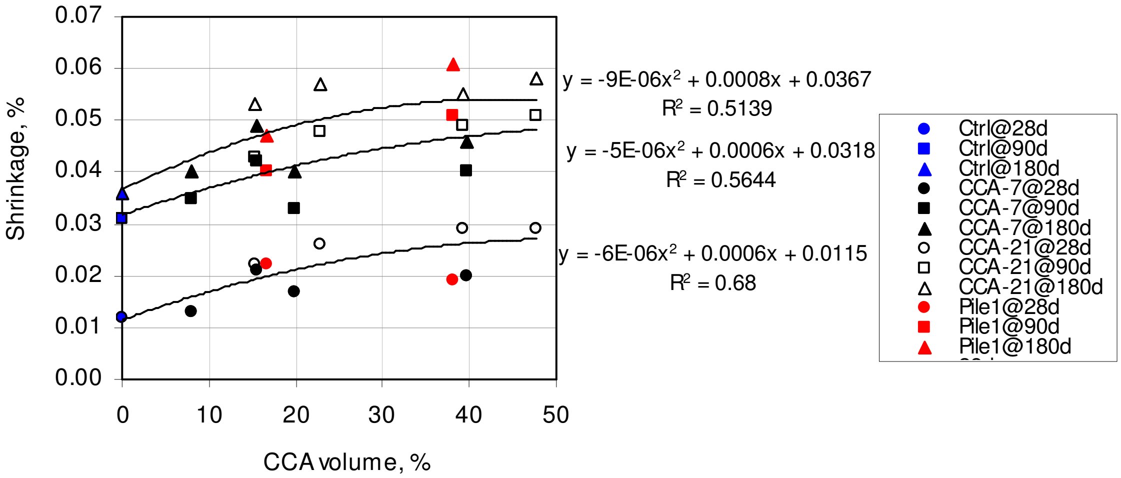


Figure 5.11 Shrinkage vs CCA Replacement by Volume in 0.76 m^3 (27 ft^3) Concrete

Shrinkage Model

The step wise multiple regression analysis was also conducted for the dry shrinkage result as dependent variable and the mixture ingredients such as volumes of air content, mixing water, cement, virgin coarse aggregate, virgin fine aggregate, and CCA as independent variables. In the multiple regression analysis, the CCA volume was found to be insignificant and removed for the model parameters. Since the CCA variable was removed in the multiple regression analysis, the drying shrinkage model was not established to the mixture compositions. As it was mentioned in the regression analysis, the CCA volume was not a good indicator for the drying shrinkage of concrete because the drying shrinkage is associated with the moisture loss in the paste matrix not in the solid – such as aggregate particle. The CCA volume was composed of the volume of the paste coated on the volume of solid aggregate particle.

As discussed the drying shrinkage is related to the cement paste content of the concrete. Therefore, the cement paste volume should be a good indicator for drying shrinkage of concrete. The cement paste is composed of the cement and the mixing water in concrete. In conventional (control) concrete the cement paste volume can be easily obtained from the mixture design. However, in CCA concrete the cement paste volume has to be the sum of the new cement paste and old cement paste from CCA. The volume of the new cement paste can be obtained from the mixture design; whereas, the volume of the old cement paste in CCA cannot. That's because CCA was obtained from the returned concrete that might be a mixture of a certain strength range if the returned concrete was controlled in separation. Thus, the paste attached/coated on CCA has to be quantified either experimentally or analytically. Yet there are no standard testing methods available to quantify the paste content on CCA, but the testing method to quantify the paste on CCA is underway. In this study, the original returned concrete mixtures, from which different strength CCAs were prepared, are provided with the mixture design proportions. Thus, the following analytical approach is proposed to estimate the quantity of the old mortar and cement paste on CCA with three steps:

- *Step 1* is to calculate the mortar paste volume in the original returned concrete mixtures from which CCAs were produced. The volume of the mortar paste was obtained with the sum of cement, mixing water, air, and fine aggregate volumes and the volume was divided by 0.76 m^3 (27 ft^3) concrete volume. The mortar paste volume in the original returned concrete for the CCA7, CCA21 was 62.4%, 60.4%, respectively.

- *Step 2* is the mortar paste volume correction with, so called, Crushing Operation Loss Factor (simply COLF). COLF is derived from the crushing operation. The returned concrete was dumped out to the ground and after a certain period of time it was fed into the crusher for breaking into smaller particles. During the crushing operation some of the mortar and aggregate fractions of the returned concrete are lost. This loss is equal to the mortar paste volume (*Step 1*) multiplied by COLF. The COLF derived from the actual crushing operation has to reflect a similar mechanical crushing operation. The LA abrasion test result was used to calculate the COLF with the net result between CCA and the virgin aggregate. The LA abrasion test result for the CCA7, CCA21, and the virgin aggregate was 23.8%, 26%, and 13%, respectively. The LA abrasion result for the CCA7, CCA21 was used with an average value of 25%. The COLF was calculated with the CCA abrasion result subtracted from the virgin aggregate abrasion result.

- *Step 3* is to calculate the cement paste volume from the mortar paste volume with COLF. The cement paste volume was calculated with the corrected mortar paste volume (in *Step 2*) multiplied by the ratio of cement to mortar paste volume obtained in the original returned concrete.

The three steps are illustrated in Figure 5.12. Also, a step by step calculation is included in the following example:

Example of cement paste volume calculation on CCA aggregate:

Mix 2 was selected to illustrate the numerical example of calculating total cement paste which is the sum of new cement paste and old cement paste from CCA.

Mix 2 had 178 kg/m^3 of CCA7 as-received condition in concrete mixture. First, the mass of CCA as-received must be divided into CCA coarse and fine fraction. The volumes of CCA coarse and fine fraction were 0.04 m^3, and 0.02 m^3, respectively. The corresponding volume of CCA coarse and fine fraction expressed as a percentage in unit concrete was 5.3% and 2.6%, respectively.

Since the aim is to calculate the volumes of the mortar and paste attached/coated on CCA7. The mortar and paste fraction in the original returned concrete can be obtained in the mixture design proportions.

In the original returned concrete mixture design of CCA7, the cement paste volume was 22% in the unit concrete volume whereas the mortar paste volume was 62.1% in the unit concrete volume. The volume ratio of the cement to mortar paste was 0.35.

As described in *Step 2,* the Corrected Mortar Paste Volume (CMPV) can be calculated by the Mortar Paste Volume (MPV) in the original returned concrete and subtracted by COLF as illustrated:

$$\text{CMPV} = \text{MPV} \times (1 - \text{COLF}) = 62.1\% \times (1 - 12\%) = 54.6\%$$

Where COLF was calculated as:

$$\begin{aligned}\text{COLF} &= \text{LA abrasion (CCA7)} - \text{LA abrasion (Virgin aggregate)} \\ &= 25\% - 13\% = 12\%\end{aligned}$$

The Corrected Cement Paste Volume (CCPV) can be obtained from CMPV multiplied by the volume ratio of cement to mortar paste in the original returned concrete as illustrated:

$$\text{CCPV} = \text{CMPV} \times \text{CP/MP} = 54.6\% \times 0.35 = 19.4\%$$

Therefore, the Total Mortar Paste (TMP) attached/coated on CCA7 coarse fraction can be obtained from CCA7 coarse fraction volume (5.3%) multiplied by CMPV (54.6%) as illustrated:

$$\text{TMP(CCA7 coarse agg.)} = 5.3\% \times \text{CMPV} = 5.3\% \times 54.6\% = 2.9\%$$

The total mortar paste attached on CCA7 fine fraction can be obtained from CCA7 fine fraction volume (2.6%) multiplied by CMPV as illustrated:

$$\text{TMP(CCA7 fine agg.)} = 2.6\% \times \text{CMPV} = 2.6\% \times 54.6\% = 1.4\%$$

The Total Cement Paste (TCP) coated on CCA7 coarse fraction can be calculated from CCA7 coarse fraction volume multiplied by CCPV (19.4%) as illustrated:

$$\text{TCP(CCA7 coarse agg.)} = 5.3\% \times \text{CCPV} = 5.3\% \times 19.4\% = 1.4\%$$

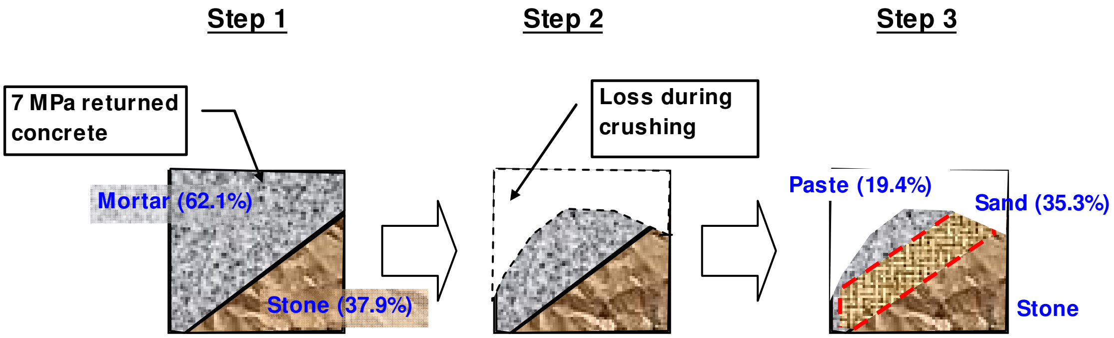
The total cement paste attached on CCA7 fine fraction can be obtained from CCA7 fine fraction volume multiplied by CCPV as illustrated:

$$\text{TCP(CCA7 fine agg)} = 2.6\% \times \text{CCPV} = 2.6\% \times 19.4\% = 0.5\%$$

Thus, the total cement paste in Mix2 can be obtained as the sum of new cement paste, old cement paste on CCA7 coarse fraction, and old cement paste on CCA7 fine fraction as illustrated by:

$$\text{TCP(New+Old)} = \text{CP(New)} + \text{CP(Old.CCA7.CA)} + \text{CP(Old.CCA7.FA)}$$

$$= 26.3\% + 1.4\% + 0.5\% = 27.8\%$$



Step2: (Numeric Example)
- Mortar loss=(25%-13%) x 62.1%=7.5%
- Mortar Vol. after Loss = 54.6%

Step3: (Numeric Example)
- Mortar Vol. after Loss = 54.6%
- Cement paste vol. in Mortar vol. after loss = 54.6% x 0.35 = 19.4%
- Cement paste to Mortar ratio from returned concrete = 0.35

Figure 5.12 Numerical examples of the Three Steps

Figure 5.13 illustrates the drying shrinkage result at the corresponding total cement paste volume both with the new cement paste and old cement paste attached on CCA. The total paste volume was expressed as a percentage of the unit concrete volume. The second degree quadratic trend line was best for statistical correlation. The R^2 values were ranged in 0.73-0.83 indicating a reasonable correlation at various ages. This shrinkage correlation with the total cement paste was much better than that with the total CCA volume.

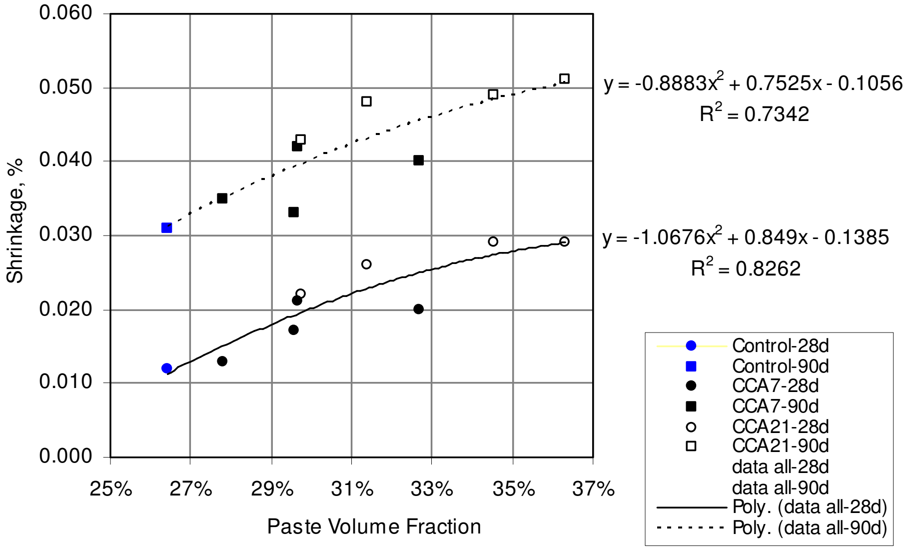


Figure 5.13 Shrinkage vs Cement Paste Volume Fraction in 0.76 m^3 (27 ft^3) Concrete

Therefore, the drying shrinkage of the CCA and the control mixtures can be modeled with the total cement paste volume. The proposed model of shrinkage at a long term age is,

$$y = -0.8883x^2 + 0.7525x - 0.1056 \qquad \textbf{Equation 20}$$

Where y is the drying shrinkage (%) at 90 days and x is the total cement paste volume expressed as a percentage of the unit concrete volume. The total cement paste volume is the sum of the new cement paste, old cement paste on CCA fine fraction, and old cement paste on CCA coarse fraction. The proposed model of shrinkage at a short term age is,

$$y = -1.0676x^2 + 0.849x - 0.1385$$ **Equation 21**

Where y is the drying shrinkage (%) at 28 days and x is the total cement paste volume expressed as a percentage of the unit concrete volume. The total cement paste volume is the sum of the new cement paste, old cement paste on CCA fine fraction, and old cement paste on CCA coarse fraction. The old cement paste on CCA must be quantified either analytically or experimentally.

Shrinkage-ACI 209 Model

ACI 209 model is defined with the drying shrinkage as hyperbolic time function and ultimate shrinkage by:

$$\varepsilon_{sh} = \frac{t}{35+t}\varepsilon_{ult} \quad \text{------ (2-9)}^*$$

(2-9)* used the same equation index in ACI 209 code

Where,

t = time (days)

ε_{ult} = ultimate shrinkage, $780\gamma_{sh} \times 10^{-6}$ m/m

γ_{sh} = correction factor as defined in sections 2.5, 2.6 of ACI 209 code provision.

For the drying shrinkage prediction in the ACI 209 model the ultimate shrinkage has to be first defined with the relevant correction factors applied for the concrete mixture other than the standard condition or composition. The two sub sections for the correction factors are provided in the ACI 209 code. These subsections are section 2.5, *correction factors for conditions other than the standard concrete composition*, and section 2.6, *correction factors for concrete composition*. In section 2.5 the five correction factors are used with i)Differential shrinkage, ii) Initial moist curing, iii) Ambient relative humidity, iv) Average thickness of member other than 150 mm or volume-surface ratio other than 38 mm, and v) Temperature other than 21 °C. A brief description of five correction factors is described in the following with the same section and subsection numbers in ACI 209 code.

Section 2.5 – correction factors for conditions other than the standard concrete composition

2.5.2 Differential shrinkage

For shrinkage considered for other than seven days for moist cured concrete, the difference can be determined in Eqs. (2-9) for any period starting after this time.

2.5.3 Initial moist curing

For shrinkage of concrete moist cured during a period of time other than 7 days, use the shrinkage factor in Table 2.5.3

Table 2.5.3 shrinkage Correction Factors for Initial Moist Curing

Moist curing duration, days	*Shrinkage* γ_{cp}
1	*1.2*
2	*1.1*
7	*1.0*
14	*0.93*
28	*0.86*
90	*0.75*

2.5.4 Ambient relative humidity

For ambient relative humidity greater than 40%, use Eqs (2-15) for shrinkage correction factor

$$\text{Shrinkage } \gamma_\lambda = 1.4 - 0.01\lambda, \text{ for } 40 \le \lambda \le 80 \qquad (2\text{-}15)$$

Where, λ *is relative humidity in percent.*

2.5.5 Average thickness of member other than 150 mm or volume-surface ratio other than 38 mm

The average-thickness method tends to compute correction factor values that are higher, as compared to the volume-surface ratio method.

a. average-thickness method

For ultimate values:

$$\text{Shrinkage } \gamma_h = 1.17 - 0.00114\, h,$$

Where h is the average thickness in mms of the part of the member under consideration

b. volume-surface ratio method

$$\text{Shrinkage } \gamma_{vs} = 1.2 \exp(-0.00472\, v/s)$$

Where v/s is the volume-surface ratio of the member in mm

2.5.6 Temperature other than 21 °C

In section 2.6, the following five correction factors have to be used with i) Slump, ii) Fine aggregate percentage, iii) Cement content, iv) Air content, and v) *S*hrinkage ratio of concretes with equivalent paste. A brief description of five correction factors is described in the following with same section and subsection numbers in ACI 209 code.

Section 2.6 – correction factors for concrete composition

The correction factors for the effect of slump, percent of fine aggregate, cement and air content are considered. It should be noted that for slump less than 130 mm, fine aggregate percent between 40-60 percent, cement content of 279-445 kg/m^3 *and air content less than 8%, these factors are approximately equal to 1. These correction factors shall be used only in connection with the average values suggested for* $\varepsilon_{uti} = 780 \times 10^{-6}$ *m/m.*

If shrinkage is known for local aggregates and conditions, Eq. (2.31), as discussed in 2.6.5, is recommended.

2.6.1 Slump

Shrinkage $\gamma_s = 0.89 + 0.00161\, s$*, where* s *= observed slump in mm*

2.6.2 Fine aggregate percentage

For $\phi > 50$,

Shrinkage $\gamma_\phi = 0.90 + 0.02\phi$, *Where ϕ is the ratio of the fine aggregate to total aggregate by weight expressed as percentage*

2.6.3 Cement content

Shrinkage $\gamma_c = 0.75 + 0.00061\,c$, c is the cement content in kg/m^3

2.6.4 Air content

Shrinkage $\gamma_\alpha = 0.95 + 0.008\,\alpha$, where α is the air content in percent

2.6.5 Shrinkage ratio of concretes with equivalent paste

If the shrinkage strain of a given mix has been determined, the ratio of shrinkage strain of two mixes $(\varepsilon_{sh})_1/(\varepsilon_{sh})_2$, with different content of paste but with equivalent paste quality is given in Eq.

$$\frac{(\varepsilon_{sh})_{u1}}{(\varepsilon_{sh})_{u2}} = \frac{1-(v_1)^{1/3}}{1-(v_2)^{1/3}} \qquad (2.31)$$

Where, v_1 and v_2 are the total aggregate solid volumes per unit volume of concrete for each one of the mixes

According to section 2.5 two correction factors with i) the ambient relative humidity and ii) average thickness of member other than 150 mm or volume-surface ratio other than 38 mm were applied to the control mixture (Mix1) whereas the other three correction factors were not applied since the control specimens had been kept in moist curing for 7 days followed by drying in 70°F, 50%RH room. The correction factor for the ambient relative humidity was 0.9 (numerical example = 1.4-0.01×50) while the correction factor for the average thickness method and volume-surface ratio method was 1.08 (=1.17-0.00114×75) and 1.11 (= $1.2e^{-0.00472\times16.6}$, *v/s* ratio = 16.6 from the 75×75×290-mm prism specimen), respectively. The product of the two correction factors was 0.97 (γ_{sh} = 0.9×1.08) which was multiplied by the suggested ultimate shrinkage value (780×10^{-6} m/m) to obtain the corrected ultimate shrinkage. The corrected ultimate shrinkage value was 758 μs ($=780\times0.97\times10^{-6}$) and was only 3% lower than the suggested ultimate shrinkage value (780 μs).

In accordance with the section 2.6 of ACI 209 code, the correction factors were obtained with 1.14 (=0.89+0.00161×152, slump 152-mm used) for slump, 0.89 (0.30+0.014×42, ϕ =42%) for fine aggregate percentage, 0.93 (=0.75+0.00061×294, 294 kg/m^3 cement used) for cement content, and 0.97 (=0.95+0.008×2.5, 2.5% air used) for air content. The correction factor for the shrinkage ratio of concretes with equivalent paste was not applied. According to the section 2.6 in ACI 209 code, these correction factors shall be used only in connection with the suggested ultimate shrinkage value of 780 μs. Thus, the product of correction factors was obtained with 0.92 (γ_{sh} = 1.14×0.89×0.93×0.97) which was multiplied by the suggested ultimate shrinkage value (780×10^{-6} m/m) to obtain the corrected ultimate shrinkage. The corrected ultimate shrinkage value was 714 μs ($780\times0.92\times10^{-6}$) and only 8% lower than the suggested ultimate shrinkage value (780 μs).

The difference of the corrected ultimate shrinkage values between two methods in the section 2.5 and 2.6 was only 44 μs. This small difference supports that the two methods were agreed upon each other in making a similar corrected ultimate shrinkage value.

However, the corrected ultimate shrinkage value of 714 μs (the lower value among two methods) for the control mixture (Mix 1) still seemed too high when it was compared to the measured shrinkage value at 180 days at which the ultimate shrinkage of the concrete would be reached. The measured shrinkage of the control mixture (Mix1) was 360 μs at 6 months (180 days). The ultimate shrinkage difference between ACI 209 model and measured shrinkage value at 180d by ASTM C157 was quite significant. The model ultimate shrinkage (714 μs) in ACI 209 code was almost doubled compared to the measured shrinkage (360 μs) at 180d. Due to this significantly high model ultimate shrinkage, the shrinkage prediction in ACI 209 model was also significantly over estimated as compared to the measured shrinkage values over the time. Therefore, the alternative drying shrinkage model is attempted to develop from the existing ACI 209 model. The alternative drying shrinkage model will be developed for the CCA and the control mixtures.

Shrinkage Model Development

The aim is to develop a shrinkage model that works for both CCA and the control mixtures from the existing ACI 209 shrinkage model which uses the hyperbolic time function with the ultimate shrinkage. In this study, the measured shrinkage at 180d can be reasonably used as the ultimate shrinkage for the concrete mixtures. Thus, only the hyperbolic time function has to be modified to satisfy the time dependent shrinkage behavior of CCA and the control mixtures. The proposed form of the time function is shown in Equation 22. The proposed time function is composed of the mixture parameter (m1) and time factor (m2). The mixture parameter (m1) is dependent on the mixture properties that affect the shrinkage behavior while the time factor (m2) is unique for the cement depending on the blain fineness, particle size distribution, and cement type.

$$\varepsilon_{sh} = \left(\frac{t^{m2}}{m1 + t^{m2}} \right) \cdot \varepsilon_{ulti} \qquad \textbf{Equation 22}$$

Where

m1 is the mixture parameter,

m2 is the time factor,

ε_{ult} is the ultimate shrinkage (μs).

First, the time factor (m2) was evaluated for the CCA and the control mixtures. The squared error between the measured shrinkage and the estimated shrinkage from the model was calculated at intervals of various ages and the sum of squared error was taken for each mixture as shown in Table 5.7. The sum of squared error for the CCA and the control mixtures was summarized with each time factor and total sum of squared error (or double sum of squared error) was obtained for each time factor as illustrated in Table 5.8. The time factor (m2) was explored from 1 through 2.5. The ultimate shrinkage value for each mixture was used with the measured shrinkage at 180 days. The analysis was conducted by the solver function in the excel software program. The total sum of squared error values at the corresponding time factors were plotted to obtain the best time factor that works for the CCA and the control mixtures as shown in Figure 5.14. The best time factor (m2) was 1.7 with the lowest the total sum of squared error value.

Table 5.7 Sum of Squared Error with the time factor (m2) = 1.7

						m1	m2	ε_{ult}
Mix no.	Age	Curing	Specement1	Specement2	Avg.	400.2	1.70	355
1	Days	condition	LC*	LC	LC	model	error^2	$\sum$error^2
Control	0	wet	-10	20	5	0	25	1897
	3	Air Dry	-50	0	-25	6	939	
	7	Air Dry	-10	30	10	23	161	
	14	Air Dry	50	90	70	64	31	
	21	Air Dry	90	140	115	109	38	
	28	Air Dry	116	150	133	149	247	
	56	Air Dry	233	274	253.5	249	22	
	90	Air Dry	280	330	305	298	47	
	180	Air Dry	330	380	355	335	387	

						m1	m2	ε_{ult}
Mix no.	Age	Curing	Specement1	Specement2	Avg.	308.5	1.70	490
3	Days	condition	LC	LC	LC	model	error^2	$\sum$error^2
CCA7 356 kg/m^3	0	wet	40	30	35	0	1225	6588
	5	Air Dry	80	70	75	23	2669	
	7	Air Dry	100	80	90	40	2512	
	14	Air Dry	140	100	120	110	110	
	21	Air Dry	200	160	180	179	2	
	28	Air Dry	230	190	210	237	718	
	56	Air Dry	370	350	360	369	75	
	90	Air Dry	430	410	420	427	52	
	180	Air Dry	490	490	490	469	449	

						m1	m2	ε_{ult}
Mix no.	Age	Curing	Specement1	Specement2	Avg.	276.8	1.70	565
6	Days	condition	LC	LC	LC	model	error^2	$\sum$error^2
CCA21 534 kg/m^3	0	wet	100	90	95	0	9025	20301
	4	Air Dry	130	90	110	21	7965	
	7	Air Dry	170	120	145	51	8878	
	14	Air Dry	180	140	160	137	518	
	21	Air Dry	250	190	220	220	0	
	28	Air Dry	280	230	255	288	1113	
	56	Air Dry	440	370	405	436	973	
	90	Air Dry	510	450	480	499	369	
	180	Air Dry	540	590	565	543	485	

* LC = Length Change

Table 5.8 Double (Total) Sum of Squared Error with Various Time Factors (m2)

Mix #	CCA Type	m1	m2	ε_{ult}	$\sum error^2$	$\sum\sum error^2$
1	control	35.4	1.00	355	14187	217424
2	7 MPa	37.6	1.00	395	27957	
3	7 MPa	28.6	1.00	490	11636	
7	7 MPa	41.5	1.00	400	19108	
8	7 MPa	40.1	1.00	455	34711	
4	21 MPa	28.1	1.00	525	10617	
5	21 MPa	25.8	1.00	565	12933	
9	21 MPa	27.9	1.00	545	23020	
11	21 MPa	31.7	1.00	575	63255	

Mix #	CCA Type	m1	m2	ε_{ult}	$\sum error^2$	$\sum\sum error^2$
1	control	400.2	1.70	355	1897	76924
2	7 MPa	435.5	1.70	395	5902	
3	7 MPa	308.5	1.70	490	6588	
7	7 MPa	498.7	1.70	400	4554	
8	7 MPa	463.4	1.70	455	8077	
4	21 MPa	305.3	1.70	525	14404	
5	21 MPa	276.8	1.70	565	20301	
9	21 MPa	285.9	1.70	545	848	
11	21 MPa	328.3	1.70	575	14353	

Mix #	CCA Type	m1	m2	ε_{ult}	$\sum error^2$	$\sum\sum error^2$
1	control	6216.7	2.50	355	3934	136095
2	7 MPa	7116.8	2.50	395	2943	
3	7 MPa	4519.0	2.50	490	19114	
7	7 MPa	8389.0	2.50	400	9567	
8	7 MPa	7404.6	2.50	455	9231	
4	21 MPa	4487.7	2.50	525	34475	
5	21 MPa	3968.0	2.50	565	43887	
9	21 MPa	3826.2	2.50	545	6596	
11	21 MPa	4545.6	2.50	575	6348	

Second, the mixture parameter (m1) for the CCA and the control mixtures at the best time factor needs to be modeled with the mixture properties which affect the shrinkage behavior of concrete. The mixture parameters (m1) were ranged from 277-499 at 1.7 time factor (m2) as shown in Table 5.8.

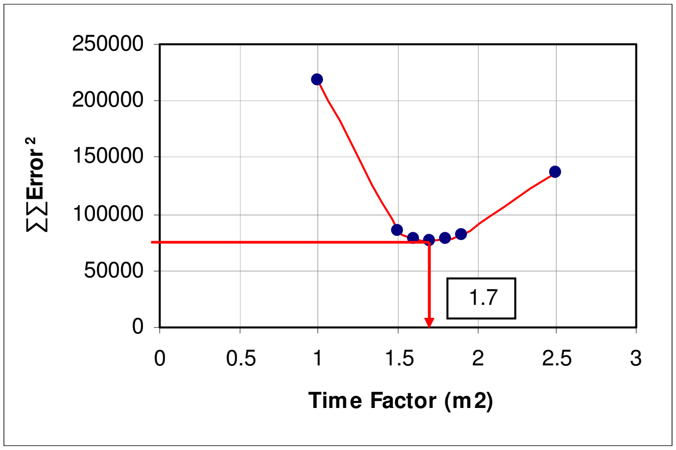


Figure 5.14 Double Sum of Squared Error vs. Time Factor

The mixture parameter (m1) was analyzed with the mixture properties by the multiple regression analysis. In the multiple regression analysis, the mixture properties such as mixture ingredients, *w/c* ratio, and air content were used as independent variables while the mixture parameter (m1) was used as dependent variable. During the stepwise regression analysis, the insignificant variables were first examined and removed one by one until the F and T tests were satisfied. As shown in Table 5.9, an acceptable F test (Significance $F < 0.05$; f theoretical equal to 15.5, $f > F_{0.05,3,5} = 5.41$) for the CCA and the control mixtures was obtained with three independent variables remaining (Significance $T < 0.05$; t theoretical equal to $t > t_{0.025,7} = 2.365$ or $t < -2.365$) with the *w/c* ratio, CCA volume, and air content. These significant variables are believed to influence the shrinkage behavior associated with the time function. The *w/c* ratio is to influence the degree of hydration associated with the porosity in the paste matrix in concrete. It is also noted that the air content affects the drying shrinkage behavior significantly. The CCA volume is also proportional to the pore volume which affects the drying shrinkage behavior.

The multiple regression analysis result with 0.95 R^2 is shown in Table 5.9.

Table 5.9 Step Wise Regression Analysis with Mixture Parameters for Dependent Variable

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.950
R Square	0.903
Adjusted R Square	0.845
Standard Error	32.9
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	50448.106	16816.04	15.495346	0.005776
Residual	5	5426.1567	1085.231		
Total	8	55874.263			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	725.3	66.111933	10.97107	0.0001	555.3726	895.2649
w/c ratio	-6019.1	978.84237	-6.149253	0.0017	-8535.34	-3502.96
cca volume	-534.8	176.0093	-3.038651	0.0288	-987.277	-82.3846
aircontent	5235705.6	2010127	2.604664	0.0480	68509.55	10402902

Thus, the proposed model of the mixture parameter (m1) is,

$$m1 = 725 - 6019 \cdot (x_1)^5 - 535 \cdot (x_2) + 5235706 \cdot (x_3)^3$$ **Equation 23**

Where

m1 = mixture parameter

x_1 = w/c ratio

x_2 = CCA volume (m^3)

x_3 = Air content (%)

Therefore, the shrinkage model is developed for the CCA and the control mixtures and proposed,

$$\varepsilon_{sh} = \left(\frac{t^{m2}}{m1 + t^{m2}} \right) \cdot \varepsilon_{ulti} \qquad \textbf{Equation 24}$$

Where

$m1$ = Equation 23

$m2$ = 1.7

ε_{ult} = ultimate shrinkage (μs)

The measured shrinkage data were also plotted over the estimated data from the shrinkage model (Equation 24) as shown in Figure 5.15-Figure 5.23. The measured shrinkage data were well fit to the model prediction.

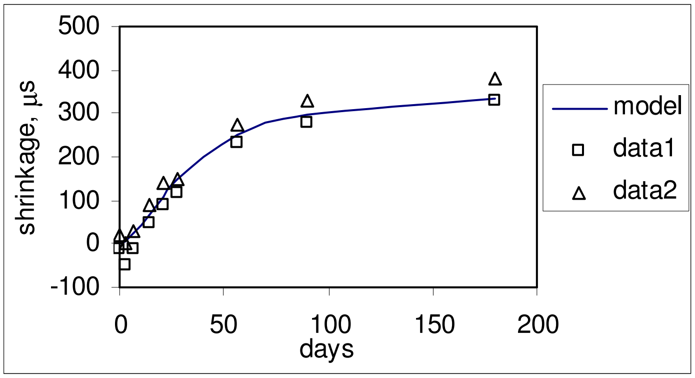


Figure 5.15 Control Mixture (Mix1) Shrinkage Result

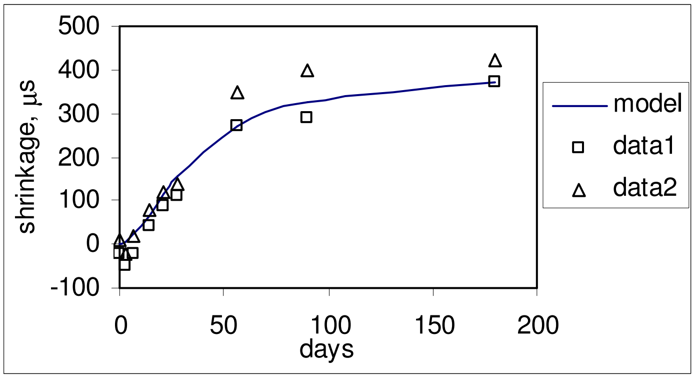


Figure 5.16 CCA7-178 kg/m^2 (Mix 2) Mixture Shrinkage Result

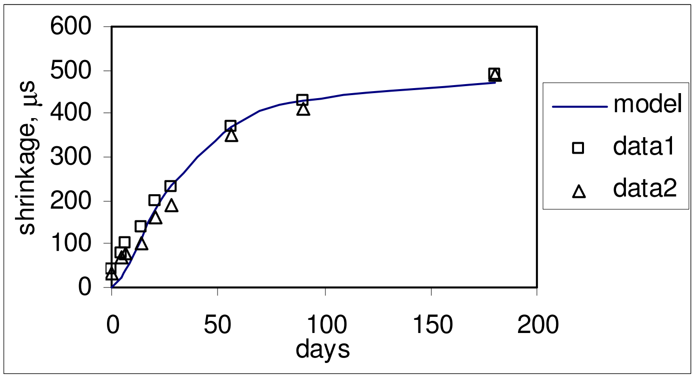


Figure 5.17 CCA7-356 kg/m^2 (Mix 3) Mixture Shrinkage Result

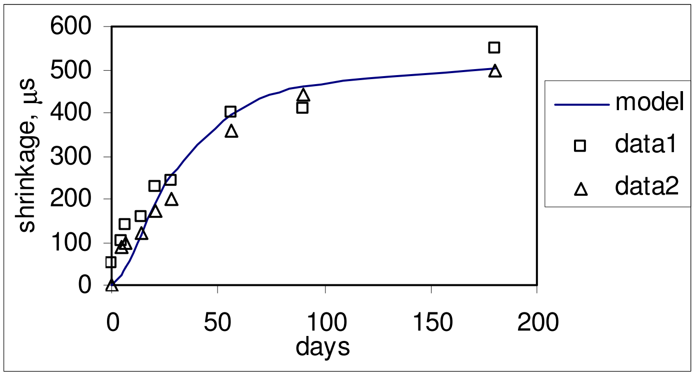


Figure 5.18 CCA21-356 kg/m^2 (Mix 4) Mixture Shrinkage Result

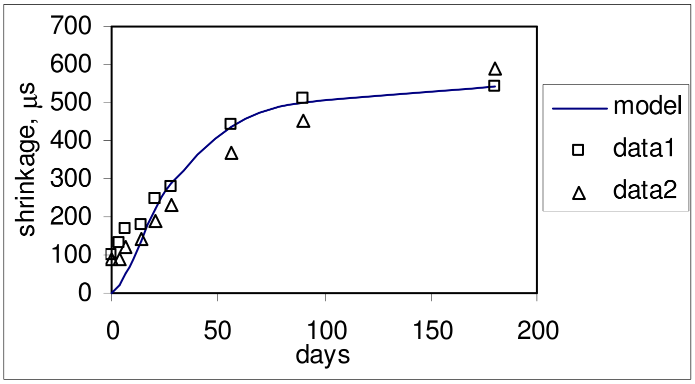


Figure 5.19 CCA21-534 kg/m^2 (Mix 5) Mixture Shrinkage Result

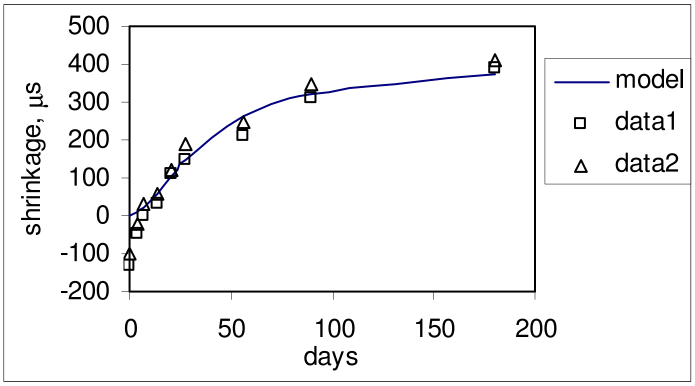


Figure 5.20 CCA7-50% Coarse Fraction (Mix 7) Mixture Shrinkage Result

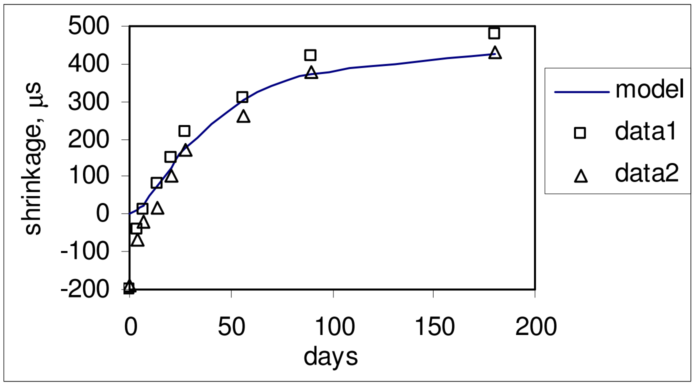


Figure 5.21 CCA7-100% Coarse Fraction (Mix 8) Mixture Shrinkage Result

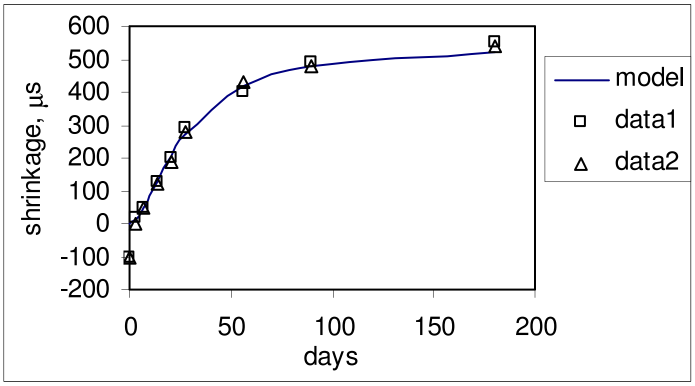


Figure 5.22 CCA21-100% Coarse Fraction (Mix 9) Mixture Shrinkage Result

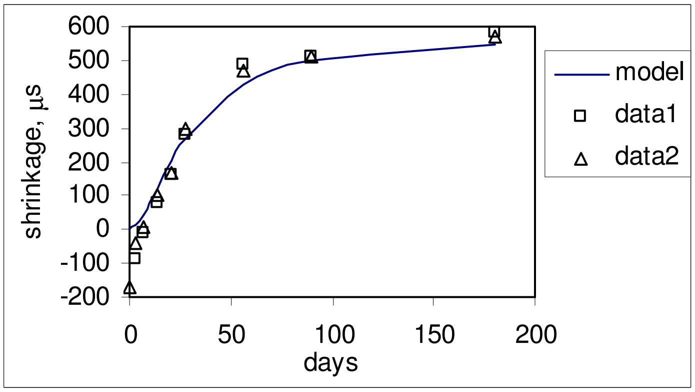


Figure 5.23 CCA21-100/25% Coarse/Fine Fraction (Mix 11) Mixture Shrinkage Result

The R^2 was also determined between the model shrinkage and the measured shrinkage for the CCA and the control mixtures. The R^2 ranged from 0.88-0.99 and provides good agreement between model predictions and experimental values. The results are summarized in Table 5.10.

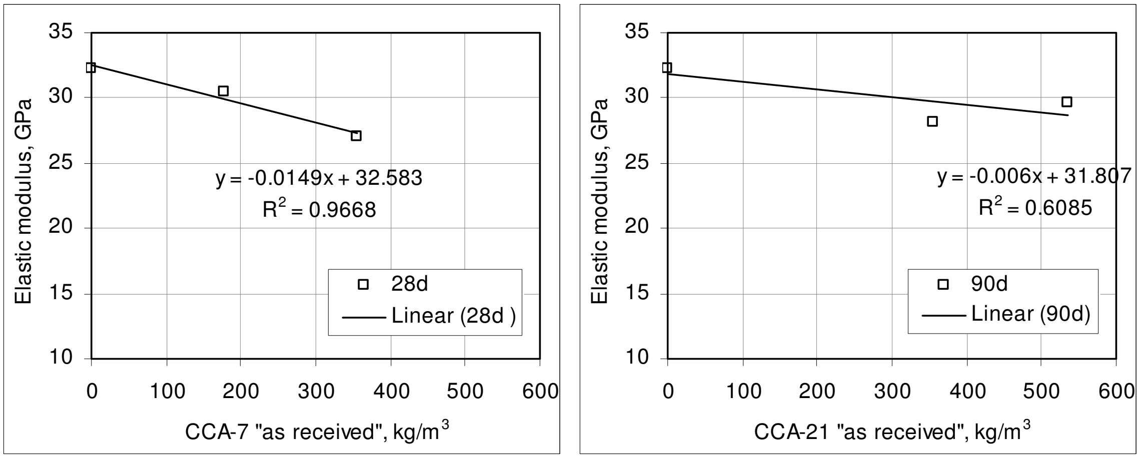
Table 5.10 R^2 between the model shrinkage and the measured shrinkage

Mix #	CCA Type	R^2
1	control	0.99
2	7 MPa	0.97
3	7 MPa	0.97
7	7 MPa	0.95
8	7 MPa	0.92
4	21 MPa	0.90
5	21 MPa	0.82
9	21 MPa	0.97
11	21 MPa	0.88

5.2.3. Static Elastic Modulus

The static elastic modulus result for the CCA7, CCA21, and the control mixtures is shown in Figure 5.24, Figure 5.25. Figure 5.24 (a) illustrates the elastic modulus result at an age of 28 days for Mix 1, Mix 2, and Mix 3 with 0 kg/m^3, 178 kg/m^3, and 356 kg/m^3 of CCA7 as-received, respectively, whereas Figure 5.24 (b) shows the elastic modulus result at 28d for Mix 1, Mix 4, and Mix 6 with 0 kg/m^3, 356 kg/m^3, and 534 kg/m^3 of CCA21 as-received, respectively, in concrete mixtures. For the CCA7 and the control mixtures a good linear relationship was made with 0.97 R^2. The elastic modulus of CCA7 mixtures was decreased by 5.8%, 16.6% for Mix 2, Mix 3, respectively, as compared to Mix 1. The elastic modulus of CCA7 mixtures was generally reduced with increasing CCA7 as-received in concrete. For the CCA21 and the control mixtures a moderate linear relationship was made with 0.62 R^2. The elastic modulus of CCA21 mixtures was decreased by 12.8%, 8.5% for Mix 4, Mix 6, respectively, as compared to Mix 1. The elastic modulus of CCA21 mixtures was also reduced, but slightly improved with increasing CCA21 as-received in concrete.

It is noted from Mix 3, 4 with similar mixture proportions except different strength CCA that Mix 4 with a higher strength CCA was improved with the elastic modulus by 5% as compared to Mix 3 with a lower strength CCA. It must also be noted that among CCA21 mixtures Mix 6 with a doubled amount of CCA as-received (178 kg/m^3 more) was improved with the elastic modulus by 5% as compared to Mix 4. From this result it indicates that the elastic modulus can be improved with increasing amount of the higher strength CCA (*ex*. CCA21 or higher strength). Also the strength of CCA must be equal or greater than the design concrete strength.



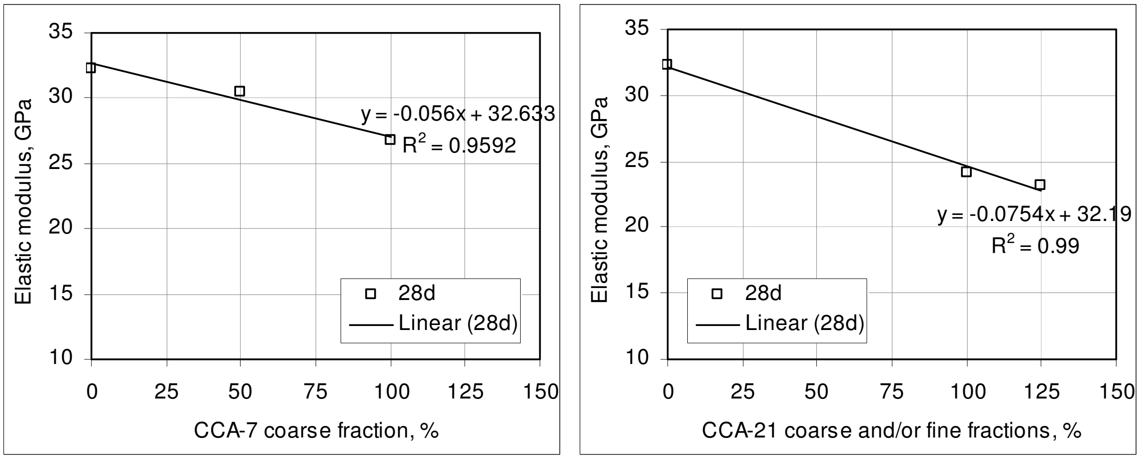
(a) (b)

Figure 5.24 Elastic Modulus vs CCA Replacements with As-Received Condition

Figure 5.25 (a) illustrates the elastic modulus result for Mix 1, Mix 7, and Mix 8 with 0%, 50%, and 100% of CCA7 coarse fraction, respectively, in concrete mixtures; whereas, Figure 5.25 (b) shows the elastic modulus result for Mix 1, Mix 9, and Mix 11 with 0/0%, 100/0%, and 100/25% CCA21 coarse/fine fraction in concrete mixtures. Both CCA7 and CCA21 mixtures had a good linear correlation with R^2 greater than 0.9 with the control mixture. The elastic modulus of CCA7 mixtures was reduced by 5.8%, 17.5% for Mix 7, Mix 8, respectively, as compared to Mix 1 (control). The elastic modulus was decreased with increasing CCA7 coarse fraction in concrete in general. The elastic modulus of CCA21 mixtures was reduced by 25.4%, 28.4% for Mix 9, Mix 11, respectively, as compared to Mix 1 (control). The elastic modulus reduction (Mix 9) was significant with 100% CCA21 coarse fraction in concrete; whereas, the elastic modulus reduction (Mix 11) was not significant with additional 25% CCA21 fine fraction in concrete.

It is noted from Mix 8, Mix 9 with similar mixture proportions except different strength CCA and varied amount of mixing water Mix 9 with 100% CCA21 coarse fraction was 8% lower than that of Mix 8 with 100% CCA7 coarse fraction. The lower elastic modulus result of Mix 9 with CCA21 compared to Mix 8 with CCA7 was a bit surprising as CCA21 is a higher strength CCA than CCA7. That was because of the higher dosage of mixing water (18.4 kg/m^3 more) in Mix 9 with a *w/c* ratio of 0.59 as compared to Mix 8 with a *w/c* ratio of 0.52. The higher *w/c* ratio was responsible to a lower degree of hydration for the new paste matrix in concrete mixture possibly resulted in reducing the quality of the new paste matrix creating relatively larger size capillary pores. Therefore, the elastic modulus result of Mix 9 with a higher strength CCA21 was lower than that of Mix 8 with a lower strength CCA.

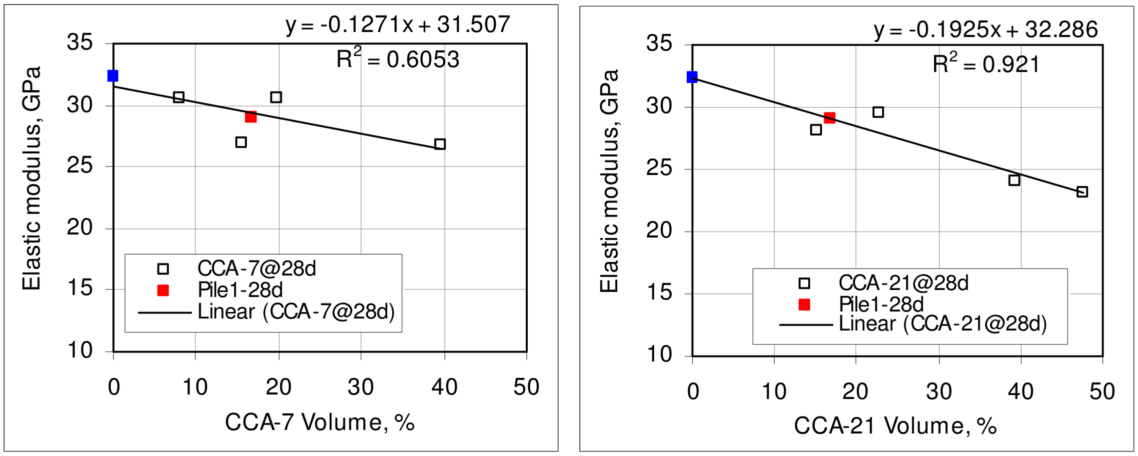
It is also noted that Mix 11 with 100% CCA21 coarse fraction and 25% CCA21 fine fraction had only 3.7% lower elastic modulus than Mix 9 with 100% CCA21 coarse fraction and no CCA21 fine fraction. The result indicates that the use of CCA21 fine fraction (25% or less) has a little influence to the effect of the elastic modulus.



(a) (b)

Figure 5.25 Elastic Modulus vs CCA Replacements with Coarse and/or Fine fractions

Figure 5.26 illustrates the elastic modulus result of CCA7, 21 mixtures against the corresponding CCA volume in 0.76 m^3 (1 yd^3) concrete with the control mixture. The Pile1 CCA mixture (Mix 5) was also plotted but not included in the analysis. The elastic modulus of Mix 5 with 356 kg/m^3 of Pile1 CCA as-received was similar to that of Mix 4 with the same amount of CCA21 as-received in concrete mixtures. For the CCA7 and the control mixtures a moderate linear correlation with 0.60 R^2 was made as shown in Figure 5.26 (a) whereas for the CCA21 and the control mixtures a good linear correlation with 0.92 R^2 was shown in Figure 5.26 (b).



(a) (b)

Figure 5.26 Elastic Modulus vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

The elastic modulus result for the CCA7, CCA21 mixtures was also put together as representing one medium strength range with the control mixture as illustrated in Figure 5.27. Generally the elastic modulus was decreased with increasing CCA volume in concrete. The R^2 of the linear trend line was 0.78 indicating a reasonable correlation statistically. Therefore, the elastic modulus can be modeled with the CCA volume between 7 MPa and 21 MPa strength levels by

$$y = -0.1684x + 31.899 \qquad \textbf{Equation 25}$$

Where y is the elastic modulus (GPa) and x is the volume of CCA (%) in 0.76 m^3 (27 ft^3) concrete volume. The volume of CCA (%) in 0.76 m^3 (27 ft^3) concrete can be calculated by:

$$V_{CCA} = V_{CCA-CA} + V_{CCA-FA} \qquad \textbf{Equation 26}$$

Where V_{cca} is CCA volume expressed as a percentage of the unit concrete volume, $V_{cca\text{-}ca}$ is CCA coarse fraction volume expressed as a percentage of the unit concrete volume, and $V_{cca\text{-}fa}$ is CCA fine fraction volume expressed as a percentage of the unit concrete volume.

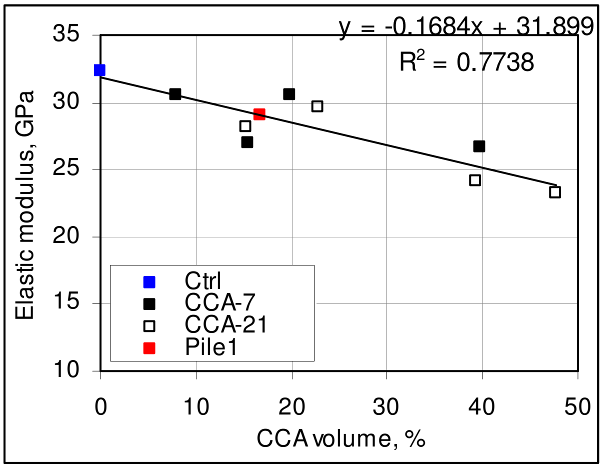


Figure 5.27 Elastic Modulus vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

Static Elastic Modulus Modeling

The elastic modulus is measured as a slope of the stress and strain behavior of the concrete. The stress and strain behavior is much relied upon the aggregate modulus, paste modulus, and porosity of concrete. In this study, the same virgin coarse and fine aggregates were used throughout all concrete mixtures. Even the original returned concretes to produce CCAs had the same virgin coarse and fine aggregates. Therefore, the aggregate modulus effect to the elastic modulus can be minimized. Also, all concrete mixtures used a constant amount of cement, but with varying mixing water to meet the slump requirement. The small change of *w/c* ratio might have increased or decreased the cement paste modulus and porosity depending on the degree of hydration. Perhaps the main factor influencing the elastic modulus of concrete was various amounts and types of CCA in concrete. As discussed the CCA was composed of the paste attached/coated partially and/or fully on the solid particle. The amount of paste coated on CCA was also increased with higher strength CCA. The higher strength CCA should have a higher paste modulus. The softer paste in concrete can make a relatively larger deformation during the stress application resulting in lower elastic modulus of concrete as opposed to the harder paste in concrete making a smaller deformation during the stress application resulting in higher elastic modulus of concrete. Therefore, the paste modulus and volume in CCA can affect the elastic modulus of CCA mixtures. Since the paste modulus for both CCAs and new cement paste was not obtained only the paste volume for both CCAs and new cement paste was examined to the effect of the elastic modulus.

Thus, the elastic modulus result for the CCA and the control mixtures was plotted against the corresponding paste volume as shown in Figure 5.28 The second degree quadratic trend line was best with 0.8 R^2 indicating a reasonable correlation. As indicated by the good correlation, the paste volume can give a good indication of the elastic modulus of CCA and the control mixtures.

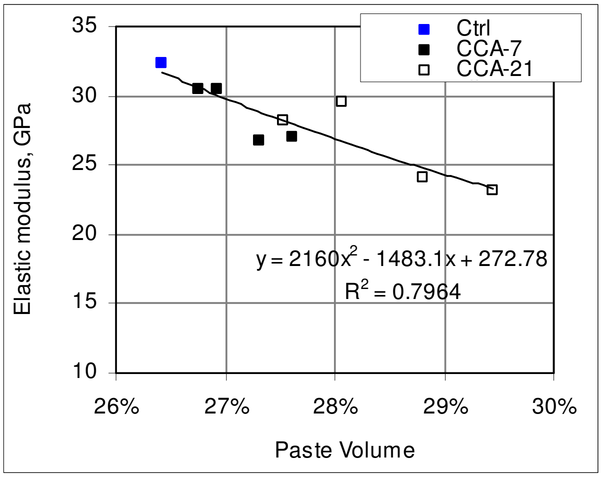


Figure 5.28 Elastic modulus vs Paste volume in 0.76 m^3 (27 ft^3) Concrete

Since a good correlation was made the elastic modulus model can be proposed with the paste volume of new cement paste and old cement paste on CCA by:

$$y = 2160x^2 - 1483.1x + 272.78 \qquad \textbf{Equation 27}$$

where y is Elastic modulus (GPa), x is Paste volume of new cement paste and old cement paste on CCA expressed as a percentage of 0.77 m^3 (1 yd^3) concrete.

The old cement paste volume of CCA must be obtained as described in section 7.2.2.

The elastic modulus was also analyzed with the mixture ingredients for the CCA and the control mixtures. The step wise multiple regression analysis was conducted to the elastic modulus result as dependent variable and the mixture ingredients (*ex*, the volumes of air content, mixing water, cement, virgin coarse aggregate, virgin fine aggregate, and CCA) as independent variables. In the stepwise regression analysis, the CCA volume was the only variable that was significant while all other mixture ingredients were insignificant for the model parameters. Therefore, the elastic modulus model with respect to the mixture ingredients was not established.

The model parameters were further investigated with the influential factors affecting the elastic modulus of the concrete. As previously discussed, the paste modulus and volume of CCA can influence the elastic modulus of CCA mixtures. The paste modulus is higher with higher degree of hydration. The higher degree of hydration is achieved with higher amount of cement when used. The higher amount of cement will generate higher amount of heat when mixed with the water over time. In chemistry, this hydration reaction with heat generation is called as the exothermic reaction. Due to the higher heat generation, the hydration of cement paste makes the paste matrix denser as a result of the expansion of the hydrated gel product (C-S-H) in hydrated cement paste and at the same time diminishing capillary water filled pores in size. Thus, the paste with higher degree of hydration will have less porosity. Considering this hydration theory the paste modulus is much associated with the paste porosity and the paste modulus can be evaluated indirectly by the measure of the porosity such as the rapid chloride permeability. Other influential factors are aggregate volume, modulus of the aggregate, aggregate porosity, aggregate shape, and air content. Also, in ACI 318 building code the empirical elastic modulus equation was formulated as a function of unit weight and the compressive strength of the concrete. Considering these various influential factors as independent variables the multiple regression analysis was conducted with the elastic modulus result as dependent variable. The analysis result was shown in Table 5.11. **A**n acceptable F test (Significance F < 0.05;

f theoretical equal to 98.7, $f > F_{0.05,5,3} = 9.01$) for the CCA and the control mixtures was obtained with five independent variables remained (significance $T < 0.05$; t theoretical equal to $t > t_{0.025,7} = 2.365$ or $t < -2.365$). These significant variables (independent variables) for the model parameters were the *w/c* ratio, CCA volume, compressive strength at 90d, rapid chloride permeability, and virgin aggregate volume as summarized in Table 5.12. The *w/c* ratio is a good indication of the degree of hydration for the new cement paste in concrete. The higher degree of hydration is proportional to the elastic modulus. The CCA volume is proportional to the volume of the old cement paste on CCA. The compressive strength is proportional to the elastic modulus of concrete. The compressive strength at 90d was reached to the maximum ultimate strength at which the paste modulus and porosity of concrete were fully matured. The RCP is a good indication of the porosity for both the new cement paste and old cement paste from CCA. The virgin aggregate volume is proportion to the aggregate modulus. The multiple regression analysis result with 0.99 R^2 is shown in Table 5.11.

Table 5.11 Elastic Modulus Analysis with CCA and Control Mixtures

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.9970
R Square	0.9940
Adjusted R Square	0.9839
Standard Error	387.5
Observations	9

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	5	74088684	14817737	98.67158	0.0016
Residual	3	450516.85	150172.28		
Total	8	74539201			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	480560	76092.34	6.32	0.008	238400.5	722720.1
w/c	-57927	6424.14	-9.02	0.003	-78371.7	-37482.7
CCA.Vol.	-822760	139472.96	-5.90	0.010	-1266625.2	-378894.8
f-90	435	81.37	5.34	0.013	175.8	693.7
RCP	311	90.85	3.43	0.042	22.0	600.3
Vir.Agg.Vol.	-805796	140540.67	-5.73	0.011	-1253059.2	-358533.0

Table 5.12 Input Data Used in Elastic Modulus Model

Mix#	CCA Type	*w/c*	CCA.Vol. (m^3)	*f'*-90 (MPa)	RCP (Coulomb)	Vir.Agg.Vol. (m^3)	E (MPa)
1	control	0.58	0.00	32.68	3618	0.54	32319
2	7 Mpa	0.56	0.06	32.20	2970	0.48	30500
3	7 Mpa	0.59	0.12	26.13	2984	0.42	26939
7	7 Mpa	0.55	0.15	29.85	5402	0.39	30461
8	7 Mpa	0.52	0.30	25.03	5187	0.24	26653
4	21 Mpa	0.58	0.12	30.68	3936	0.43	28211
5	21 Mpa	0.59	0.17	32.54	4276	0.37	29605
9	21 Mpa	0.59	0.30	29.44	6248	0.25	24140
11	21 Mpa	0.59	0.36	28.34	7231	0.18	23192

Thus, the proposed model is,

$$E = 480560 - 57927(x_1) - 822760(x_2) + 435(x_3) + 311(x_4)^{0.4} - 805796(x_5) \quad \textbf{Equation 28}$$

Where

x_1 = w/c ratio

x_2 = CCA volume (m^3)

x_3 = compressive strength at 90d (MPa)

x_4 = RCP (Coulombs)

x_5 = Virgin coarse and fine aggregate volume (m^3)

In Table 5.13 an acceptable F test (significance F < 0.05; f theoretical equal to 250.8, f > $F_{0.05,5,2}$ = 19.3) for only CCA mixtures was also obtained with the same variables remained (significance T < 0.05; t theoretical equal to t > $t_{0.025,6}$ = 2.447 or t < -2.447). The multiple regression analysis result with 0.99 R^2 is shown in Table 5.13.

Table 5.13 Elastic Modulus Analysis with CCA mixtures only

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.999
R Square	0.998
Adjusted R Square	0.994
Standard Error	206.5
Observations	8

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	5	53485084	10697017	250.7598	0.004
Residual	2	85316.85	42658.425		
Total	7	53570401			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	403669	31506.572	12.812229	0.006	268107.6	539231.3
w/c	-56613	3332.8363	-16.98639	0.003	-70952.9	-42272.8
CCA.Vol.	-691179	59351.224	-11.64558	0.007	-946546.9	-435811.4
f-90	441	42.675188	10.328558	0.009	257.2	624.4
Vir.Agg.Vol.	-678591	59991.881	-11.31138	0.008	-936715.3	-420466.8
RCP	1	0.1445788	4.9262712	0.039	0.1	1.3

Thus, the proposed model is,

$$E = 403669 - 56613(x_1) - 691179(x_2) + 441(x_3) - 678591(x_4)^{1.05} + (x_5)$$ **Equation 29**

Where

x_1 = *w/c* ratio

x_2 = CCA volume (m^3)

x_3 = compressive strength at 90d (MPa)

x_4 = Virgin coarse and fine aggregate volume (m^3)

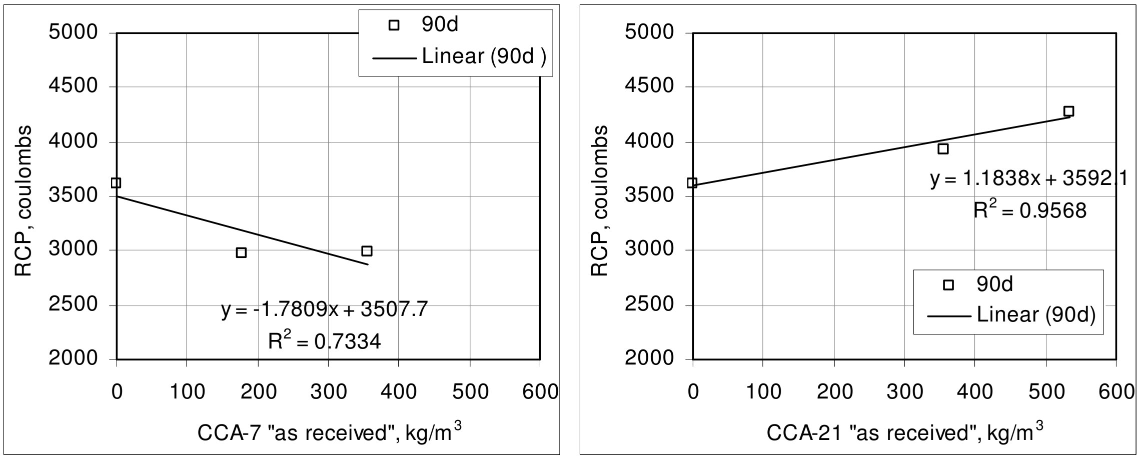
x_5 = RCP (Coulombs)

5.2.4. Rapid Chloride Permeability (RCP)

The rapid chloride permeability test result for the CCA7, CCA21, and the control concrete mixtures is shown in Figure 5.29, Figure 5.30. Figure 5.29 (a) illustrates the RCP test result at an age of 90 days for Mix 1, Mix 2, and Mix 3 with 0 kg/m^3, 178 kg/m^3, and 356 kg/m^3 of CCA7 as-received, respectively, in concrete mixtures; whereas, Figure 5.29 (b) shows the RCP test result for Mix 1, Mix 4, Mix 6 with 0 kg/m^3, 356 kg/m^3, and 534 kg/m^3 of CCA21 as-received, respectively, in concrete mixtures. The linear trend line was best. The CCA7 and the control mixtures indicated a reasonable correlation with 0.73 R^2 as shown in Figure 5.29 (a) while the CCA21 and the control mixtures had an excellent correlation with 0.96 R^2 as shown in Figure 5.29 (b). For the CCA7 mixtures, the RCP result was decreased (or improved) by 18% (600 coulombs) with increasing CCA7 as-received up to 356 kg/m^3 in concrete as compared to the RCP result of Mix 1. For the CCA21 mixtures, the RCP result was increased by 9-18% (about 300-600 coulombs) with increasing CCA21 as-received up to 534 kg/m^3 in concrete as compared to that of Mix 1. According to the chloride ion penetrability based on charge passed in Table 1 of ASTM C1202, the charge passed (coulombs) between 2000-4000 is classified with “Moderate” whereas the charge passed greater than 4000 is classified with “High”. The chloride ion penetrability for both CCA7, and CCA21 mixtures was in “Moderate” classification when used with less than 356 kg/m^3 in concrete. The chloride ion penetrability for the control mixture was also in “Moderate” classification.

The RCP testing in accordance with ASTM C1202 measures the electric conductivity of 50 mm thick concrete specimen applying with a 60 constant voltage over 6 hour periods.

Among other influencing factors the RCP result is mainly dependent on the pore size, pore volume, and pore solution in concrete. As discussed previously with respect to the porosity of concrete the CCA mixtures are consisted with two porosity phases for both the new cement paste and the old cement paste on CCA in concrete. In CCA mixtures the porosity of the new cement paste can be determined by the w/c ratio and degree of the hydration whereas the porosity of the old cement paste on CCA can be easily determined by the absorption test. The absorption test can capture the water permeable pores. The absorption of CCA7, CCA21 fine fraction was 11.9%, 10.25%, respectively while the absorption of CCA7, CCA21 coarse fraction was 4.4%, 4.31%, respectively. The absorption of CCA7 for both coarse and fine fraction was 0.1-1.7% higher than that of CCA21 for both coarse and fine fraction. The higher absorption is an indication of the larger pore size in the old cement paste on CCA. Therefore CCA7 with a higher porosity should have increased the RCP result compared to CCA21 with a lower porosity in concrete mixtures. A good example is Mix 3 (CCA7 as-received with 356 kg/m^3) and Mix 4 (CCA21 as-received with 356 kg/m^3). Mix 3 had 0.01 higher w/c ratio than Mix 4. Mix 3 had 2984 coulombs while Mix 4 had 3936 coulombs. Mix 3 had 952 coulombs lower than Mix 4. Partly the lower RCP result of Mix 3 as compared to Mix 4 was the higher w/c ratio but 0.01 increment higher w/c ratio shouldn't be responsible for significant RCP reduction. The significant RCP reduction of Mix 3 should be made by denser packing effect which makes a less permeable concrete. The denser packing can be achieved by the fine particles (minus 75 μm). As indicated in Chapter 3 (aggregate characterization) the CCA fine fraction contained a higher amount of minus 200 sieve size particles (smaller than 75 □m) which could help improve the denser packing and reduce the permeability. The CCA7 as-received condition was consisted with 67/33% coarse/fine ratio; whereas, the CCA21 as-received condition was composed of 74/26% coarse/fine ratio. From the coarse/fine ratio of CCA as-received condition it becomes clear that CCA7 had 7% more fine fraction than CCA21. Thus, the improved RCP result of Mix 3 was also contributed by the denser packing effect with minus 200 sieve size particles.



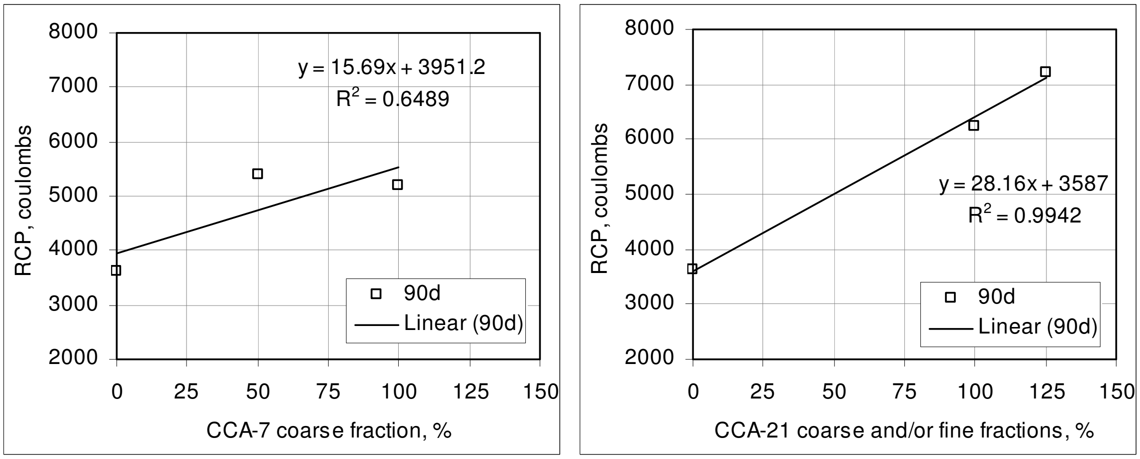
(a) (b)

Figure 5.29 RCP vs CCA Replacements with As-Received Condition

Figure 5.30 (a) illustrates the RCP test result for Mix 1, Mix 7, and Mix 8 with 0%, 50%, and 100% of CCA7 coarse fraction, respectively, in concrete mixtures whereas Figure 5.30 (b) shows the RCP test result for Mix 1, Mix 9, and Mix 11 with 0/0%, 100/0%, and 100/25% of CCA21 coarse/fine fraction in concrete mixtures. The linear trend line was best. The CCA7 and the control mixtures showed a moderate correlation with 0.65 R^2 while the CCA21 and the control mixtures had an excellent correlation with 0.99 R^2. As compared to the control mixture for the CCA7 mixtures the RCP was increased by 43-

46% (about 1500-1700 coulombs) with increasing CCA7 coarse fraction from 50% to 100% in concrete whereas for the CCA21 mixtures the RCP was increased by 73-100% (about 2600-3600 coulombs) with increasing CCA21 coarse/fine fraction from 100/0% to 100/25% in concrete. For the CCA7 mixtures Mix 8 with 50% more CCA7 coarse fraction had 215 coulombs lower RCP result than Mix 7 with 50% less CCA7 coarse fraction in concrete. The lower RCP result of Mix 8 was partly due to the lower *w/c* ratio as Mix 8 had 0.03 increment lower w/c ratio than Mix 7 with 0.55 *w/c* ratio. For the CCA21 mixtures Mix 9 had no CCA21 fine fraction in concrete while Mix 11 had 25% CCA21 fine fraction in concrete. Both Mix 9 and Mix 11 had a *w/c* of 0.59. Mix 11 with 25% CCA21 fine fraction had nearly 1000 coulombs higher RCP result than Mix 9 with no CCA21 fine. The rapid chloride ion permeability was also increased with increasing CCA fine in concrete. The porous characteristic of CCA fine fraction is responsible for increasing the RCP result.

According to the chloride ion penetrability based on charge passed in Table 1 of ASTM C1202, the chloride ion penetrability for both CCA7, and CCA21 mixtures was in “high” classification when used with 50/0%-100/25% of CCA coarse/fine fraction in concrete.

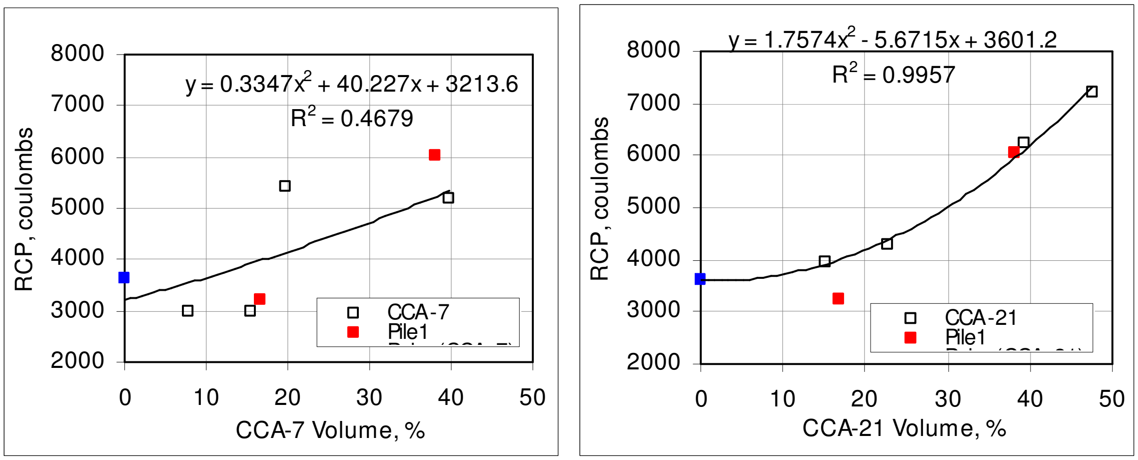


(a) (b)

Figure 5.30 RCP vs CCA replacements with Coarse and/or Fine fraction(s)

Figure 5.31 (a), (b) illustrates the RCP result against the corresponding CCA volume in 0.76 m^3 (27 ft^3) concrete. The RCP result of Pile1 CCA (red color) mixtures was also plotted but not included in the analysis. Mix 5 had 356 kg/m^3 of Pile1 CCA as-received in concrete mixture; whereas, Mix 12 had 100% of Pile1 CCA coarse fraction in concrete mixture. Mix 5 showed a similar RCP result to Mix 3 (356 kg/m^3 CCA7 as-received); whereas, Mix 12 had a similar RCP result to Mix 9 (100% CCA21 coarse fraction).

The second degree quadratic trend line was best as shown in Figure 5.31. The CCA7 and the control mixtures had a poor correlation with 0.47 R^2 whereas the CCA21 and the control mixtures had an excellent correlation with 0.99 R^2. The poor correlation of CCA7 mixtures was partly contributed by the relatively broader range of *w/c* ratio (0.52-0.59); whereas, the good correlation of CCA21 mixtures was partly contributed by the relatively narrow range of w/c ratio (0.58-0.59).



(a) (b)

Figure 5.31 RCP vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

The CCA7, CCA21 mixtures were also put together representing as one broader strength range and the RCP result plotted against the corresponding CCA volume as illustrated in Figure 5.32. The second degree quadratic trend line was best. The CCA7, CCA21, and the control mixtures had a reasonable correlation with 0.8 R^2. Therefore, the RCP model as a function of the CCA volume is proposed,

$$y = 1.36x^2 + 12.987x + 3318.8 \qquad \textbf{Equation 30}$$

Where y is the RCP result (coulombs) by ASTM C1202 and x is the CCA volume (%) in 0.76 m^3 (27 ft^3) concrete volume.

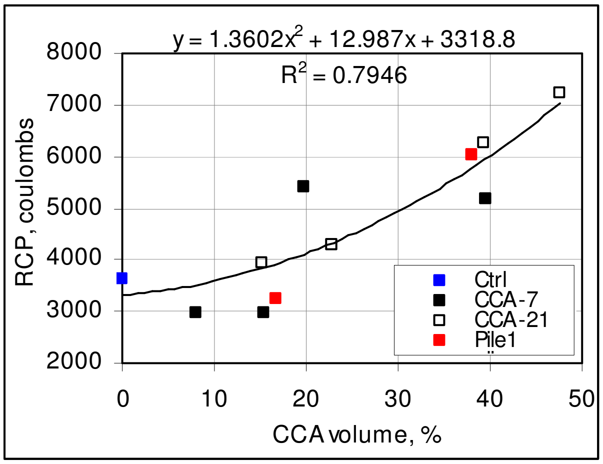


Figure 5.32 RCP vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

Rapid Chloride Permeability Model

The RCP modeling was also attempted with the mixture ingredients using the stepwise multiple regression analysis. In the multiple regression analysis, the RCP result was used as dependent variable while the mixture ingredients such as volumes of air content, mixing water, cement, virgin coarse aggregate, virgin fine aggregate, and CCA were considered as independent variables. During the stepwise multiple regression analysis, the CCA volume (independent variable) was found to be insignificant and removed for the model parameter with 95% confidence. Without CCA variable the RCP model with respect to the mixture ingredients was not established. As indicated, the permeability is dependent on the pore size, volume, and solution which are closely related to the porosity of the paste matrix in concrete. Although the CCA volume is proportional to the old cement paste volume attached on CCA the CCA volume itself couldn’t meet the 95% statistical significance.

The RCP modeling was further investigated with the porosity for both new cement paste and old cement paste on CCA and other influencing factor such as w/c ratio. The porosity of new cement paste was quantitatively obtained using Power's model whereas the porosity of old cement paste on CCA was obtained with absorption test result. In Power's model the porosity of the new cement paste was obtained with a reasonable assumption of 80-100% degree of hydration as the RCP test of CCA and the control mixtures was conducted at an age of 90 days in accordance with ASTM C1202. The detail calculation using Power's model was described in Appendix B. With these influencing factors the step wise multiple regression analysis was conducted with the RCP result for dependent variable and the porosity of the new and old cement paste, w/c ratio for independent variables.

In Table 5.14 an acceptable F test (significance $F < 0.05$; f theoretical equal to 11.4, $f > F_{0.05,3,5} = 5.41$) for the CCA and the control mixtures was obtained with three independent variables remained (significance $T < 0.05$; t theoretical equal to $t > t_{0.025,7} = 2.365$ or $t < -2.365$). These significant variables were the porosity of the new cement paste, porosity of the old cement paste on CCA, and w/c ratio.

The multiple regression analysis result with 0.93 R^2 is shown in Table 5.14.

Table 5.14 Step Wise Regression Analysis for RCP Modeling

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.933
R Square	0.870
Adjusted R Square	0.791
Standard Error	673.3
Observations	9

ANOVA

	df	*SS*	*MS*	*F*	*ignificance F*
Regression	3	15115261	5038420	11.115	0.0119
Residual	5	2266428	453286		
Total	8	17381690			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-348054	124155	-2.803	0.038	-667205	-28903.951
New.Cem.Mat.	-21954600	7730620	-2.840	0.036	-41826792	-2082407.8
Old.Cem.Mat.	466249	82551	5.648	0.002	254046	678452.6
w/c	747759	264304	2.829	0.037	68344	1427173.7

Thus, the proposed model is,

$$y = -348054 - 21954600(x_1)^{1.7} + 466249(x_2)^{1.1} + 747759(x_3)$$ **Equation 31**

Where

y = RCP (Coulombs)

x_1 = Porosity of new cement paste (m^3)

x_2 = Porosity of old cement paste (m^3)

x_3 = w/c ratio

The dependent and independent variables used in the analysis are also summarized in Table 5.15.

Table 5.15 Input Data Used in Elastic Modulus Model

Mix #	CCA Type	RCP coulombs	Por.N.C.* m^3	Por.O.C.+ m^3	w/c ratio
1	Control	3618	0.038	0.000	0.58
2	7 MPa	2970	0.033	0.004	0.56
3	7 MPa	2984	0.040	0.008	0.59
7	7 MPa	5402	0.031	0.007	0.55
8	7 MPa	5187	0.024	0.013	0.52
4	21 MPa	3936	0.037	0.007	0.58
5	21 MPa	4276	0.040	0.010	0.59
9	21 MPa	6248	0.039	0.013	0.59
11	21 MPa	7231	0.040	0.019	0.59

* Por.N.C. = Porosity of New Cement Paste (Degree of Hydration at 100%)

\+ Por.O.C. = Porosity of Old Cement Paste

Simplified Indication of Concrete's Ionic Conductivity and Rapid Chloride Permeability Test

ASTM C1202 is a test method of the electrical conductance of concrete measured by a total charge (current) passed over 6 hour testing periods. Since RCP test per ASTM C1202 uses the electric conductivity method the total charge passed over 6 hour periods can be correlated to the electric conductivity (σ). The electric conductivity (σ) is defined as the ratio of the current density (J) to the electric field strength (E) as illustrated by

$$\sigma = \frac{J}{E} \qquad \textbf{Equation 32}$$

The conductivity is also the reciprocal of electrical resistivity (ρ) and has the SI units of Siemens per meter (Sm^{-1}) as illustrated by,

$$\sigma = \frac{1}{\rho}$$ **Equation 33**

The resistivity is a measure of the material's ability to oppose electric current (charge) and has the following relationship with the electric resistance,

$$\rho = R \times \frac{A}{l}$$ **Equation 34**

Where, l is the length, A is the cross sectional area of the test specimen, and R is the electric resistance. The electric resistance can be obtained by the current flowed divided by the electric strength as illustrated by,

$$R = \frac{I}{V}$$ **Equation 35**

Where, I is the electric current and V is the electric voltage. Therefore the concrete resistivity can be simply measured by the concrete's electrical resistance per unit cross section and length. The concrete resistivity measurement is simpler and quicker (1-5 min.) as compared to the coulomb test in ASTM C1202 which requires more testing procedures and longer testing time for 6 hours. Most of all, the concrete resistivity measurement can overcome the heat effect that adversely affects the RCP measurement for highly porous concrete. The heat effect is caused by the high flow of the current for 6 hour testing periods during which the electric resistance is increased with the temperature of the specimen thus, deviating the true RCP result.

The RCP (coulombs) result of the CCA and the control mixtures against the corresponding conductivity was plotted as shown in Figure 5.33. The power trend line showed the best correlation with 0.98 R^2. Therefore the RCP coulombs result can be modeled as a function of the conductivity.

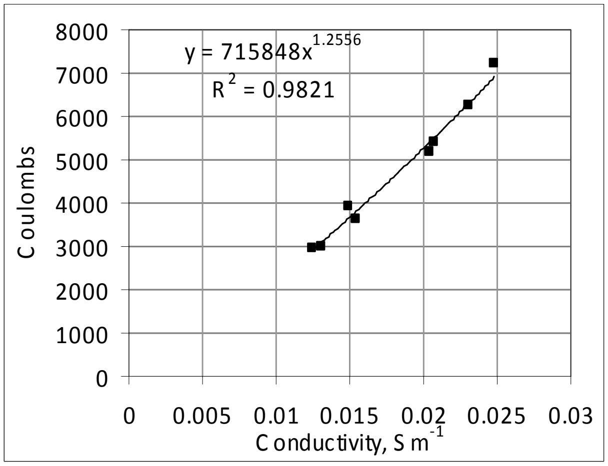


Figure 5.33 RCP coulombs vs. Conductivity

Thus, the proposed model is,

$$y = 715848\sigma^{1.2596} \qquad \textbf{Equation 36}$$

Wherer,

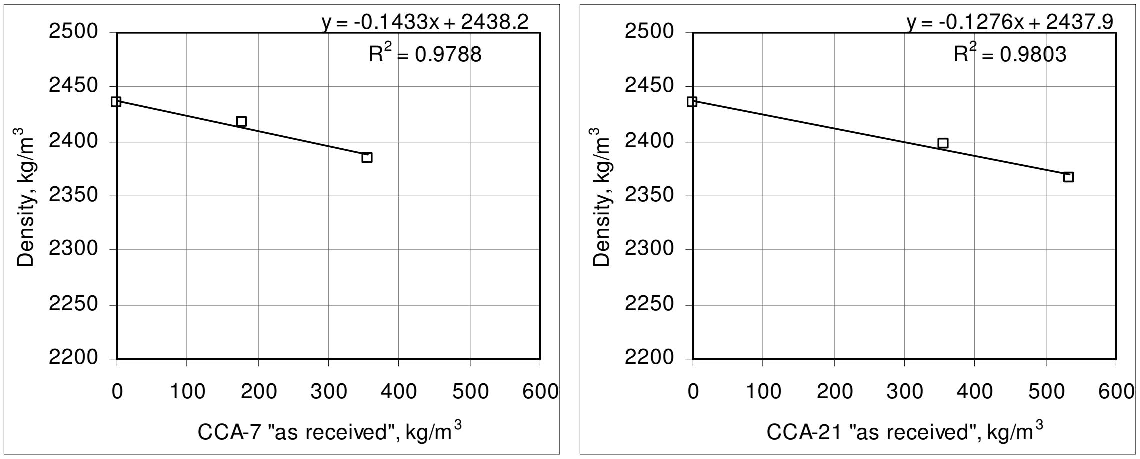
y = conlombs

σ = conductivity (S-m^{-1})

5.3. Analysis on Fresh Concrete Property

The fresh concrete properties such as density, air content, slump, and temperature are often used for the quality control (QC) of the concrete in the field. These fresh concrete properties are the earliest concrete properties that can be obtained at the job site and are used as an indicator of the concrete quality. Since the hardened concrete properties such as strength, shrinkage, RCP, etc., are highly dependent upon these fresh (or plastic) concrete properties, the plastic concrete properties are equally important and can be served both as a quality measure and as a performance measure of CCA concrete. In this study, only the fresh density result of CCA and the control mixtures was used as all other fresh concrete properties such as temperature, air content, and slump were maintained to constant.

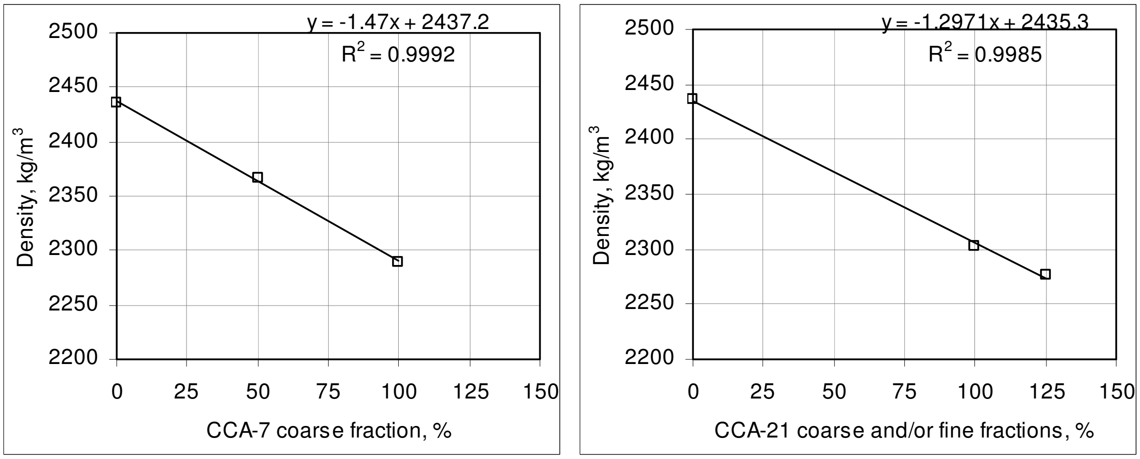
The fresh density result at the corresponding CCA mass as-received is shown in Figure 5.34. Figure 5.34 (a) illustrates the fresh density result for Mix 1, Mix 2, and Mix 3 with 0 kg/m^3, 178 kg/m^3, 356 kg/m^3, respectively, of CCA7 as-received in concrete mixtures; whereas, Figure 5.34 (b) shows the fresh density result for Mix 1, Mix 4, and Mix 6 with 0 kg/m^3, 356 kg/m^3, 534 kg/m^3, respectively, of CCA21 as-received in concrete mixtures. The linear trend line with R^2 was made in the chart. Both CCA7 and CCA21 mixtures had a good correlation with 0.98 R^2 with the control mixture as shown in Figure 5.34. The fresh density of the CCA7 mixtures was decreased by 0.8%-2.1% with increasing CCA7 as-received from 178 kg/m^3 (Mix 3)-356 kg/m^3 (Mix 3) compared to the control mixture whereas the fresh density of the CCA21 mixtures was reduced by 1.6%-2.9% with increasing CCA21 as-received from 356 kg/m^3 (Mix 4)-534 kg/m^3 (Mix 6) as compared to Mix 1. In general, the fresh density of CCA mixtures was decreased with increasing CCA as-received in concrete as compared to the control concrete.



(a) (b)

Figure 5.34 Density vs CCA Replacements with As-Received Condition

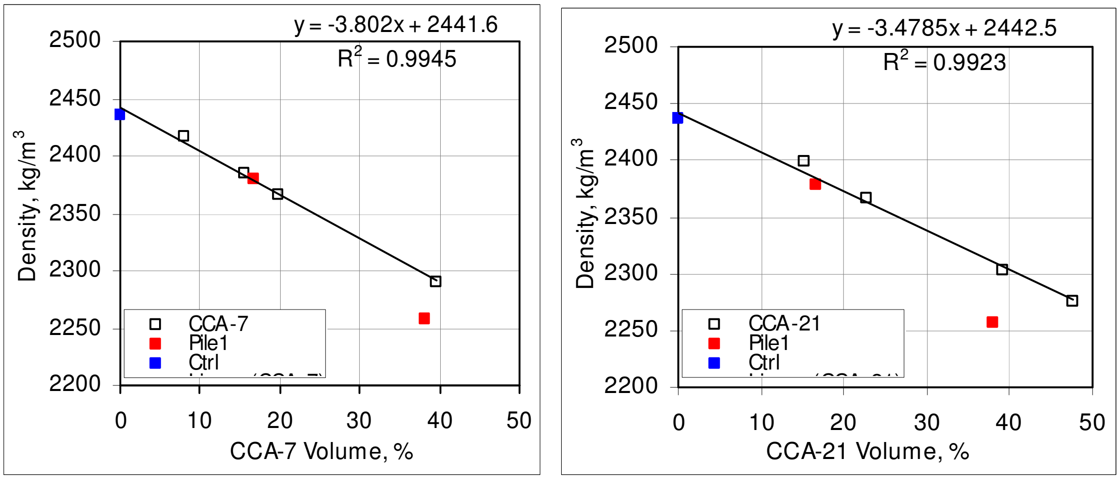
Figure 5.35 (a) illustrates the fresh density result for Mix 1, Mix 7, and Mix 8 with 0%, 50%, and 100%, respectively, of CCA7 coarse fraction in concrete mixtures whereas Figure 5.35 (b) shows the fresh density result for Mix 1, Mix 9, and Mix 11 with 0/0%, 100/0%, and 100/25%, respectively, of CCA-21 coarse/fine fraction in concrete mixtures. The linear trend line with the R^2 was made in the chart. Both CCA7 and CCA21 mixtures had a good correlation with 0.99 R^2. The fresh density of CCA7 mixtures was decreased by 2.9%, 6% for Mix 7, Mix 8, respectively, as compared to Mix 1; whereas, the fresh density of CCA21 mixtures was reduced by 5.5%, 6.6% for Mix 9, Mix 11, respectively, as compared to the control mixture. The similar trend was observed as the fresh density of CCA mixtures was decreased with increasing CCA coarse/fine fraction in concrete.



(a) (b)

Figure 5.35 Density vs CCA replacements with Coarse and/or Fine fraction(s)

Figure 5.36 illustrates the fresh density result at the corresponding CCA volume in 0.76 m^3 (27 ft^3) concrete for the CCA and the control mixtures. The fresh density result of Pile1 CCA mixtures (red color) was also plotted but not included in the analysis. It can be noted that the fresh density of Pile1 CCA mixture was similar to that of CCA7, CCA21 mixtures when used with less than 15% by volume whereas the fresh density of Pile1 CCA mixture was significantly reduced when used with more than 20% by volume. Therefore, it is desirable to use Pile1 CCA with less than 15% by volume in concrete if the fresh density is used for the quality measure such as limiting the fresh density for the project specification. If Pile1 CCA is used more than 20% by volume in concrete the stable (predictable) fresh density may not be achieved subsequently risking to the penalty. Both CCA7 and CCA21 mixtures had a good correlation with 0.99 R^2.



(a) (b)

Figure 5.36 Density vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

The fresh density result for both CCA7 and CCA21 mixtures was put together representing as one broader strength range with the control mixture as shown in Figure 5.37. The linear trend line was best to achieve the highest correlation. The fresh density of CCA and the control mixtures had an excellent correlation with 0.99 R^2. Namely, the fresh density with CCA mixtures is highly predictable so that it can benefit the quality measure of the concrete. As there is a good correlation established the fresh density of CCA, and the control mixtures can be estimated as a function of the CCA volume by;

$$y = -3.595x + 2442.4 \qquad \textbf{Equation 37}$$

Where y is the fresh density (kg/m^3) and x is the CCA volume (%) in 0.76 m^3 (27 ft^3) concrete volume.

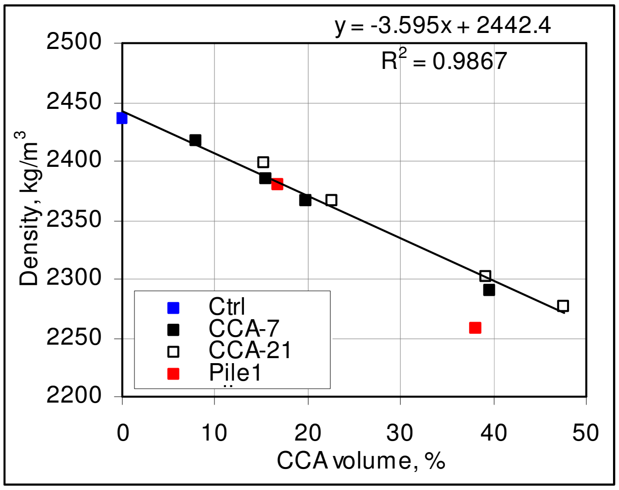


Figure 5.37 Density vs CCA volume in 0.76 m^3 (27 ft^3) Concrete

Chapter 6. Specification

6.1. Introduction

In this chapter, the benefits of a performance-based specification are demonstrated with an example of an experimental case study with conventional concrete without CCA aggregates as well as the current study with concrete with CCA aggregates, compared to the prescriptive specification. Since it is of importance to understand the codes and specifications that are essential to practical concrete projects, they will be discussed briefly. Codes, such as a building code, establish the framework of a construction project while specifications provide specific instructions for the various parts of the project. The current building code and specifications were developed many years ago and have been used in practice till this year. Particularly, the concrete industry has used prescriptive specifications for its job specifications for many years. While the prescriptive specification based on codes written many years ago stayed the same, the concrete industry has made significant progress with the help of new and emerging technologies and research and development, by which concrete performance and quality are highly optimized, with supplementary cementitious materials and chemical admixtures for example. However, with this new technology and advancement, prescriptive specifications cannot accommodate the changes due to its “one size fits all approach” . Thus, an alternative approach is sought that can embrace the progressive changes of concrete technology, while maintaining peace within conflicted interest sectors such as engineers (designers) and producers. That alternative approach is the performance-based specification.

6.2. Codes and Specifications

A building code establishes minimum requirements for buildings to protect public safety. In the US, ACI 318 is the commonly referenced building code for structural concrete. It has been developed by committee 318 of the American Concrete Institute (ACI). It is generally the responsibility of the structural engineer to ensure that the design of the structure complies with the requirements of the code. A specification for concrete construction consists of the written instructions prepared by a structural engineer on behalf of the owner to the concrete contractor. A specification is the basis of a contract including a legal agreement between the owner and the contractor and establishes the joint and separate responsibilities throughout the construction project.

6.2.1. Prescriptive specification

A prescriptive specification is guided by means and methods of construction and composition of the concrete ingredients. The prescriptive specification includes controls on the composition of the concrete mixture such as minimum cement content, type of cement, limits on the quantity of supplementary cementitious materials, maximum water to cementitious materials (*w/cm*) mass ratio, limits on the grading of aggregates or type used, brand of admixture and required dosage, etc. In addition, there may be requirements on minimum compressive strength or other properties.

6.2.2. Performance specification

A performance specification is guided by the functional requirements for fresh and hardened concrete depending on the application. For example, the performance criteria for interior columns in a building might be compressive strength only, whereas performance criteria for a bridge deck or parking garage slab, besides design strength, might include limits on permeability, since the concrete will be subjected to a harsh environment.

The performance specification also provides the necessary flexibility on mixture composition to accommodate the source variability of ingredient materials. The contractor and producer will work together to develop a mixture proportion for the plastic concrete that meets additional requirements for placing and finishing, such as flow and set time, while ensuring the performance requirements for the hardened concrete are not compromised. A performance specification will avoid requirements for means and methods, and avoid limitations on the ingredients or proportions of the concrete mixture.

6.3. Experimental Case Study Demonstrating Advantages of Performance Specifications

The experimental case study is illustrated to show the advantages of performance specifications. This section consists of two subsections in which the first illustrates the advantages of performance specifications for conventional concrete while the second illustrates the advantages of using performance specifications for concrete with CCA aggregates.

6.3.1. Conventional Concrete

The following three scenarios are discussed with the conventional concrete.

Scenario 1 considers a typical floor slab specification. A concrete mixture was first designed to meet the prescriptive specification. Three alternative concrete mixtures were developed that considered various options to optimize the mixtures. These three mixtures did not meet the prescriptive criteria. The concrete performance characteristics most relevant to that application such as workability, setting time, strength, and shrinkage are compared.

Scenario 2 considers a HPC bridge deck specification. A prescriptive mixture that complied with the typical HPC bridge deck specification requirements was first designed. Three alternative optimized mixtures that did not meet the prescriptive specification were developed. The concrete performance characteristics most relevant to that application such as strength, shrinkage and rapid chloride permeability are compared.

Scenario 3 evaluates some of the prescriptive provisions of the ACI 318 Building Code. Provisions for durability in the code primarily restrict the *w/cm* and compressive strength of concrete mixtures as a means to control its permeability. Four mixtures were designed to evaluate if that approach is valid given the advances that have been made in recent decades with the widespread use of chemical admixtures and supplementary cementitious materials.

To help understand the ACI 318 Building Code, according to the ACI 318 code the required average compressive strength (f'_{cr}) when a history of strength data are available to establish a sample standard deviation is obtained by choosing the higher value from Eq. 38and 39, if the specified design compressive strength (f'_c) is less than 34 MPa:

$$f'_{cr} = f'_c + 1.34S \qquad \textbf{Equation 38}$$

$$f'_{cr} = f'_c + 2.33S - 3.45 \qquad \textbf{Equation 39}$$

where f'_{cr} = required average strength (MPa),

f'_c = specified design strength (MPa),

S = standard deviation (MPa)

The required average compressive strength when the history of testing data are not available to establish a sample standard deviation is obtained by Table 5.3.2.2 in the ACI 318 code at various specified compressive strength levels as shown in Table 6.1

Table 6.1 ACI 318-08 Required Average Compressive Strength with No Test Data

Specified Compressive Strength, MPa	Required average compressive strength, MPa
$f'_c < 21$	$f'_{cr} = f'_c + 7$
$21 \leq f'_c \leq 34$	$f'_{cr} = f'_c + 8.5$
$f'_c > 34$	$f'_{cr} = f'_c + 10$

For example, if the specified design compressive strength is 28 MPa then the required average compressive strength when the past test record is not available is calculated to be 36.5 MPa (f'_{cr} =28+8.5) whereas the required average compressive strength when the past test record is available is used with the higher value from Eq.5-1 (f'_{cr} = 28+1.34×3.45 MPa = 32.6 MPa, when a sample standard deviation is 3.45 MPa from the past test data), 5-2 (f'_{cr} =28+2.33×3.45-3.45 = 32.6 MPa, when a sample standard deviation is 3.45 MPa from the past test data). Thus, the required average compressive strength is 32.6 MPa with the past test record is available and 36.5 MPa without the past test record. It is noted that the difference of the required average compressive strength between these two code provisions is 3.9 MPa.

6.3.1.1. Concrete Floor Slab

The main features of the concrete floor slab specification are as follows:

a. Specified 28 day compressive strength (f'_c) =28 MPa; for a required over design of 8.5 MPa, the required average strength (f'_{cr}) will be 36.5 MPa
b. Maximum water to cement ratio of 0.52. Water content to be measured by microwave oven test to estimate the *w/cm* – Penalties for higher w/cm and concrete rejected with a w/cm higher than 0.55
c. No fly ash or slag is allowed
d. Maximum Slump = 100 mm
e. Non air entrained concrete
f. Combined aggregate gradation shall be 8% - 18% retained on each sieve below the top size and above the No. 100 sieve. Maximum aggregate size will be 38 mm.
g. No high range water reducing admixture allowed

The performance criteria will be targeting the following requirements:

a. Specified 28 day compressive strength (f'_c) =28 MPa; required average strength (f'_{cr}) based on ACI 318 or ACI 301 from past test records
b. Supplementary cementitious materials may be used
c. Slump = 100 – 150 mm
d. Length Change (drying shrinkage) (ASTM C157) ≤ 0.05% at 90 days of drying after 7 days of moist curing.
e. Length Change (ASTM C157) ≤ 0.05% at 90 days of drying after 7 days of moist curing.
f. Setting time (ASTM C 403) under laboratory conditions = 5 ± 1/2 hours

The described prescriptive and performance criteria are summarized in Table 6.2.

Table 6.2 Prescriptive and Performance Criteria for Concrete Floor Slab

Prescriptive Specification		Performance Specification	
Strength at 28d	28 MPa	Strength at 28d	28 MPa
Max. w/cm	0.52		
Slump	Max. 100 mm	Slump	100-150 mm
Aggregate Grading	8-18% grading requirement		
No SCM		Initial setting time	5±½ hr
		Drying Shrinkage	≤ 0.05% at 90d
		No restriction on materials and mix proportions	

Results and Discussions

The experimental test result for five concrete mixtures is summarized in

Table 6.3.

Table 6.3 Results for Concrete Floor Slab Mixtures

Mixtures	FS-1 (Control)	FS-2	FS-3	FS-4
Aggregate Grading	8-18%	8-18%	Gap grading	8-18%
w/cm ratio	0.49	0.53	0.53	0.54
Total Cemtitious, kg/m^3	363	314	314	314
Fly ash, % replaced		20	20	15
Slag, % replaced				20
Strength at 28d, MPa	40.5	33.5	34.3	32.5
% of control		83%	85%	80%
Shrinkage at 90d, %	0.032	0.031	0.026	0.040
% of control		97%	80%	125%
Initial setting time, h:m	4:12	5:30	5:17	5:59
% of control		131% (1:18)	126% (1:05)	142% (1:47)
RCP[*], coulombs at 200d	3050	538	635	584
% of control		18%	21%	19%

[*] RCP = Rapid Chloride Permeability

Initial Setting Time

The setting time of mixture FS-1 (control prepared by the prescriptive specification) was 4:12 hours, which was modestly faster than those of the other mixtures. The target concrete initial setting time of 5 ± 1/2 hours was met by all the performance-based mixtures except Mixture FS-4 which contained both fly ash and slag and had an initial setting time of 5:59 hours, which failed to meet the performance criteria.

Compressive Strength

All concrete mixtures met the acceptance criteria for a specified 28-day compressive strength of 28 MPa. For Mixture FS-1 (control), the lower w/cm resulted in a compressive strength close to 36.5 MPa. This significantly exceeded the required average strength of 32.6 MPa. This illustrates that the control of the acceptance criteria on *w/cm* forces a higher strength that is not beneficial for this particular application. This mixture also has a higher material cost. For the performance-based mixtures, the average strength exceeded the target 32.6 MPa except FS-4 with 0.1 MPa lower (negligible). The target 32.6 MPa was the required average strength based on a past test record with a standard deviation less than about 3.45 MPa. The over design factor of 8.5 MPa as a default requirement of the specification is not necessary as it assumes a poor level of quality control and penalizes concrete producers who practice good quality control.

Drying Shrinkage

The target length change limit for the performance-based mixtures of 0.05% after 90 days of drying was achieved by all the mixtures. The comparison of results for mixtures FS-2 and FS-3 shows the effect of the aggregate grading limit as intended by the 8 – 18 grading requirement. This result shows that FS-2 mixture, which satisfied the 8-18 grading requirement did not reduce the shrinkage compared to FS-3 mixture with gap grading. The drying shrinkage for the performance-based mixtures was lower by 3-20% except FS-4 that was 25% higher than that of the control (FS-1 followed by the prescriptive specification). It is presumed that higher length change will result in increased curling of the floor slab.

Rapid Chloride Permeability (RCP)

The RCP value for all performance based mixtures was lower by 79-82% than that of the prescriptive mixture (FS-1). The use of supplementary cementitious materials such as fly ash and slag helps attain the lower permeability.

The above experimental study brings out the following conclusions:

1. Prescriptive specifications do not necessarily ensure good performance. Aggregate grading limit in this study did not have significant impact on the drying shrinkage of the concrete. Specifying a strength with over design of 8.5 MPa, and establishing a *w/cm* ratio acceptance criteria could in fact adversely impact intended performance such as drying shrinkage.
2. Another analysis that can be conducted is the economy of the concrete mixture. Using certain assumptions of material costs, it is estimated that the material costs of Mixture FS-1 (control) will be about \$56.7/m^3. In comparison the performance-based concrete mixtures will have a reduced materials cost ranging from 8.8% to 15.2%.

6.3.1.2. High Performance Concrete (HPC) Bridge Deck

The main features of the high performance concrete bridge deck specification are as follows:

a. Specified 28 day compressive strength (f'c) =28 MPa; required average strength (f'_{cr}) will be based on a historical test record in accordance with ACI 318 or ACI 301.
b. Maximum water to cementitious ratio is 0.39
c. Total Cementitious Content = 418 kg/m^3. Cementitious composition should be at 15% fly ash and 7% to 8% silica fume
d. Slump ranges 100 – 150 mm
e. Air entrainment of 4%-8% required

The performance criteria were established with the following requirements:

a. Specified 28 day compressive strength (f'_c) =28 MPa; required average strength (f'_{cr}) based on ACI 318 or ACI 301 using past test records
b. Supplementary cementitious materials are allowed and their quantities will not exceed limits of ACI 318 to protect against deicer salt scaling
c. Slump ranges 100 – 150 mm
d. Air entrainment of 4%-8% required
e. RCP testing (ASTM C 1202) = 1500 coulombs after 45 days of moist curing
f. Length Change (drying shrinkage) < 0.04% at 28 days of drying after 7 days of moist curing

The described prescriptive and performance criteria are summarized in Table 6.4.

Table 6.4 Prescriptive and Performance Criteria for HPC Bridge Deck Mixture

Prescriptive Specification		Performance Specification	
Strength at 28d	28 MPa	Strength at 28d	28 MPa
Max. w/cm	0.39		
Total Cementitious content	418 kg/m^3		
Fly ash, Silica fume dosage	15% & 7%		
Slump	4 - 6”	Slump	100 – 150 mm
Air content	4 – 8%	Air content	4 – 8%
RCP		RCP (coulombs)	1500 c at 45d
		Shrinkage	≤ 0.04% at 28d
		No restriction on materials and mix proportions	

Results and Discussions

The experimental test results for four concrete mixtures are summarized in Table 6.5.

Table 6.5 Results for HPC Deck Mixtures

Mixtures	BR-1 (control)	BR-2	BR-3	BR-4
w/cm ratio	0.39	0.39	0.39	0.36
Total Cemtitious, kg/m^3	418	356	356	356
Fly ash, % replaced	15	25		25
Slag, % replaced			50	
Silica fume, % replaced	7	4		
UFFA, % replaced				5.6
Strength at 28d, MPa	51.6	46.9	61.8	49.5
% of control		91%	120%	96%
Shrinkage at 28d, %	0.037	0.017	0.021	0.018
% of control		46%	57%	49%
RCP, coulombs at 45d	1563	1257	1126	1244
% of control		80%	72%	80%

Compressive Strength

All mixtures exceeded the specified 28-day compressive strength of 28 MPa. Relatively speaking, the compressive strength for the performance-based mixtures was slightly lower by 4% and 9% for BR-4 and BR-2, respectively, but stronger by 20% for BR-3 than that of the prescriptive mixture (BR-1, control).

Drying Shrinkage

The specified length change of 0.04% after 28 days of drying was achieved by all mixtures. The drying shrinkage for all performance-based mixtures was lower by 43%-54% than that of the prescriptive mixture (BR-1). The highest shrinkage (0.037%) was observed for the mixture that complied with the prescriptive HPC Bridge specification (BR-1).

Rapid Chloride Permeability (RCP)

The specified RCP testing value of 1500 coulombs after 45 days of moist curing was achieved by all the mixtures except for the prescriptive BR-1 mixture which had a slightly higher value of 1563 coulombs. The RCP value for all performance-based mixtures was lower by 20-28% than that of the prescriptive mixture (BR-1).

The above experimental study brings out the following conclusions:

1. The prescriptive specification for bridge deck concrete can be significantly optimized for improved performance on drying shrinkage, strength, and rapid chloride permeability.
2. Concrete mixtures optimized for performance can achieve remarkable cost savings. It is estimated that the material costs of Mixture BR-1 will be about $\$75.6/m^3$. In comparison the performance-based concrete mixtures achieve reduced material costs ranging between 15.5% and 22.8%.

6.3.1.3. ACI 318 Code Provisions

Durability provisions for buildings are specified in Chapter 4 of ACI 318 Building Code for Structural Concrete. The Code addresses durability requirements for concrete exposed to freeze-thaw cycles, deicer salt scaling, sulfate resistance, protection from corrosion of reinforcing steel, and conditions needing low permeability. In all cases, the primary requirement of controlling the permeability of concrete is a maximum limit on the water to cementitious materials ratio (*w/cm*), along with a minimum specified strength. The four concrete mixtures having the same *w/cm* at various amounts of cementitious materials are compared with respect to permeability. Drying shrinkage measurements are also compared even though this is not a limitation in the Code.

The described prescriptive and performance criteria are summarized in Table 6.6.

Table 6.6 Prescriptive and Performance Criteria for ACI 318 mixtures

Prescriptive Specification		Performance Specification	
Strength at 28d	28 MPa	Strength at 28d	28 MPa
Max. w/cm	0.42		
Total Cementitious content	445 kg/m^3		
		Shrinkage	
		RCPT	
		No restriction on materials and mix proportions	

Results and Discussions

The experimental test results for the four concrete mixtures are summarized in Table 6.7.

Table 6.7 Results for ACI 318 Mixtures

Mixtures	318-1	318-2	318-3	318-4
w/cm ratio	0.42	0.42	0.42	0.42
Total Cemtitious, kg/m^3	445	415	335	335
Fly ash, % replaced		25	25	25
Type F admixture			Yes	Yes
Strength at 28d, MPa	37.6	41.0	39.2	38.7
% of control		109%	104%	103%
Shrinkage at 90d, %	0.064	0.048	0.039	0.033
% of control		75%	61%	52%
RCP, coulombs at 28d	8356	5610	4462	4036
% of control		67%	53%	48%

Compressive Strength

All mixtures exceeded the minimum specified strength. The measured 28-day compressive strength varied between 37.6 MPa and 41 MPa. The compressive strength for all performance-based mixtures was 3-9% higher than that of the prescriptive mixture (318-1, control).

Drying Shrinkage

The average length change after 90 days of drying varied between 0.064% and 0.033%. The reduction in the paste content and possibly the use of fly ash resulted in a reduction in shrinkage in Mixtures 318-2, 318-3, and 318-4, as compared to the control mixture. The drying shrinkage for performance-based mixtures was lower by 25-53% than that of the prescriptive mixture (318-1). It is presumed that a higher length change will increase the propensity for drying shrinkage cracking.

Rapid Chloride Permeability

The 28 day RCP test results varied between 8356 coulombs and 4036 coulombs. At the same low w/cm of 0.42 the RCP for the performance-based mixtures was lower by 33-52% than that of the prescriptive mixture (318-1).

The above experimental study brings out the following conclusions:

1. At the same *w/cm*, concrete's performance, as exemplified by drying shrinkage and transport properties, can be drastically altered by changing the type and quantity of cementitious materials and by using chemical admixtures. Code limitations on *w/cm* do not assure that concrete mixture with a low permeability will be achieved. In this study, substantial variation in concrete performance was observed at the

same *w/cm*. Even though the compressive strength had a smaller variation, the drying shrinkage varied over a wide range, between 0.033% and 0.064%. The durability represented by the 28 day rapid chloride permeability values varied between 8356 coulombs and 4036 coulombs. The use of supplementary cementitious materials (in this case fly ash) substantially influences permeability to chloride ions and durability at the same *w/cm*.

2. Over the years, considerable advances have been made in understanding the influence of concrete mixture optimization for concrete durability. Requirements in the ACI 318 Building Code have not developed side by side. This study shows that significant differences in durability and shrinkage can be attained at the same *w/cm* and similar strength levels. Alternative options for durability should be considered to the current prescriptive limitations of the ACI 318 Building Code.

6.3.2. CCA Concrete

6.3.2.1. Concrete Floor Slab with CCA

The concrete floor slab specification was used with minor modifications. The specified compressive strength at 28 days was reduced to 21 MPa at a higher maximum *w/c* ratio of 0.58. The 8-18% aggregate grading requirement was removed as the aggregate grading was found to be insignificant. With a specified 28-day compressive strength of 21 MPa, the target application would be covered by general residential concrete work, concrete footings, concrete parking lots, and driveways.

The modified concrete floor slab specification was as follows:

a. Specified 28 day compressive strength (f'_c) =21 MPa; required average strength (f'_{cr}) based on ACI 318 or ACI 301 from past test records
b. Maximum water to cement ratio of 0.58.
c. No fly ash or slag is allowed
d. Slump ranges 100-150 mm
e. Non air entrained concrete
f. No high range water reducing admixture allowed

The performance criteria targeted the following requirements:

a. Specified 28 day compressive strength (f'_c) =21 MPa; required average strength (f'_{cr}) based on ACI 318 or ACI 301 from past test records
b. Supplementary cementitious materials may be used
c. Slump ranges 100 – 150 mm
d. Length Change (ASTM C 157) < 0.05% at 90 days of drying after 7 days of moist curing.
e. Setting time (ASTM C 403) = 5 ± 1/2 hours

The described prescriptive and performance criteria are summarized in Table 6.8.

Table 6.8 Concrete Floor Slab with CCA

Prescriptive Specification		Performance Specification	
Strength at 28d	21 MPa	Strength at 28d	21 MPa
Max. w/c	0.58		
Slump	100-150 mm	Slump	100-150 mm
No SCM		Initial setting time	5±½ hr
		Shrinkage	≤ 0.05% at 90d
		No restriction on materials and mix proportions	

Results and Discussions

The experimental test results are selected from the concrete mixtures with different types and amounts of CCA aggregates along with the control mixture without CCA aggregates. These test results are summarized in Table 6.9.

Table 6.9 Results for Concrete Floor Slab Mixtures with CCA

Mixtures	Mix1	Mix2	Mix4	Mix9	Mix10
Type	Control	CCA7	CCA21	CCA21	CCA34
w/c ratio	0.58	0.56	0.58	0.59	0.57
Total Cemtitious, kg/m^3	297	297	297	297	297
CCA, kg/m^3		178	356		
CCA, coarse, %				100	100
Strength at 28d, MPa	28.3	27.5	25.4	27.1	26.1
% of control		97%	90%	96%	92%
Shrinkage at 90d, %	0.031	0.035	0.043	0.049	0.041
% of control		113%	139%	158%	132%
RCP, coulombs at 90d	3618	2970	3936	6248	4729
% of control		82%	109%	173%	131%
Initial setting time, h:m	4:14	4:03	3:52	3:00	-
% of control		96% (-0:11)	91% (-0:22)	71% (-1:14)	

Initial Setting Time

The setting time of the control mix (Mix1) which satisfied the prescriptive specification was 4:14 hours, whereas the setting times of all performance-based mixtures were between 3:00 hours and 4:03 hours. The target concrete initial setting time of 5 ± 1/2 hours was met by all the mixtures. The initial setting time for all performance-based concrete mixtures containing CCA aggregates was faster by 11 to 74 minutes than that of the control mixture (Mix1, prescriptive mixture).

Compressive Strength

All concrete mixtures met the acceptance criteria for the specified 28-day compressive strength of 21 MPa. For Mix1, the compressive strength was 28.3 MPa. This exceeded the required average strength of 25.6 MPa based on the past test record with a standard deviation less than about 3.45 MPa. All performance-based concrete mixtures containing CCA aggregates also exceeded the required average strength.

Drying Shrinkage

The target length change limit for the performance-based mixtures of 0.05% after 90 days of drying was achieved by all mixtures. The drying shrinkage for the performance-based mixtures with CCA aggregates was higher by 13%-58% than that of the prescriptive mixture (Mix1). The amount of CCA aggregates used in the performance-based mixtures resulted in increasing the paste content while increasing the drying shrinkage. Therefore, it is necessary to identify how much paste is contained in CCA aggregates for mixture design optimization, as discussed in Chapter 5.

Rapid Chloride Permeability (RCP)

The RCP value of the prescriptive mixture (Mix1) was 3618 coulombs which is "moderate" for the chloride ion penetrability based on charge passed in accordance with ASTM C1202. The RCP performance for Mix2 (178 kg/m^3 of 1000 CCA aggregate) was improved by 18% compared to the prescriptive mixture, whereas the RCP performance for all other performance-based mixtures with higher strength level CCA aggregate was increased by 9%-73% than that of the prescriptive mixture. According to ASTM C1202 classification Mix1, Mix2, and Mix4 are "moderate" for chloride ion penetrability whereas Mix9 and Mix10 are "high" for chloride ion penetrability based on charge passed.

The above experimental study brings out the following conclusions:

1. Prescriptive specifications do not necessarily ensure good performance. The performance-based mixtures containing different strength levels and amounts of CCA aggregates performed reasonable for their initial setting time, being faster by 11 to 74 minutes than that of the prescriptive mixture. The performance-based mixtures with CCA aggregates achieved the specified 28-day design strength. The compressive strength of the performance-based mixtures with CCA aggregates was similar and/or slightly lower by less than 10% than that of the prescriptive mixture. The performance-based mixtures containing CCA aggregates also met the target

length change limit of 0.05% after 90 days of drying. The RCP value of the performance-based mixture (Mix2) was better than that of the prescriptive mixture. The RCP of the prescriptive mixture was “moderate” for chloride ion penetrability, along with several of the performance-based mixtures.

2. The performance-based mixtures with CCA aggregates can be further improved with the addition of supplementary cementitious materials such as slag, fly ash, and silica fume. Likewise, the performance-based specification allows the concrete producer to develop better performance mixtures while utilizing the CCA aggregates.
3. The performance-based specification leads the concrete producer to participate in sustainable development which may be the ultimate goal of the human society due to limited resources.

6.4. Guidance to the Engineer

Both the ACI 318 Building Code for Structural Concrete (Section 3.3.1) and ACI 301 Reference specification for Structural Concrete require that concrete aggregates shall conform to ASTM C33. It is clear from the discussions in Chapter 3 (materials characterizations) that CCA aggregate meets ASTM C33. However, as discussed in this chapter, the CCA based concrete mixtures have to be optimized when used to produce new concrete and be proven for their performance with a clear testing methodology. If there is not enough experimental data available for the use of CCA aggregate in concrete, a more conservative approach is recommended.

Chapter 7. Application with CCA as Internal Curing Agents

7.1. Introduction

Every year an average of 6% of the 460 million cubic yards of ready-mixed concrete produced in the U.S. is returned to the concrete plant. The returned concrete is used in several ways, such as adding on top of fresh material, processing the returned concrete through a reclaimer system that separates ingredients, producing other products such as concrete blocks, or discharging the returned concrete at the concrete plant for later crushing and reuse for other application. The amount of crushed material produced by the ready-mixed concrete industry is on the order of 30 million tons per year, with most of it currently being diverted to landfills. Thus, recycling crushed returned concrete aggregate (CCA) is critical. The CCA aggregate has useful aggregate properties among which it is free of any contamination. Thus, CCA aggregate is distinguished from other recycled concrete aggregates (RCA) that come out of existing old structures with high contamination from many years of exposure during the service life.

Amongst possible applications CCA aggregate has potential as an internal curing agent due to its high absorption capacity and low specific gravity. The practice of internal curing has been demonstrated to reduce autogenous shrinkage and minimize early-age cracking of high performance concrete. Philleo (1991) suggested the concept of “water-entrained” concrete with the addition of saturated lightweight fine aggregates (LWAS) as a remedy to offset the chemical shrinkage that occurs during hydration of the cementitious paste. Due to the similar aggregate properties such as specific gravity and absorption capacity found in LWAS, the CCA aggregate was explored to study the potential application as internal curing agent. In this study, the CCA aggregate in 7 MPa, 21 MPa, and 34 MPa strength range were prepared for evaluation as internal curing agent. Also the best performed CCA aggregate for internal curing was blended with LWAS to examine the combined performance.

7.2. Experimental Program

7.2.1. Materials Characterization

A blended cement containing about 20 % by mass ground granulated blast furnace slag was obtained from a cement manufacturer. The cement's chemical and physical characteristics are included in

Table 7.1. CCA was separated into coarse and fine fractions using an No. 4 (4.75 mm) sieve. Then, the CCA fines were sampled and tested for their material characteristics according to relevant ASTM standards with the test results shown in

Table 7.2 and Table 7.3. For the purposes of this study the high percentage of minus 200 (0.003 in or 0.075 mm) particles in the CCA fines were removed to avoid extra variances. It is observed that the CCA fines have a higher absorption capacity and a lower specific gravity as shown in Table 7.3, due to the mortar fraction that is combined with the virgin low absorption aggregate.

Table 7.1 Characteristics and Compositions of Slag Blended Cement

Characteristic	
Blending agent	Slag (GGBFS[*])
Mass fraction	20 %
Blended cement specific gravity	3.16 ± 0.01
CaO (mass basis)	58.8 %
SiO_2	22.6 %
Al_2O_3	5.8 %
Fe_2O_3	2.4 %
MgO	4.5 %
SO_3	2.7 %
Loss on ignition	1.5 %
Equivalent alkalies	0.6 %

[*] GGBFS = ground granulated blast furnace slag

Table 7.2 Measured Particle Size Distributions after Removing Minus 200 Sieve Fraction

Sieve no. (opening)	***Percent passing***			
	LWAS	CCA7	CCA21	CCA34
4 (4.75 mm)	98.6	99.6	99.1	97.0
8 (2.36 mm)	70.1	71.6	69.9	58.6
16 (1.18 mm)	44.7	58.3	55.0	42.8
30 (0.6 mm)	29.6	37.7	35.2	26.3
50 (0.3 mm)	20.4	5.5	11.7	9.4
100 (0.15 mm)	14.5	1.0	0.0	2.6
Pan	0.0	0.0	0.0	0.0

The LWAS, an expanded shale, was obtained from a lightweight aggregate manufacturer. It has a saturated-surface-dried (SSD) specific gravity of 1.80 and a total absorption capacity of 23.8 % by mass. The measured particle size distributions of all internal curing materials (after removing the minus 200 particles from the CCA materials) are provided in

Table 7.2.

Table 7.3 Fine Aggregate Properties

Fine Aggregate	***Normal weight sand***	***LWAS***	***CCA7***	***CCA21***	***CCA34***
Specific Gravity (SSD)	2.61	1.80	2.15	2.23	2.15
Absorption (mass %)	Negligible	23.8	16.0	12.4	12.0
Minus 200 sieve (mass %)	0.57	Not meas.	7.31	9.50	7.64
Fineness Modulus	Not meas.	3.2	2.73	2.71	3.05

7.2.2. Internal Curing Agent Desorption Characterization

A desorption isotherm indicates the moisture content of a material during drying from the full saturation down to 0 % RH. Desorption isotherms for the four internal curing agents (ICAs) were measured according to the general procedures provided in ASTM C1498, using saturated salt solutions (slurries) of potassium sulfate, potassium nitrate, and potassium chloride. The measured desorption isotherms indicate that the three CCA aggregates have released about 60%-80% of the contained water while the LWAS has released about 90% of the contained water at RH above 93%, indicating that a higher volume fraction of CCA may be required to provide equivalent internal curing. In a study conducted by Bentz et al. (2005) the maximum potential water available for internal curing is assumed to be that amount desorbed from full saturated condition down to an RH of about 93%. It is also noted that the three CCA aggregates had different desorption abilities in which the CCA5000 aggregate had released less contained water than the other two CCA aggregates at RH greater than 93%. This is possibly related to the pore sizes in the paste of the CCA aggregate. The LWAS as expected showed the highest desorption ability in which above 90% of the contained water was released at RH greater than 93% as shown in Figure 7.1.

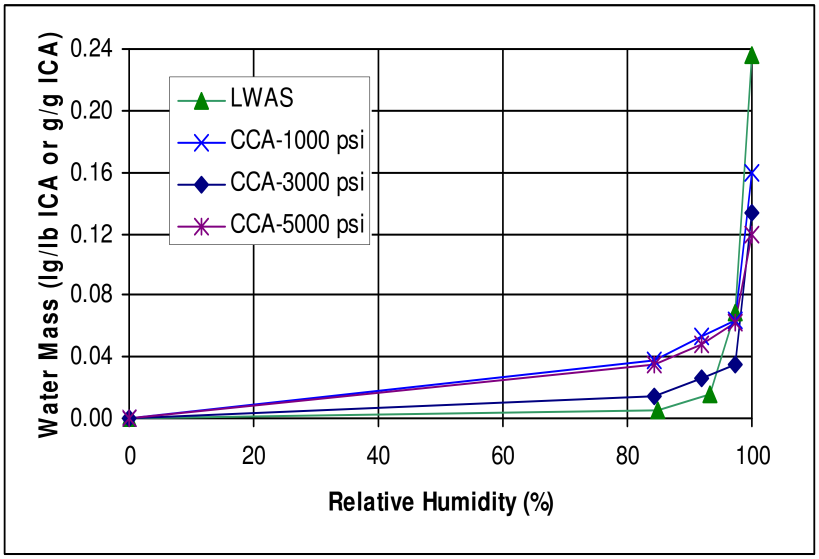
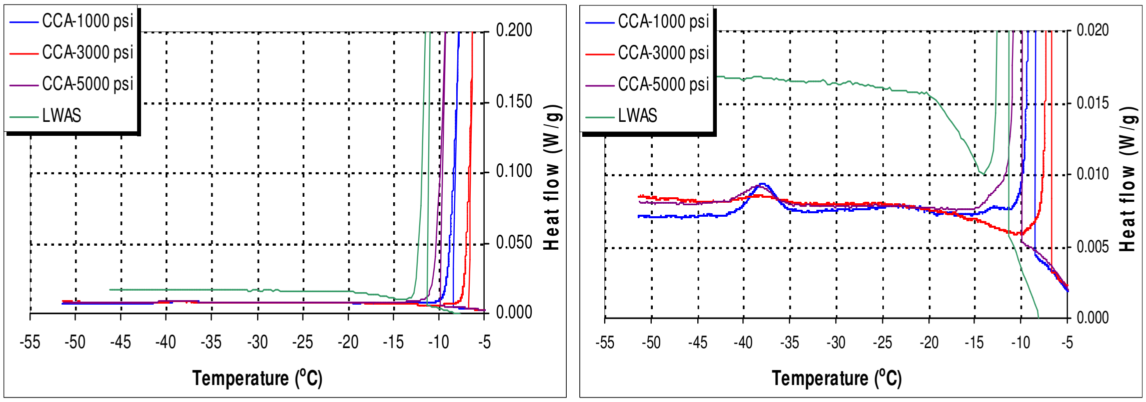


Figure 7.1 Desorption Isotherms for the CCAs and LWAS.

7.2.3. Low Temperature Calorimety (LTC)

To examine the size of the pores in each internal curing agent, low temperature calorimetry (LTC) scans were conducted. The LTC scans for the various internal curing materials are presented in Figure 7.2. Aggregate particles were first saturated in distilled water and then sampled to obtain an individual representative aggregate. The aggregate was surface dried and placed in the differential scanning calorimeter (DSC) for the LTC scan. In the DSC, as the temperature is lowered, water freezes in pores with successively smaller and smaller entryway diameters. The results in Figure 7.2 (a) suggest that the

CCA aggregates have a slightly larger pore size than the LWAS as indicated by their higher freezing points.



(a) (b)

Figure 7.2 Low Temperature Calorimetry Scans for the CCAs and LWAS.

Data is presented in SI units as they are the ones conventionally employed in DSC measurements. For temperature conversion, °F=(1.8 °C + 32); for heat flow, 1 W/g = 1548 BTU/(h·lb).

The results are rescaled in Figure 7.2 (b) to indicate that the hydrated cement paste present in the CCA aggregates is detectable as producing a peak near -40 °C, as reported in studies conducted by Snyder and Bentz (2004), and Bentz (2006) for hydrated cement paste specimens. Based on the size of this lower temperature peak, for the three CCA aggregates examined, the CCA3000 aggregate appears to contain less hydrated paste than the other two CCA aggregates. This could be a sampling error amongst the individual CCA aggregates selected for LTC analysis.

7.2.4. Mixtures Proportions

Seven mortar mixtures were prepared, including a control mortar mixture with no internal curing agent, three mortar mixtures with the various CCA fine materials, a mortar mixture with a CCA/LWAS blend, and two mortar mixtures with LWAS alone, to examine the performance of these internal curing agents with respect to their influence on autogenous deformation and compressive strength. The sieve size distributions of each CCA and the LWAS were determined (see

Table 7.2) so that a similar size distribution of the normal weight sand (a blend of four sands to achieve high performance) could be replaced. Mortars were proportioned with a constant volume of (blended) cement paste and a *w/cm* of 0.3. For the mortars with internal curing an extra 0.08 mass units of “free” water per mass unit of cementitious binder (*w/cm* basis, “free” water determined as that desorbed from SSD conditions down to 93 % RH for each internal curing agent) were added via the various internal curing agents. Thus, different replacements of CCA aggregates and LWAS were required to provide equivalent quantities of additional “free” water in each respective mixture. Mortar mixture proportions and fresh air contents are summarized in Table 7.4.

The 7 MPa CCA exhibited a higher air content than the other six mixtures. The LWAS-2 mixture was formulated to contain the same LWAS content as the CCA/LWAS blend so that the contribution of the CCA to the blend’s properties could be more fairly evaluated.

Table 7.4 Mortar Mixture Proportions.

Material or Property	***Control (g)[A]***	***LWAS-1 (g)***	***LWAS-2 (g)[B]***	***CCA7 (g)***	***CCA21 (g)***	***CCA34 (g)***	***CCA7/ LWAS (g)***
Blended cement	2000	2000	1000	2000	2000	2000	2000
Water	584.6	584.6	292.3	584.6	584.6	584.6	584.6
Type A admixture	25.6	25.6	12.8	25.6	25.6	25.6	25.6
F95 fine sand	950	696.1	379.8	569.8	625	466.6	664.6
Graded sand	722	613.2	320.2	341.8	356.3	238.6	545.4
20-30 sand	722	576.9	306.6	278.4	295.4	57.3	502.3
GS16 coarse sand	1406	704.9	440.1	497.7	491.8	16.2	653.1
SSD LWA	-	833.7	312.6	-	-	-	625.3
SSD CCA	-	-	-	1740	1735.8	2488.9	435
“Free” water in SSD LWA	-	160	60	-	-	-	120
“Free” water in SSD CCA	-	-	-	160	160	160	40
Fresh air content	3.1 %	2.9 %	4.2 %	6.6 %	4 %	4.4 %	5 %

[A] Masses are reported in grams as these were the units employed in preparing the mortar mixtures. For mass conversion, 1 g = 0.0022 lb.

[B] Note that the mixture size for LWAS-2 mortar is only 50 % of that of the other mixtures due to blended cement supply limitations.

7.2.5. Measurements

Mortar cubes were prepared according to ASTM C109 procedures and cured under sealed conditions; corrugated tube autogenous deformation specimens were also prepared for evaluation using the equipment developed by Jensen and Hansen (Jensen and Hansen 1995). Curing and autogenous deformation measurements were conducted at 25 °C. The procedure is currently being standardized in ASTM subcommittee C09.68; in the draft standard, the single laboratory precision is listed as 30 microstrains for mortar specimens.

7.3. Results and Discussion

7.3.1. Compressive Strength

The mortar cube compressive strengths for the CCA7, CCA21, and CCA34 mixtures were about 63%, 81%, and 65%, respectively, whereas the strengths for the LWAS-1, LWAS-2, and CCA/LWAS mixtures were 109%, 116%, and 94%, respectively, of the control mortar strength at an age of 28 days, as shown in Table 7.5. Similar trends of the strength gain for all mortar mixtures were observed at 56 days as shown in Figure 7.3. Three factors are likely contributing to the reduced strengths in the CCA mortars. First, the replacement of virgin fine aggregate by CCA aggregates may produce a strength reduction as the CCA aggregate tends to be more porous than the virgin aggregate. Second, a portion of the water contained in CCA aggregate might be readily released into the mortar mixture during the mixing thus increasing its true *w/cm* resulted in the strength reduction. Third, relatively higher air content in the CCA mortar mixtures would further reduce the strength.

It is also noted that the strength of the CCA21 mixture was superior to that of the CCA7 and CCA34 mixtures. As compared to the CCA7 mixture the similar strength result of the CCA34 mixture may seem surprising given the inherent strength of CCA aggregates that are made of. But this was because of a much larger volumetric substitution of the CCA34 aggregate to supply the same quantity of internal curing water due to its lower desorption ability from full saturation down to 93% RH as indicated in Figure 7.2 and Table 7.4.

Thus, the higher inherent strength of the 34 MPa CCA aggregate was offset by its larger volumetric content in the mortar mixture, ultimately producing lower compressive strength.

7.3.2. Autogenous Deformation

Autogenous deformation results are illustrated in Figure 7.4. The CCA mixtures reduced the autogenous shrinkage at early age up to 7 days throughout 56 days as compared to the control mixture except the CCA21 mixture.

In CCA mixtures the CCA7 and CCA21 mixtures had similar amounts of mixture ingredients where as the CCA34 mixture had much less amounts of 20-30 sand, GS16 coarse sand but much larger amount of CCA aggregate as indicated in Table 7.4. Therefore, the comparison between CCA7 and CCA21 mixtures can give the net performance in autogenous shrinkage due to its different CCA aggregate. Since the performance in autogenous shrinkage is highly depended on the three properties of the internal curing material: i) absorption capacity, ii) desorption ability at RH greater than 90%, and iii) pore sizes. These three properties will be discussed for the CCA7 and CCA21 aggregates as internal curing materials in relation to the performance in autogenous shrinkage hereafter.

First, does the absorption capacity of the CCA aggregates influence the autogenous shrinkage? The answer is Yes in general as the absorption capacity of the internal curing material is probably the most important property. However in this study the same amount of "free water" was designed to all three CCA mortar mixtures regardless of each CCA aggregate's own absorption capacity. Namely all three CCA mortar mixtures are supposed to have the same amount of "free water" for internal curing in design standpoint. The "free water" was supplied by the CCA aggregate as internal curing material but due to its different absorption capacity and the desorption ability the CCA aggregate had to be substituted with various amounts depending on the grade of CCA aggregates in order to provide the same amount of "free water" in the mortar mixtures for internal curing. Since in this study the different absorption capacity of the three CCA aggregates was normalized by adjusting the amounts of CCA replacement in the mortar mixture the absorption capacity of three CCA aggregates had not affected the performance in autogenous shrinkage.

Second, does the desorption ability of the CCA aggregates influence the autogenous shrinkage? The answer is Yes. The desorption ability is probably the second most important property for internal curing materials. The desorption ability provides how much contained water in the internal curing materials can effectively be released into the surrounding paste for hydration during the curing. In the desorption isotherms (Figure 7.1) the desorption ability (rate) of CCA7, CCA21 aggregates was similar where as that of CCA34 aggregate was reduced at RH greater than 90%. The desorption ability for the CCA aggregates is closely related to the pore sizes in the paste system coated to the virgin aggregate. Also the pore sizes are closely related to the degree of hydration and the cement(itious) content in the original returned concrete.

Third, do the pore sizes of the CCA aggregates influence the autogenous shrinkage? The answer is Yes. The larger pore sizes in the CCA aggregate can benefit to release most of the contained water easier than the smaller pore sizes in the CCA aggregate as the contained water in the smaller pore sizes will not be easily released. The flip side is the larger pore sizes in the CCA aggregate may also readily release the contained water during the mixing and handling that will result in potentially increasing the true *w/cm* ratio which is not desirable for the internal curing materials. This mechanism related to the pore sizes in the paste of the CCA aggregates is not clearly understood yet. However in light of the well established theory for the cement hydration and pore structure of the cement based material the pore sizes in the cement paste (composed of the CCA aggregates) can be explained with the compositions of the original returned concretes. The inherent material difference between CCA7 and CCA21 aggregate was different amount of Portland cement in the original returned concretes. The original returned concrete produced to CCA7 aggregate had less cement where as the original returned concrete produced to CCA21 aggregate had more cement (83 kg/m^3 more). In CCA aggregates the absorption capacity mainly accounted from the cement paste attached to the virgin aggregate is depended on the pore sizes being formed during the cement hydration over the time. As the more cement content is participated in the cement hydration in concrete the higher heat of hydration will be generated thus resulting in more hydration product (C-S-H gel getting larger in sizes) expanded but with getting less voids (filled with capillary water) remained in the paste. Therefore, the CCA aggregate produced with higher cement content from the original returned concrete will have relatively less absorption capacity than that produced with lower cement content from the original returned concrete due to different degree of the cement hydration. This analogy seems true as indicated by the absorption results of CCA aggregates in Table 7.3. On the contrary to the strength and permeability aspects as the smaller pore sizes in paste are desirable to achieve the high performance relatively larger pore sizes are desirable to achieve the high internal curing performance.

As shown in LTC scan (Figure 7.2) the CCA21 aggregate had the largest pore sizes among others. The poor performance in autogenous shrinkage for the CCA21 mixture is possibly explained by the larger pore sizes in the paste of CCA21 aggregate in which much of the contained water was readily released during the mixing. The CCA7 aggregate had the second largest pore sizes as shown in LTC scan. The performance in autogentous shrinkage for the CCA7 mixture was quite improved as compared to that of the CCA21 mixture while both CCA aggregate mixtures had similar ingredients except different grade of CCA aggregate. This indicates that the pore sizes in the CCA7 aggregate were proper to keep the most of contained water from mixing and handling and were able to release the most of contained water during the internal curing. The CCA34 aggregate had the second smallest pore sizes as shown in LTC scan. The performance in Autogenous shrinkage for the CCA34 mixture was also quite improved as compared to that of the CCA21 aggregate. It seems clear that the pore sizes in the CCA aggregate can influence the performance in Autogenous shrinkage.

Since CCA7 had an improved reduction in autogenous shrinkage with a lower replacement level (Table 7.4) among other CCA aggregates, the CCA7 aggregate was selected for preparing the CCA/LWAS blend. In contrast to the other two CCA mixtures, the CCA21 mixture basically produced an autogenous deformation response that was quite similar to that of the control mortar at 56 days. The LWAS had the smallest pore sizes among all other internal curing materials as shown in LTC scan. The autogenous shrinkage of the control mixture observed during 56 days was almost eliminated by the addition of the larger quantity of LWAS-1 and reduced significantly by the CCA/LWAS blend.

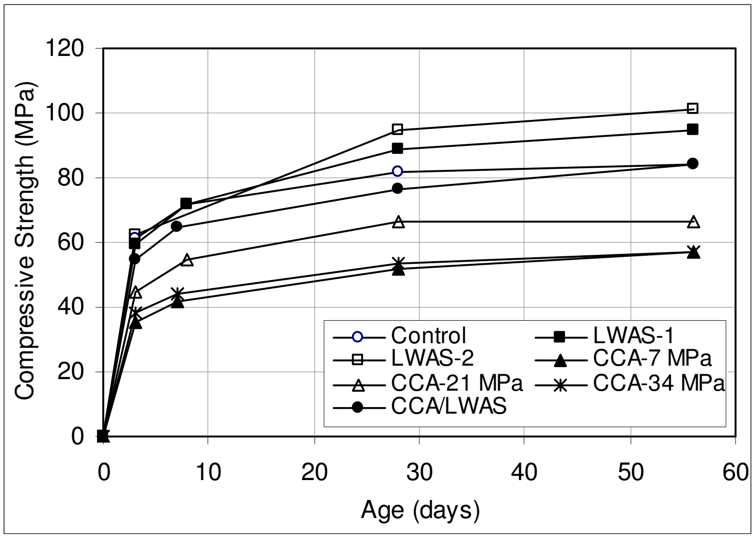


Figure 7.3 Compressive Strength Results for the 7 Mortar Mixtures

Table 7.5 Compressive Strength Results

	Control *(MPa)*	*LWAS-1* *(MPa)*	*LWAS-2* *(MPa)*[A]	*CCA7* *(MPa)*	*CCA21* *(MPa)*	*CCA34* *(MPa)*	*CCA7/LWAS* *(MPa)*
3 d	60.9 (0.9)[B]	59.2 (4.2)	62.5 (0.2)	35.2 (0.2)	44.8 (0.6)	38.4 (0.3)	54.5 (1.9)
7 d	---	---	---	41.6 (0.9)	---	43.9 (1.8)	64.8 (1.0)
8 d	71.5 (2.0)	71.7 (2.3)	---	---	55 (0.6)	---	---
28 d	81.8 (3.2)	88.8 (3.9)	95 (3.2)	51.6 (0.9)	66.2 (3.0)	53.3 (0.6)	76.6 (1.9)
56 d	84.3 (5.7)	94.7 (1.0)	101.4 (0.4)	57.1 (0.8)	66.5 (6.4)	56.8 (3.1)	84.3 (8.0)
28 d, % control	100	109	116	63	81	65	94
56 d, % control	100	112	120	68	79	67	100

[A] For LWAS-2 mixture, two cubes tested at each of 3 ages, due to cement supply limitations.
[B] Standard deviation in testing three (or two) cubes at each age.

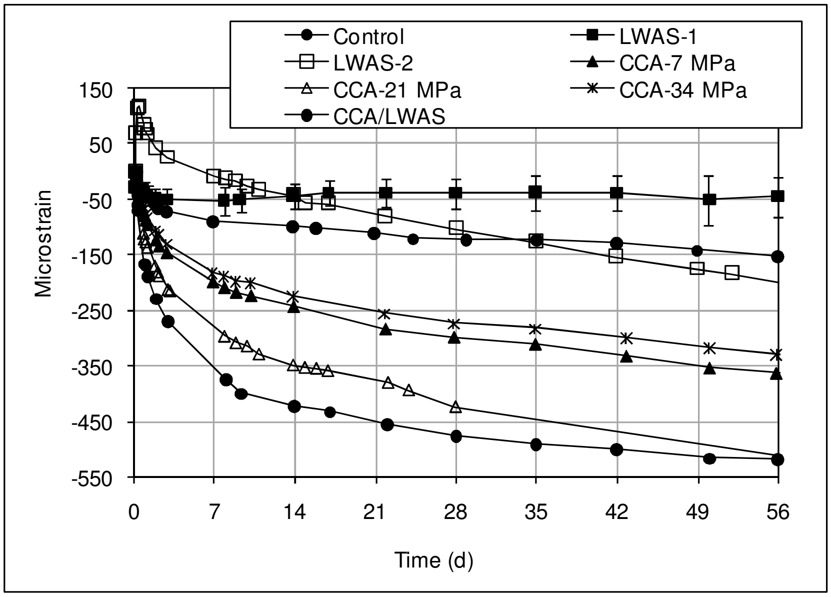


Figure 7.4 Autogenous Deformation Results for the 7 Mortar Mixtures

Table 7.6 Autogenous Deformation Results

	Control	*LWAS-1*	*LWAS-2*	*CCA7*	*CCA21*	*CCA34*	*CCA/LWAS*
Net Autogenous Shrinkage (ε_{min} - ε_{max}) (Microstrain)							
1 d	-167	-37	-41	-79	-122	-69	-35
8 d	-376	-53	-131	-209	-297	-189	-89
28 d	-476	-39	-220	-298	-425	-274	-121
56 d	-519	-45	-318	-363	-511	-329	-153
1 d reduction, % of control	-	77.8 %	75.4 %	52.7 %	27.0 %	58.7 %	79.0 %
8 d reduction, % of control	-	85.9 %	65.2 %	44.4 %	21.0 %	49.7 %	76.3 %
56 d reduction, % of control	-	91.3 %	38.8 %	30.1 %	1.5 %	36.6 %	70.5 %

As summarized in Table 7.6 , for the first day, the net autogenous shrinkage reductions for the 7 MPa CCA, 21 MPa CCA, 34 MPa CCA, LWAS-1, LWAS-2, and CCA/LWAS blend each relative to the control were 52.7 %, 27 %, 58.7 %, 77.8 %, 75.4 %, and 79.0 %, respectively, whereas the corresponding net autogenous shrinkage reductions after 8 d were 44.4 %, 21.0 %, 49.7 %, 85.9 %, 65.2 %, and 76.3 %, respectively. In Table 7.6, for each mortar mixture, net autogenous shrinkage has been computed as the difference between the initial maximum (measured expansion value or zero when immediate shrinkage is observed) and the minimum (deformation value) achieved up to the specific age being evaluated, (ε_{min} - ε_{max}), according to the approach recently advocated by Cusson (Cusson 2008). Autogenous shrinkage reductions have then been computed relative to the measured net autogenous shrinkage of the control mortar. Clearly, the autogenous shrinkage reduction is most effective when using the LWAS or the CCA/LWAS blend as the internal curing agents. Cusson has further hypothesized that shrinkage reduction effectiveness (at 7d) should be proportional to the volume of additional internal curing water provided by the mixture (Cusson 2008). This theory can be examined using the two mixtures with LWAS investigated in this study. Specifically, one finds that the measured 8 d effectiveness for the LWAS-2 mortar of 65.2 % compares quite favorably with that predicted from the measured effectiveness of the LWAS-1 mortar (85.9 %)*(0.06/0.08)= 64.4 %, where 0.06 and 0.08 represent the fractional free internal curing water contents of the LWAS-2 and LWAS-1 mixtures (grams of water per gram of cement), respectively. For a later age of 56 days, however, the measured effectiveness of 38.8 % for the LWAS-2 mortar is significantly less than that of (91.3 %)*(0.06/0.08)= 68.5 % predicted by the theory, as beyond 8 days, the LWAS-2 mortar is apparently providing little if any further internal curing water to prevent autogenous deformation. This is well illustrated by the measured autogenous deformation for the LWAS-2 mortar of -187 microstrains that is produced between 8 days and 56 days, as compared to a shrinkage of -143 microstrains produced by the control mortar and an expansion of 8 microstrains produced by the LWAS-1 mortar during the same time period.

Another indication of the effectiveness of the various internal curing agents investigated in this study is provided by examining the trends in their shrinkage reduction vs. time, as provided in Figure 7.4. While this value decreases dramatically from 1 day to 56 days for all three of the CCA internal curing agents when used by themselves (indicating a decreasing supply of the needed internal curing water), for the LWAS-1 mortar, it is seen to consistently increase from 1 day through 8 days to 56 days, suggesting that at this higher addition level of 0.08 mass units of internal curing water per mass unit of cement, the LWAS is continuously providing needed curing water throughout the first 56 days of sealed curing. As the cement paste hydrates, the sizes of its water-filled capillary pores are continuously reduced, increasing the "suction" potential that is pulling the internal curing water from the LWA sand and perhaps contributing to the increased effectiveness at later ages. For the LWAS-2 mortar with only 0.06 units of internal curing water, the shrinkage reduction value decreases after 1 day, suggesting that much of the needed supply of internal curing water has been depleted by 8 days. For the CCA/LWAS mortar, this decrease, while present, is not as dramatic, suggesting that at least some part of the additional water present in the CCA portion of the blend is contributing to effective internal curing at later ages. Of course, the fact that the effectiveness of the CCA/LWAS blend at later ages is significantly less than that of the LWAS-1, with an identical "free" water addition, indicates that a significant fraction of the "free" water in the CCA is not functioning effectively for internal curing.

In summary, the CCA aggregates had a relatively high absorption capacity varied at 12%-16% depending on the grade (strength) of the original returned concretes. The CCA aggregates had 60%-80% desorption ability where as the LWAS had above 90% desorption ability at RH greater than 90%. The desorption ability of the CCA aggregates seems influenced by the pore sizes in the paste of CCA aggregate. The pore sizes in the CCA21 aggregate were the largest among all other internal curing materials but resulted in the poor performance in autogenous shrinkage possibly due to the portions of the contained water released during the mixing. The pore sizes between CCA7 aggregate and CCA34 aggregate indicated by LTC scan were found to be acceptable for internal curing with improved performance in autogenous shrinkage without losing much of the contained water during the mixing. The acceptable pore sizes in the CCA aggregates as internal curing materials need to be understood with further researches.

The results presented here indicate the engineering potential of the CCA aggregates that can achieve the best fit performance in a special application such as mitigation of the autogenous shrinkage in HPC concrete. The different grade (strength) of CCA aggregates made in the returned concretes can have a various range of the absorption capacity subsequently with the various pore sizes in the paste as a result of the degree of cement hydration and cement(itious) content. In this study the replaced CCA aggregates in the CCA mixtures were resulted in decreasing the compressive strength by 63%-81% at 28 days as compared to the control mixture. Therefore, optimization of the mixture design will be critical to achieve the best performance for both the autogenous shrinkage and the compressive strength. Also the optimum utilization of CCA aggregate with LWAS can give the best performance in autogenous shrinkage and compressive strength. Even so, when considering the cost of CCA aggregate relative to LWAS, the potential cost savings are significant and the utilization of the CCA aggregates in new concrete can provide a sustainable solution to the problems associated with their conventional disposal (in landfills, etc.).

7.4. Conclusions

The crushed return concrete aggregates are viable internal curing materials in mitigating autogenous shrinkage. However the compressive strength will be compromised with the replacements of the CCA aggregates in concrete. Therefore, the CCA aggregate made in the returned concrete has to be optimized for its absorption capacity, desorption ability, and pore sizes to balance the designed performances such as autogenous shrinkage and compressive strength starting from the production. It is highly recommended for the concrete producer to separate the returned concrete in different strength levels thus producing more homogeneous CCA aggregates in terms of their strength.

The blending of the CCA aggregate with LWAS as internal curing material is another option to mitigate autogenous shrinkage without compromising the compressive strength in concrete. In any cases the trial batches will be of utmost importance for optimization of the concrete performance.

Chapter 8. Conclusions

The CCA aggregates are viable materials for both the general concrete application and the special concrete application. The main obstacle of CCA aggregate is a lack of testing methodology to quantify the composition of the CCA aggregate which is composed of the aggregate and paste phases. Further research will be needed for the proper testing methodology to quantify the composition of the CCA aggregate.

For aggregate characterization and concrete performance containing CCA aggregates the following conclusions were obtained from this research:

- The CCA aggregates have lower specific gravity, higher absorption, higher minus 75 μm fines, and higher mass loss of the sulfate soundness as compared to the virgin aggregate. Both the coarse and fine fraction of CCA aggregate meet most of the ASTM C33 requirements for aggregates except the minus 75 μm fines, and sulfate soundness.
- CCA coarse aggregate made from a higher compressive strength of the returned concrete had a lower percentage of finer particles (minus No. 4 size fraction), lower amount of minus 200 fines, and potentially improved resistance to degradation as indicated by the LA Abrasion and soundness tests.

- CCA fine aggregate made from a higher compressive strength of the returned concrete indicated higher fineness modulus, higher specific gravity, lower absorption, and potentially improved resistance to degradation as indicated by the soundness test.
- The compressive strength of mixtures containing CCA aggregates was generally 3% to 22% lower at 28 days compared to the control mixture. In general, as the quantity of CCA in the mixture was reduced, the reduction in strength was less. However, concrete containing 100% coarse Pile1 CCA had significantly lower strengths. Further the higher the strength of the returned concrete from which the CCA aggregate was prepared the lower the strength reduction.
- The static elastic modulus of mixtures containing CCA aggregates was generally lower than the control mixture between 6% and 28% lower at 28 days. Generally mixtures containing lower quantities of CCA aggregate in the mixtures had smaller reductions in the modulus of elasticity. Strength of the returned concrete from which the CCA aggregate was prepared does not seem to influence the elastic modulus.
- The drying shrinkage of mixtures containing CCA aggregates was generally higher than the control mixture between 11% and 93% higher on average for 180 day drying periods. The addition of CCA aggregates tends to increase the average length change due to the old cement paste adhered to the CCA aggregates, which increases the total cement paste content (new cement paste + old cement paste) in concrete.
- The rapid chloride ion penetrability (RCP) of mixtures containing small amounts of CCA (178 kg/m^3, 356 kg/m^3) does not change the RCP values as compared to the

control mixture. However the use of 100% coarse CCA led to a significant increase in the RCP values with the chloride ion penetrability going from moderate to high.

- The alkali silica reactivity (ASR) of mixtures containing CCA aggregates were in the range of 0.022% to 0.032% after 1 year as summarized in Table 4.2. While the three strength levels of CCA mixtures had higher expansions than the control mixture the values were still below 0.04% limit.
- The freeze thaw durability of mixtures containing coarse CCA fraction was acceptable with up to 100% replacement but the freeze thaw durability of mixtures containing CCA "as received" condition was not acceptable. The use of 356 kg/m^3 of "as received" CCA reduced the concrete's freeze-thaw durability. However, the use of 100% coarse 21 MPa CCA did not reduce freeze-thaw durability even though it did increase surface scaling of the test specimens. The use of 21 MPa 100% coarse CCA to replace virgin coarse aggregate should be admissible even in concrete applications that are exposed to freeze-thaw environment. However, concrete containing CCA in the "as received" condition should be evaluated for its freeze-thaw resistance prior to its use.
- Based on the results of this research, the use of "as received" CCA up to 10% by weight of the total aggregate should be permitted in most concrete applications. The concrete produced should still meet all the performance requirements for that application. In light of the European experience, for structural concrete applications coarse CCA should be allowed to be used at 10% by weight of total aggregate. Greater amounts of CCA could be allowed in non-structural applications.

In regards to the performance assessment and modeling, the following results were reached from this research:

- The compressive strength of the mixtures containing CCA aggregates can be modeled with the porosity of new cement paste, porosity of old cement paste adhered to CCA, *w/c* ratio, and the volume of virgin coarse/fine aggregates. The w/c ratio is an indication of the cement hydration in new cement paste while the volume of virgin aggregates is related to the ITZ zone between paste and aggregate particles.
- The drying shrinkage of the mixtures containing CCA aggregates can be modeled with the ACI 209 hyperbolic equation with changes in the time factor (m2) and the mixture parameter (m1). The time factor is unique for the cement depending on the blain fineness, particle size distribution, and cement types while the mixture parameter is dependent on the mixture properties.
- The static elastic modulus of the mixtures containing CCA aggregates was modeled with the w/c ratio, CCA volume, compressive strength at 90 days, rapid chloride ion penetrability, and virgin aggregate volume. As expected the stiffness of concrete it depends, among others, on the characteristics of the aggregate (in this case volume of aggregate), quality of the cement matrix (in this analysis the porosity indicated by the rapid chloride ion penetrability) and is related to concrete strength.
- The rapid chloride ion penetrability of the mixtures containing CCA aggregates were modeled with the porosity of the new cement paste, porosity of old cement paste

adhered to CCA aggregate, and the *w/c* ratio. The porosity of new cement paste was calculated with the volume of capillary water at 80% DOH and multiplied by the volume of mixing water used in control mixtures. The porosity of old cement paste on CCA was obtained by the water absorption test in which the water filled in the permeable pore on CCA was obtained for CCA coarse and fine fraction.

- The rapid chloride ion penetrability measured by a total charge (current) passed over 6 hour testing periods in accordance with ASTM C1202 can be modeled as a function of the electric conductivity of the mixture.

Regarding the development of material specifications for concrete containing CCA the following conclusions were reached:

- The prescriptive specifications do not necessarily ensure good performance. The prescriptive specifications can be significantly improved for better performance related to drying shrinkage, strength, and rapid chloride permeability.
- The performance based specifications can better prescribe the use of CCA aggregates in concrete for improved performance.

For the special application the CCA aggregate serving as mineral admixture (i.e. internal curing agent) can mitigate the autogenous shrinkage. The following conclusions were reached from this study:

- The CCA aggregates had a relatively high absorption capacity varying between 12%-16% depending on the strength levels of the CCA aggregates. The CCA aggregates had 60%-80% desorption ability whereas the lightweight aggregate sand (LWAS) had above 90% desorption ability at RH greater than 90%.
- The net autogenous shrinkage of mortar mixtures containing CCA fine aggregates was lower than the control mixture between 27% and 59% lower at 1 day and between 21% and 50% lower after 8 days. The CCA/LWAS blended mixture indicated a significant reduction of 79%, and 76%, at 1 day, and 8 days, respectively, as compared to the control mixture.
- The compressive strength of mortar mixtures containing CCA fine aggregates was generally lower than the control mixture between 63% and 81% lower at 28 days.

Therefore, optimization of the mixture design will be critical to achieve the best performance for both autogenous shrinkage and compressive strength. An optimum utilization of CCA aggregate with LWAS can provide improved performance in testing of autogenous shrinkage and compressive strength.

Appendix A : Slump Retention Study

Appendix A introduces the slump retention study

A.1 Introduction

An important aspect is the slump retention capabilities of concrete mixtures considering delivery time and ambient conditions. This portion of the study evaluated the slump retention or slump loss characteristics of limited conditions with the use of CCA. The same materials were used as in Phase I. Mixing was similar to Phase I.

A.2 Mixture Design

A total of four concrete mixtures were prepared. The batch size was 0.02 m^3. The experimental variables, yield adjusted mixture proportions and test results are provided in Table A. 1. The cement content was maintained at 326 kg/m^3 for all mixtures. Water content was adjusted to achieve a target slump of 150 to 200 mm.

The concrete mixtures were designed to evaluate the following conditions:

- Mixture SL-1 was the control mixture with virgin aggregates.
- Mixture SL-2 used 7 MPa CCA in "as received" state at a replacement of 178 kg/m^3 for virgin aggregate. The CCA was kept moist close to SSD prior to batching.

- Mixture SL-3 used the coarse fraction of 21 MPa CCA to replace virgin coarse aggregate at 100% replacement. The CCA was kept moist close to SSD prior to batching.
- Mixture SL-4 used the coarse fraction of 21 MPa CCA to replace virgin coarse aggregate at 100% replacement. The CCA was batched in a dry condition. The total moisture measured was 0.61% while the absorption was 4.31%. This condition was included to evaluate the effect of using CCA in a dry condition on the slump retention.

Table A.1 Details of Mixtures designed to Study Slump Retention

	SL-1	SL-2	SL-3	SL-4
CCA Type	0	7	21	21
CCA, kg/m^3	0	178	NA	NA
CCA, coarse, %	0	NA	100	100
CCA, fine, %	0	NA	NA	NA
Calculated Batch Quantities, kg/m^3				
Cement	321	323	322	323
Virgin Coarse Agg. (No. 57)	1073	1022	0	0
CCA (as received)	0	176	-	-
Coarse fraction of CCA	-	-	955	957
Virgin Fine Aggregate	780	705	781	783
Mixing Water	180	174	176	170
Fresh Concrete Properties				
Slump, mm	165	178	184	171
Density, kg/m^3	2430	2430	2283	2283
Air, %	2.7	2.5	3.2	3
Temperature, ^{0}C	23	23	24	23
Slump Retention Study				
Slump, mm				
Slump1	165	178	184	171
Slump2	146	102	152	114
Slump3	152	178	165	191
Slump loss, % of slump1	11.5%	42.9%	17.2%	33.3%
Water Adjustment, kg/m^3				
Slump2 □ Slump3	8.2	10.2	7.1	10
Hardened Concrete Properties				
Compressive Strength at 14 days, MPa				
Sampled with Slump1	29.9	29.9	28.3	26.7
Sampled with Slump3	29.2	26.5	27.7	27.3

Mixture SL-4 was identical to Mixture SL-3 except that the CCA was in a dry condition as opposed to a moist condition for Mixture SL-3

All concrete batches were tested for slump, air content, density, and temperature. The slump retention study was conducted as follows:

Concrete batches were mixed to target an initial slump (called Slump 1) of 150 to 190 mm. After the initial mixing, a portion of the concrete was discharged from the mixer and tested for slump (Slump 1), unit weight, air content, and temperature. Two 4x8 concrete cylinders were cast from this portion to be tested after 14 days of moist curing.

After the initial sample of concrete the mixer was set at a agitating speed (4 revolutions per minute as opposed to the normal mixing speed of 19 revolutions per minute) for about 30 minutes. Following this the mixer was set at the normal mixing speed for 2 minutes after which a concrete sample was obtained and the second slump was measured (called Slump 2). The difference in the slump at 30 minutes and the initial slump is the slump loss as a percentage of the initial slump reported in Table A.1. After this step additional water was added to the remaining concrete followed by mixing for 2 minutes to obtain close to the initial slump. The concrete was discharged from the mixer and the third slump of the concrete was measured (called Slump 3). This was intended to simulate what occurs in actual practice where water might be added at the job site to increase slump to required or specified levels. Two 100 x 200-mm concrete cylinders were made to be tested after 14 days of moist curing. The resulting strength on retempering (as a result of adding additional water) the concrete after 30 minutes represents the impact of slump loss of concrete over a typical delivery period as a result of jobsite addition of water to obtain the required slump for placing concrete.

A.3 Discussion of Test Results

The initial or original slump (Slump 1) for all the mixtures ranged between 165 to 190 mm. The temperature of the concrete mixture was maintained between 23°C and 24°C. The air content varied between 2.5% and 3.2% and the density varied between 2283 kg/m^3 and 2430 kg/m^3. The slump loss of the control mixture SL-1 over the 30 minute period was 12%. The highest slump loss of 43% was observed for Mixture SL-2 which contained CCA in the "as received" state and batched in a moist condition. The slump loss for Mixture SL-3 which contained the coarse 21 MPa CCA at 100% was in the same range as that of the control mixture. The slump loss for Mixture SL-4 in which the coarse 21 MPa CCA was used in the dry state was higher at 33%. Based on these results, it is recommended that CCA stockpiles should be sprinkled prior to batching to avoid significant slump loss, especially if larger quantities are used. Even with maintaining CCA in a moist condition, significant slump loss was observed with the "as received" 7 MPa CCA, presumably due to the increased quantity of fines. Slump retention of concrete is an operational issue that the concrete producer faces on a daily basis and should evaluate whether the level is excessive for the conditions and the market he is furnishing to. In this study simulating a 30 minute delivery time with 24°C concrete, the addition of 7.1 to 10.7 kg/m^3 of water was adequate to bring the slump back to required or specified levels. This extra water addition resulted in a negligible loss in strength measured at 14 days Mixture SL-2 which had the largest slump loss resulted in a strength reduction due to water addition of approximately 3.4 MPa or 12% of the strength.

A.4 Appropriate Test to Measure Air Content of Concrete Containing CCA

In this project the air content of concrete containing CCA was determined using the ASTM C 231 Type B pressure meter. Considering the lower relative density and higher absorption of the CCA, there was concern whether the pressure method for measuring air content was appropriate. The pressure method measures entrained air in the concrete and that of pores in aggregates not saturated with water. For this reason, the method includes an aggregate correction factor that is subtracted from the measured air content to obtain the air content in the paste fraction of the concrete. With natural aggregates with a high absorption (higher aggregate correction factor) or for lightweight aggregate the volumetric method, ASTM C 173, is more applicable for measuring the air content in fresh concrete as it measures only the air contained in the mortar and is not affected by the air that may be present inside porous aggregate particles. ASTM C 231 does not state any limit for the aggregate correction factor for which the method would not be applicable. Coarse CCA has a relative density exceeding 2.50 with absorption of about 4% and it is assumed that ASTM C 231 could be used to measure the air content of containing just the coarse fraction of CCA. Fine CCA has a relative density in the range of 2.20 and so when CCA is used in the "as received" condition the resultant relative density of the aggregate is about 2.3 with absorption of about 6%.

The measured air content by the C 231 and the gravimetric air content calculated by ASTM C 138 are compared in Table 10 for all the concrete mixtures prepared in this study. The air content determined by the gravimetric approach should be accurate as long as the batch weights, material's relative density and C 138 measurements are accurate. Gravimetric air contents also are not affected by the air that may be present inside porous aggregate particles. So, in the absence of the C 173 tests they serve as a good check for the accuracy of the air content as measured by the pressure meter.

Table A.2 indicates that with the exception of two mixtures the air contents measured by the pressure meter correlate to within 1% of that determined by the gravimetric method. In particularly the four air entrained Stage II mixtures which are reflected by the prefix II the correlation is extremely good with the maximum difference being 0.34%.

Table A.2 Air Test Results - Pressure Meter Air (C 231) vs. Gravimetric Air (C 138)

Mix ID	Air (C 231) %	Air (C 138) %	Diff. of C231 %
1	2.50	2.70	-0.20
2	2.10	2.76	-0.66
3	2.40	2.51	-0.11
4	2.10	2.28	-0.18
5	2.30	2.63	-0.33
6	2.70	2.39	0.31
7	2.80	3.18	-0.38
8	3.10	3.98	-0.88
9	2.80	2.10	0.70
10	3.00	3.34	-0.34
11	3.50	1.80	1.70
12	3.80	4.49	-0.69
13	3.20	3.49	-0.29
14	2.50	2.31	0.19
15	2.20	1.18	1.02
16	1.80	1.50	0.30
17	3.00	2.79	0.21
II-1	6.40	6.19	0.21
II-2	4.80	4.61	0.19
II-3	5.60	5.32	0.28
II-4	8.50	8.84	-0.34
SL-1	2.70	2.53	0.17
SL-2	2.50	1.90	0.60
SL-3	3.20	2.74	0.46
SL-4	3.00	3.10	-0.10

Further the aggregate correction factors have been measured for aggregate proportions used in several of these mixtures and listed in Table A.3. The virgin aggregate had very low aggregate correction factor, about 0.10%. The CCA also had very low values, less than 0.40%. Light weight aggregates generally show much higher aggregate correction factors. From these evaluations, it appears that the pressure meter test is appropriate to measure the air content of concrete containing CCA. If the choice of method is a concern, one might chose to run ASTM C 231 and C 173 in parallel for concrete using CCA. If the results compare well, air content measurements can be made by C 231.

Table A.3 Aggregate Correction Factor Test Results

Mix No.	Description	ACF^{+} #1	ACF^{+} #2
1	No.57 Virgin Coarse + Virgin Fine	0.10	0.10
2	No.57 Virgin Coarse + 178 kg/m^3 7 Mpa CCA + Virgin Fine	0.15	0.15
3	No.57 Virgin Coarse + 356 kg/m^3 7 Mpa CCA + Virgin Fine	0.20	0.20
4	No.57 Virgin Coarse + 356 kg/m^3 Pile1 CCA + Virgin Fine	0.30	0.30
5	No.57 Virgin Coarse + 534 kg/m^3 21 Mpa CCA + Virgin Fine	0.30	0.30
6	No.57 Virgin Coarse + 50% Coarse fraction of 7 MPa CCA + Virgin Fine	0.18	0.20
7	Coarse fraction of 21 MPa CCA + Virgin Fine	0.30	0.40
8	No.57 Virgin Coarse + 356 kg/m^3 7 Mpa CCA* + Virgin Fine	0.30	0.30

$^{+}$ ACF = Aggregate Correction Factor,
* 7 MPa CCA was oven dried for 1 hour

Appendix B : Porosity Calculation

The porosity of the new cement paste matrix was calculated by the T. C. Power's model (1947)[55, 56]. Power classified the water in the hardened cement paste into evaporable and nonevaporable water. The evaporable water includes water contained in the capillaries (capillary pores) and water adsorbed held close to solid surface. In his study Power indicated the nonevaporable water is a fixed amount with 0.24 α grams of water per gram of original cement, where α is the degree of hydration. He also indicated the water held in the gel pores is constant with 0.18 α grams of water per gram of original cement while the total volume of hydration products (C-S-H gel) is 0.68 α cm^3 per gram of original cement, where α is the degree of hydration. The volume proportions of the cement paste are composed of the chemical shrinkage, capillary water, gel water, hydrated products, and cement. The corresponding volume proportions of the cement paste can be quantified by Equations 40-44 provided by Power's model [57].

$$V_{cs} = \rho_c \times 6.4 \times 10^{-5} \times (1-p) \times \alpha \Rightarrow 0.2 \times (1-p) \times \alpha \qquad \textbf{Equation 40}$$

$$V_{cw} = p - \frac{\rho_c}{\rho_w} \times (0.19 + 0.23) \times (1-p) \times \alpha \Rightarrow p - 1.3 \times (1-p) \times \alpha \qquad \textbf{Equation 41}$$

$$V_{gw} = \frac{\rho_c}{\rho_w} \times 0.19 \times (1-p) \times \alpha \Rightarrow 0.6 \times (1-p) \times \alpha \qquad \textbf{Equation 42}$$

$$V_{gs} = \left(1 - \rho_c \times 6.4 \times 10^{-5} + \frac{\rho_c}{\rho_w} \times 0.23\right) \times (1-p) \times \alpha \Rightarrow 1.5 \times (1-p) \times \alpha \qquad \textbf{Equation 43}$$

$$V_c = (1-p) \times (1-\alpha) \qquad \textbf{Equation 44}$$

Where,

V_{cs} = Volume of Chemical Shrinkage

V_{cw} = Volume of Capillary Water

V_{gw} = Volume of Gel Water

V_{gs} = Volume of Gel Solid

V_c = Volume of Cement

p = Initial Porosity

The initial porosity is also obtained by,

$$p = \frac{\frac{w}{c}}{\frac{w}{c} + \frac{\rho_w}{\rho_c}}$$ **Equation 45**

Where,

w/c = water to cement ratio

ρ_w = Density of water (1000 kg/m^3)

ρ_c = Density of cement (3150 kg/m^3)

The Power's quantitative model of the cement paste was used to calculate the volume proportions of the new cement paste for CCA and control mixtures as illustrated in Figure B.1. In Figure B.1 the volume proportions of the new cement paste matrix were graphically shown for CCA7 and control mixtures. Since the strength of concrete is affected by relatively larger pores the capillary pores (≥ 50 nm) are therefore considered to the effect of the concrete strength. The volumes of capillary pore and gel pore at various degree of hydration for CCA7, CCA21, and control mixtures are summarized in

Table B.1. Only the capillary pore of the new cement paste matrix was used for the strength analysis.

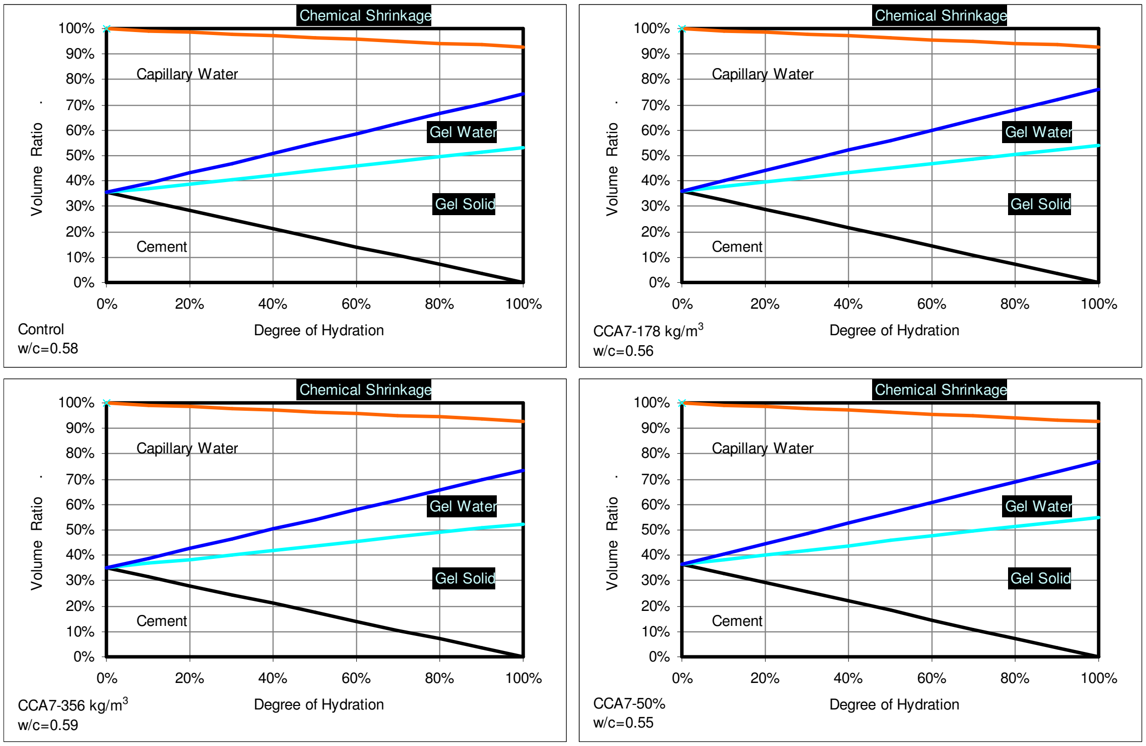


Figure B.1 Powers Volume Proportions of Cement Paste vs Degree of Hydration

Table B.1 Volume of Capillary Pore and Gel Pore at Various Degree of Hydration

Mix#	1		2		3		7		8		4		6		9		11	
Type	Control		CCA7-178 kg/m^3		CCA7-356 kg/m^3		CCA7-50%		CCA7-100%		CCA21-356 kg/m^3		CCA21-534 kg/m^3		cca21-100%		CCA21-125%	
DOH	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}	V_{gw}	V_{cw}
0%	0.00	0.65	0.00	0.64	0.00	0.65	0.00	0.63	0.00	0.62	0.00	0.65	0.00	0.65	0.00	0.65	0.00	0.65
10%	0.02	0.60	0.02	0.59	0.02	0.60	0.02	0.59	0.02	0.57	0.02	0.60	0.02	0.60	0.02	0.60	0.02	0.60
20%	0.04	0.55	0.04	0.54	0.04	0.56	0.04	0.54	0.05	0.52	0.04	0.55	0.04	0.56	0.04	0.56	0.04	0.56
30%	0.06	0.51	0.07	0.50	0.06	0.51	0.07	0.49	0.07	0.47	0.06	0.51	0.06	0.51	0.06	0.51	0.06	0.51
40%	0.08	0.46	0.09	0.45	0.08	0.47	0.09	0.44	0.09	0.42	0.09	0.46	0.08	0.47	0.08	0.47	0.08	0.47
50%	0.11	0.42	0.11	0.40	0.10	0.42	0.11	0.40	0.11	0.37	0.11	0.42	0.11	0.42	0.11	0.42	0.10	0.42
60%	0.13	0.37	0.13	0.35	0.13	0.38	0.13	0.35	0.14	0.32	0.13	0.37	0.13	0.38	0.13	0.37	0.13	0.38
70%	0.15	0.32	0.15	0.31	0.15	0.33	0.15	0.30	0.16	0.27	0.15	0.32	0.15	0.33	0.15	0.33	0.15	0.33
80%	0.17	0.28	0.17	0.26	0.17	0.29	0.18	0.25	0.18	0.22	0.17	0.28	0.17	0.29	0.17	0.28	0.17	0.29
90%	0.19	0.23	0.20	0.21	0.19	0.24	0.20	0.21	0.21	0.18	0.19	0.23	0.19	0.24	0.19	0.24	0.19	0.24
100%	0.21	0.19	0.22	0.16	0.21	0.20	0.22	0.16	0.23	0.13	0.21	0.18	0.21	0.19	0.21	0.19	0.21	0.20
Ini. *P*	0.65		0.64		0.65		0.63		0.62		0.65		0.65		0.65		0.65	
w/c	0.58		0.56		0.59		0.55		0.52		0.58		0.59		0.59		0.59	

The porosity is highly influenced by the degree of hydration. Namely as the degree of hydration advances, the porosity of cement paste is getting smaller and smaller with increasing gel product (C-S-H). In this study the porosity of the new cement paste was reasonably assumed at 80% degree of hydration (DOH) as the concrete strength was obtained at 28 days at which about 80-90% of the maximum strength is typically achieved.

Therefore, the porosity of the new cement paste was obtained with the volume of capillary water at 80% DOH and multiplied by the volume of mixing water used in concrete mixtures. For example, the control mixture (Mix1) has 0.28% of the capillary water volume with 0.58 *w/c* at 80% DOH. Thus, the volume of capillary water filled in the capillary pores for the control mixture was obtained by,

Vol.Cap.Por.(Mix1) = *Vol.Mix.Wat.(Mix1)* × *Porosity@80%DOH / Initial Porosity*

Vol.Cap.Por.(Mix1) = 0.13 m^3 × 0.28 / 0.65 = 0.038 m^3

Where,

Vol.Cap.Por.(Mix1) = Volume of Capillary Pores for Mix1

Vol.Mix.Wat.(Mix1) = Volume of Mixing Water for Mix1

Porosity@ 80%DOH = Porosity at 80% Degree Of Hydration

Initial Porosity = Porosity at 0% Degree Of Hydration

On the other hand, the porosity of old cement paste on CCA was obtained by the water absorption test in which the water filled in the permeable pore on CCA was obtained for CCA coarse and fine fraction. For example, Mix2 had 0.04 m^3, and 0.02 m^3, respectively, of CCA7 coarse, and fine fraction. The water absorption of the CCA coarse and fine fraction was 4.4%, and 11.9%, respectively. Therefore the volume of water permeable pore was calculated by,

Vol.Wat.Por.(Mix2) = *Vol.(CCA7.CA)* × *Abs.(CCA7.CA)* + *Vol.(CCA7.FA)* × *Abs.(CCA7.FA)*

Vol.Wat.Por.(Mix2) = 0.04 m^3 × 4.4% + 0.02 m^3 × 11.9% = 0.03 ft^3

Where,

Vol.Wat.Por.(Mix2) = Volume of Permeable Water Pores for Mix2

Vol.(CCA7.CA) = Volume of CCA7 Coarse Fraction

Vol.(CCA7.FA) = Volume of CCA7 Fine Fraction

Abs.(CCA7.CA) = Absorption of CCA7 Coarse Fraction

Abs.(CCA7.FA) = Absorption of CCA7 Fine Fraction

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