Fresh, Mechanical, and Durability Characteristics of Self-Consolidating Concrete Incorporating Recycled Concrete Aggregate

By

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ABSTRACT

One of the major challenges faced by civil engineering industry is to execute projects in harmony with nature. This is achieved to some extent by judicious use of natural resources in construction practices. In recent years, the demand for construction materials has grown tremendously, so has the amount of construction and demolition waste, putting huge pressure on the environment. This has encouraged the use of recycled aggregate in concrete, which not only allows for a more efficient life cycle of natural resources but also contributes to environmental protection leading to sustainable development. In this study recycled concrete aggregate (RCA) are used in the production of self-compacting concrete (SCC) in varying percentage replacements of natural coarse aggregate (NCA) The use of sustainable technologies such as supplementary cementitious materials (SCMs), and/or recycled material is expected to positively affect the performance of concrete mixtures. However, it is important to study and qualify such mixtures and check if the required specifications of their intended application are met before they can be implemented in practice. This study presents the results of a laboratory investigation of Self Consolidating concrete (SCC) containing sustainable technologies. A total of 20 concrete mixtures were prepared and tested. Mixtures were divided into five different groups, with constant water to cementitious material ratio of 0.38, based on the Recycled concrete aggregate (RCA) content: 0, 25, 50, 75, and 100% of coarse aggregate (CA) replaced by RCA. All mixtures were designed to achieve a target slump flow higher than 500 mm (19.7 in). The control mixture for each group was prepared with 100% Portland cement while all other mixtures were designed with 50% of Portland cement substituted by a combination of Supplementary Cementitious Materials (SCMs) such as class C fly ash, and granulated blast furnace slag. Several properties of fresh concrete were investigated in this study such as: flow ability, deformability; filling capacity, and resistance to segregation. Moreover, the compressive strength at 3, 14, and 28 days, the tensile strength, the unrestrained shrinkage up to 90 days and permeability were investigated. Partial replacement of the cement using Supplementary Cementitious Materials resulted in smaller 28-days-compressive strength compared to those of the control mixes. Based on the results of this study, it is not recommended to replace the natural coarse aggregate in self-consolidating concrete by more than 75% of RCA.Although, the partial replacement of cement by Supplementary Cementitious Materials had an adverse effect on the 28-days-compressive strength, most of the mixes have exceeded the SCC minimum requirements, including those with up to 100% RCA. Finally, several mix designs from the study have met the minimum Illinois Department of Transportation (IDOT) compressive strength requirements for several engineering applications such as pavements and bridges. This suggests that a practical application of results from the research is feasible in the near future.

Dedicated to
My Parents
And Saroja

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

There has been a dramatic decline in good quality aggregate available for construction use. World-wide aggregate use is estimated to be ten to eleven billion tons each year. Of this, approximately eight billion tons of aggregate (sand, gravel, and crushed rock) is being used in Portland Cement Concrete (PCC) every year [Naik 2005, Mehta 2001]. Additionally, there is a critical shortage of natural aggregate and an increasing amount of demolished concrete [Hansen 1984]. It is estimated that 150 million ton of concrete waste is produced in the United States annually [Salem 2003]. Concrete structures that are designed to have service lives of at least 50 years have to be demolished after 20 or 30 years because of early deterioration. In 2005, the American Society of Civil Engineers reported US infrastructure in poor condition with an estimated repair cost of $1.6 trillion over five years [ASCE 2005]. The environmental impact of waste concrete is significant. Not only there is an environmental impact of transporting the waste concrete away from the site but the waste concrete also fills up valuable space in landfills. The United States produces 123 million tons of waste from building demolition, and most ends up in landfills [FHWA 2004]. Construction and demolition (C&D) waste makes up a large portion of all generated solid waste [Meyer 2008]. In 1980 the Environmental Resources Limited in the East European Communities (EEC) estimated 80 million tons of demolition waste, mostly concrete, is produced each year. This number is expected to double by 2000, and triple by 2020 [Bairagi 1990].

There is a huge impact on the new pavement structure. “Durability performance of RCA is not well understood because of the limited and contradictory research results” [Salem 2003]. Concrete that contains RCA has decreased compressive strength and flexural strength, increased dry shrinkage, decreased sulfate resistance and increased chloride resistance. Construction and demolition wastes generated from demolished buildings and infrastructures form one of the largest waste streams in many developed countries. The excess and tested concretes also constitute a considerable portion of construction waste, particularly in developing countries. The recycling of construction and demolition wastes such as RCA resolves disposal problem, reduces landfill space, conserves natural resources, decreases transport costs, diminishes environmental pollution, and protects ecological balance. This research investigates the use of RCA obtained from the building demolition waste and sustainable cementitious material SCMs to produce new concrete known as Self Consolidating Concrete. The experimental research has emphasized the effects of coarse RCA on a range of fresh (slump, slump flow), mechanical (compressive, splitting tensile), and durability properties (dry shrinkage, chloride permeability), and thus assessed its suitability for use in high-workability concrete. The research findings are expected to encourage the sustainable development by using RCA in structural and non-structural concretes.

1.2 Objectives of the Study

The main objective is to study the effect of using Recycled Concrete Aggregate (RCA) on the fresh, mechanical, and durability characteristics of Self-Consolidating Concrete (SCC). Twenty concrete mixtures with different combinations of fly ash, slag and recycled concrete aggregate were developed and tested. All mixtures were designed to achieve a target slump flow higher than 500 mm (19.7 in). The control mixture for each group was prepared with 100% Portland cement while all other mixtures were designed with 50% of Portland cement substituted by a combination of Supplementary Cementitious Materials (SCMs) such as class C fly ash, and granulated blast furnace slag. Several properties of fresh concrete were investigated in this study such as: flow ability, deformability; filling capacity, and resistance to segregation. Moreover, the compressive strength at 3, 14, and 28 days, the tensile strength, and the unrestrained shrinkage up to 90 days investigated. Rapid chloride permeability (RCP) is used to evaluate concrete durability.

1.3 THESIS OUTLINE

Chapter1: “Introduction”: This chapter provides an overview of the problems encountered by the current concrete industry with aggregates and describes the objective and scope of the thesis.

Chapter 2: “Literature review”: This chapter summarizes relevant existing research and previous studies conducted on self-consolidating concrete using RCA their physical, mechanical properties, durability of these concretes and sustainability.

Chapter 3: “Experimental Study”: This chapter covers all the materials used and their properties; providing detailed proportions of the various concrete mixtures; describing the set up of all tests used; testing procedures; and data collection.

Chapter 4: “Analysis and Discussions”: This chapter covers analysis and the effect of all mixtures design on workability, durability, and strength.

Chapter 5: “Summary, Conclusion, and Recommendations”: Conclusions drawn from chapters 3 and 4 are presented in this chapter. Based on the results obtained from the analysis, recommendations are furnished.

CHAPTER 2

LITERATURE REVIEW

2.1INTRODUCTION

Self consolidating concrete (SCC) is one of the most significant advances in concrete technology and it is a new category of High Performance Concrete (HPC). It was first developed by Japanese researchers in the late 1980s to avoid problems such as honeycombing and segregation due to the incapacity to pour concrete in congested reinforced concrete elements and lack of skilled labors needed to achieve adequate compaction required for concrete durability (Okamura H, Ouchi 2003). SCC can ideally be used in highly congested reinforced structures, especially in seismic regions. Self-consolidating concrete (SCC) is a highly flowing concrete that gets consolidated under its own weight, hence, improve the productivity and on-site working conditions (Ozawa, K., (1989), Yurugi, M. (1998) Petersson, O. (1998), Paultre, P., and Tremblay, S. (2001) Lachemi, M., Hossain, (2003) Khatib, J. M. (2008) Hossain, K. (2010)). SCC is produced by incorporating supplementary cementitious materials such as fly ash (FA), slag cement and viscosity modifying agents(Lachemi, M., Hossain, K.M.A., Lambros, V., and Bouzoubaa, N. (2003), Hossain, K. M. A., and Lachemi, M. (2010), Poon CS, Ho DWS (2004)). SCC needs to possess three basic characteristics: high deformability, restrained flowability and high resistance to segregation. Khayat (1999), studied the workability requirements that is needed for self-consolidation to take place and presented some field-oriented tests that can be used to assess deformability, filling capacity, and stability of SCC (Khayat K.H 1999).Additionally, the paper discusses the principals involved in proportioning SCC in a manner that reduces coarse aggregate volume and provide high deformability and adequate viscosity. The fresh concrete properties of seven SCC mixes made with either low w/cm or no viscosity-enhancing admixture (VEA), or higher w/cm and VEA are compared for mixes made with relatively medium and high contents of cementitious materials. The study concluded that the filling capacity or V-funnel flow test should be used to assess the ability of the concrete flowing through congested spacing without blockage, in addition to the slump flow test used to evaluate deformability, and to use lower w/cm ratio to enhance viscosity or to include a low to moderate dosage of VEA without lowering the w/cm ratio. Hwang et.al. (2006), conducted an experimental program to assess the adequacy of various test methods in evaluating workability and to recommend performance specifications of concrete used in structural applications. The workability properties for approximately 70 SCC mixtures made with w/cm of 0.35 and 0.42 were determined. The workability properties included the slump flow, J-Ring, V-funnel flow time, L-box, filling capacity, and surface settlement tests. It was concluded that: 1) performance-based specifications are suggested for high-performance SCC designated for the filling of congested sections which are common in many structural applications, 2) the slump flow along with either the L-box blocking ratio (*h2/h1*), J-Ring, or V-funnel flow time can be used to evaluate the filling capacity of SCC for quality control and design of SCC to be placed in congested areas, and 3) SCC designed for structural applications should have a slump flow value between 620 to 720 mm. Hossain et al., (2010), studied the fresh, mechanical, and durability characteristics of volcanic ash (VA) based SCC mixtures (VA-SCCs). VA-SCCs mixes are designed by changing water-to-binder ratio, replacing cement by different percentages of VA, and including dosages of super plasticizer (SP). In this study, the mix design parameters were changed to achieve minimum use of SP and optimum use of VA. The fresh concrete characteristics were investigated using slump flow-funnel flow time, bleeding, air content, and segregation tests. The mechanical and durability characteristics such as compressive strength, freezing-thawing resistance, rapid chloride permeability, surface scaling resistance, and drying shrinkage were determined to study the efficiency of using VA-SCCs. The study concluded that the production of satisfactory VA based SCC mixtures with acceptable properties is possible.

In the past few years, the recycled concrete aggregate (RCA) obtained from concrete wastes has been used as an alternative to natural coarse aggregate (NCA) in the production of new concrete. The scarcity of NCA and the increasing charges for landfill have attracted the attention to the use of RCA in concrete (Katz. 2003). In addition; sources of natural aggregates are usually distanced from construction sites which constrained the contractors to consider the use of RCA as an alternative to NCA (Grdic,et.al.(2003)). Using RCA in concrete is economically and environmentally viable. However, RCA obtained from crushing of old concrete can exhibit inconsistent properties depending on the composition, particularly the water to cement (W/C) ratio and cement content of the original concrete. The quality of RCA is generally inferior to that of NCA. RCA contains not only the original aggregate, but also hydrated cement paste adhered to the surface of this aggregate. This paste makes RCA more porous than NCA. The higher porosity of RCA leads to a higher porosity and water absorption in concrete (Kou SC, Poon CS. 2003). Also, RCA can contain various contaminants such as chlorides, sulphates, carbonates, organic matters, etc., depending on the source of parent concrete. Despite the inferior quality of RCA, many researchers have shown that it can be used as an alternative of NCA in construction, particularly for non-structural or lower level application (Rao A, Jha KN, Mishra S. 2007, Sagoe-Crentsil KK, Brown T, Taylor AH. 2001, Tu T-Y, Chen

Y-Y, and Hwang C-L 2006). Levy and Helene (2004), as well as Poon et al. (2007), have graded RCA as potentially good for use in new concrete. Properly processed RCA can be used in new concrete for pavements, shoulders, barriers, embankments, sidewalks, curbs, gutters, and bridge foundations; it can also be used in structural grade concrete, bituminous concrete, and soil-cement pavement bases (Md. Safiuddin et.al 2011). However, the RCA obtained from demolished concrete must be strictly scrutinized to pass the acceptability criteria set in relevant specifications for a particular use. It is generally recommended that RCA should have a total contaminant level lower than 1% of the bulk mass (CCAA; 2008). Limited studies have been conducted to investigate the effect of using RCA in SCC. (Poon et al., 2004; Kou & Poon, 2009; Grdic et al., 2010) have studied the hardened properties of SCC produced by partial and full replacement of NCA using RCA. Safiuddin et al. (2011) studied the fresh properties such as filling ability, passing ability, and segregation resistance of SCC using RCA substituting 0–100% NCA by weight. The research concluded that SCC with up to 50% replacement of NCA has good filling and passing abilities and adequate segregation resistance.

2.2 Sustainability

Sustainability is defined by the World Commission on Environment and Development as “Meeting the needs of the present without compromising the ability of the future generations to meet their own needs" [Naik 2005]. One author describes achieving sustainability as the greatest challenge facing the concrete industry in the 21st century [Mehta 2001]. He claims that the industry has a short-term view point on the consumption of natural resources [Mehta 2001] and that "in a finite world the model of unlimited growth, unrestricted use of natural resources and uncontrolled pollution of the environment is a recipe for planetary self-destruction." The Factor of Ten Club states that "Within one generation, nations can achieve a ten-fold increase in the efficiency with which they use energy, natural resources and other materials" [Mehta 2001]. There are three keys to sustainable development in the concrete industry [Mehta 1999]. First, conserve concrete making material. This can be achieved by recycling aggregate by crushing demolished concrete. Also, using recycled water from mixing plants and wash water from trucks would decrease the need for fresh mixing water. Finally, using byproducts, such as fly ash, slag and silica fume, from other industries reduces the amount of cement needed in the concrete. Second, to aid in sustainable development, concrete structures need improved durability. Sustainable concrete structures minimize the short and long-term societal impacts; however, to achieve this durable concrete is needed [Naik 2005]. The current thinking is that designing for high strength means durable concrete is achieved; however, designing concrete for durability and achieve the necessary strength could also potentially improve sustainability. Concrete designs are needed that minimize the greatest causes of deterioration such as corrosion, exposure to freeze/thaw, alkali-silica reaction and sulfate attack [Mehta 1999]. Decreasing the permeability of the concrete through the use of supplementary cementitious materials (SCMs) is an option. Third, in order to achieve sustainable development training and education must be improved. A 1995 survey of Civil engineering departments showed that less than half of the responding schools have an optional full semester course on concrete technology. To properly educate tomorrow's engineers in schools today, North American students need more education on cement and concrete topics [Mehta 1999].

2.3 Recycled Concrete Aggregate

2.3.1 Producing Recycled Concrete Aggregate

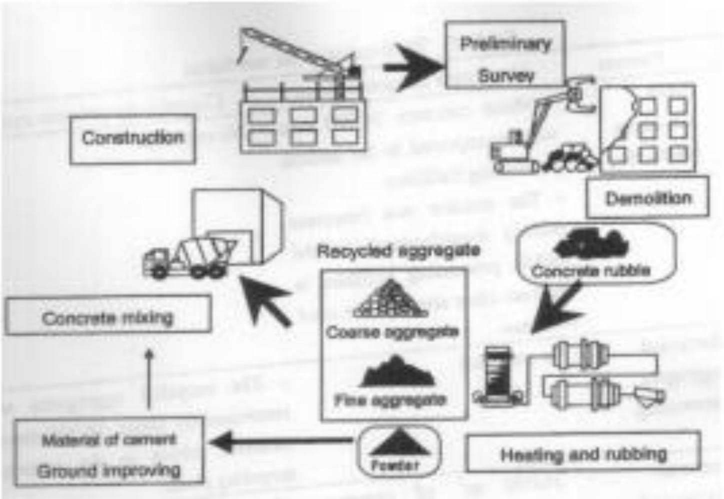


Figure 2.1 shows a closed-loop concrete system [Kuroda 2005].

Crushing concrete for use as RCA uses similar equipment and processes as when preparing virgin aggregate. There are two types of crushers: compression and impact. Figure 2.2 shows both a cone compression crusher and a jaw compression crusher [ACPA 2003]. Figure 2.3 shows a vertical and a horizontal impact crusher where repeated blows against break plates reduce the size of the concrete pieces [ACPA 2003].

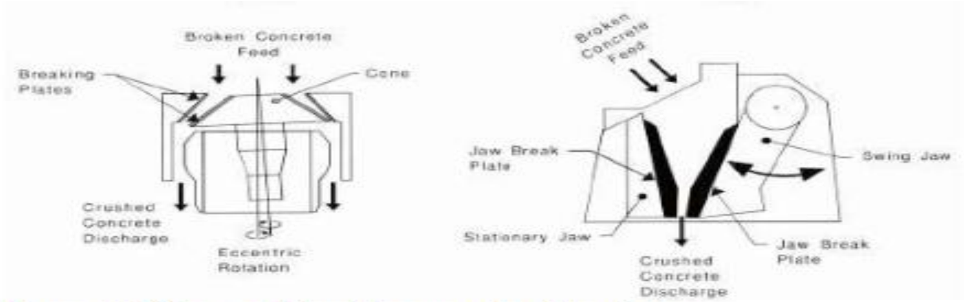


Figure 2.2 Cone and Jaw Compression Crushers

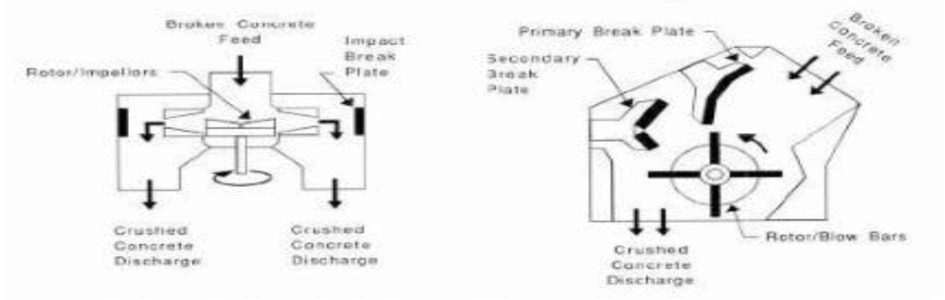


Figure 2.3 Vertical and Horizontal Impact Crushers

Defects and irregular voids can be reduced by over 50% by sending RCA through a jaw or impact crusher twice. Additional mechanical grinding will remove adherent mortar improving physical properties while only introducing a negligible amount of new cracking. Cracking of the interface transition zone was not affected significantly [Nagataki 2004].

2.3.2 Current Use of Recycled Concrete Aggregate

Many countries successfully use RCA including the United States, South Africa, Netherlands, United Kingdom, Germany, France, Russia, Canada, and Japan [Olorunsogo 2002]. Currently, RCA is used as an aggregate in granular sub-bases, lean-concrete sub-bases, soil-cement, and in new concrete as the only source of aggregate or as a partial replacement of new aggregate [CAC 2004] [Kuo 2002, Masood 2001, ACPA 1993]. The Ministry of Land, Infrastructure, and Transportation has been instrumental in Japan recycling 96% of the nation's concrete waste through initiatives Recycling Plan 21 and Construction Recycling Promotion Plan '97 [Noguchi 2005]. Japan developed a special technique that removes the original mortar from the concrete. This technique produces only 20 –35% coarse aggregate compared to the 60 – 70% coarse aggregate that is produced in the current system because of the large amount of adhered mortar [Dosho 2005]. In 2002, 28 states used RCA in pavement construction, 26 states use RCA as base or sub-base material only and two states allow for sub-base use only [Kuo 2002]. By 2004, 41 of the 50 states are using recycling waste concrete into aggregate [FHWA 2004]. Figure 2.4 shows the 38 states where recycled material is used as aggregate in road construction base material. Figure 2.5 shows the eleven states where RCA is used in new concrete.

Figure 2.4 United States Using RCA as Base Material

Figure 2.5 United States Using RCA as Concrete Aggregate

The states leading the way in the use of RCA are Texas, Virginia, Michigan, Minnesota, and California [FHWA 2004]. In 1980 the Minnesota Department of Transportation saved approximately $600,000 by recycling sixteen miles of plain concrete pavement on US-59 [Salem 2003]. It is estimated that using RCA saves approximately $4.80 per m^2 ($4 per y^2) [ACPA 1993]. A US geological survey conducted in 2000 showed that of the approximately 100 million tons of RCA produced annually, 68% is used as a broad base, six percent is used in new concrete, nine percent is used in asphalt, fourteen percent as riprap and other fill and seven percent in other uses [Li 2005] Silica fume (SF). The use of such industrial-by-product as partial replacement of cement in the development of *SCC* will not only reduce the waste in the land fill but it will also help reducing the amount of cement production leading to a significant reduction in the development cost of SCC as well as the amount of CO_2 released in the air.

2.3.3 Properties of RCA

Working with RCA can be challenging since often the specifics about the original concrete are unknown [Oikonomou 2005]. Recycled concrete aggregate is highly heterogeneous and porous, with a large amount of impurities. This makes it difficult to model and predict the resulting concrete properties [Zaharieva 2003]. Better characterization of the properties of RCA would increase the confidence needed to use RCA in new rigid pavements [Cuttell 2008].

2.3.3.1 Shape, Texture, and Gradation

In general, RCA has 100% crushed faces [Salem 2003]. The age and strength at which concrete is crushed does not influence the amount of mortar attached to the aggregate or the gradation of the RCA [Katz 2003]. Coarse RCA material contains about 6.5% adherent original mortar and the fine material contains about 25% [Katz 2003].

2.3.3.2 Specific Gravity

Specific gravity or relative density is defined by the ASTM as the ratio of the density of a material to the density of distilled water at a stated temperature. ASTM C 128 is the procedure for obtaining specific gravity. Virgin aggregate has a specific gravity of 2.7 and RCA 2.4. This difference is due to the relative density of the old mortar attached to the RCA [Salem 2003] [Katz 2003]. Coarse RCA typically has a specific gravity between

2.2 and 2.6 for saturated surface dry conditions. This value decrease as the particle size decreases. Fine RCA has a specific gravity between 2.0 and 2.3 for saturated surface dry conditions [Katz 2003, ACPA 1993].

2.3.3.3 Absorption

The ASTM defines absorption as the increase in mass of aggregate due to water penetration into the pores of the particles during a prescribed period of time, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry mass. Using the ASTM C 128 process virgin aggregate has a lower absorption of 0.3%. Coarse RCA has absorption of 2-6% and fine RCA has an even higher absorption of 4-12% [Katz 2003, Kerkhoff 2001, and ACPA 1993]. This difference is due to the higher absorption of the old mortar contained in the RCA [Salem 2003][ACPA 1993].

2.3.3.4 Abrasion Resistance

Abrasion resistance is used as an index of aggregate quality and its ability to resist weathering and loading action [CAC 2002]. Abrasion resistance of RCA is twelve percent lower than virgin aggregate [Sagoe-Crentsil 2001]. The abrasion resistance results are not dependent on full or partial RCA use [Abou-Zeid 2005]. Abrasion resistance for RCA ranges between 20-45% with an upper range at 50% [ACPA 1993].

2.3.3.5 RCA Fines

Creation of high quality RCA produces a large amount of fines that can be problematic to deal with [Naik 2005]. RCA fines can be mixed with a clay soil to improve the soil properties. Although the addition of RCA fines did not significantly impact the clay soils liquid limit initially or after 21 days, it almost doubled the plastic limit. The plasticity index at 21 days was 17.6 for clay soil containing RCA fines compared to 35.9 for the control. This improves the soil classification from clay to silty sand [Hansen 1986].

2.3.4 Properties of RCA Concrete

The cement mortar that is a part of the RCA significantly impacts the characteristics and performance of the RCA containing concrete [Sagoe-Crentsil 2001]. Removal of some of the adherent mortar helps to improve the properties of RCA containing concrete. The properties of the original concrete have a significant influence on the properties of the RCA containing concrete (compressive strength, tensile strength, bond stress at failure, F/T resistance) [Ajdukiewicz 2002]. There is a general lack of knowledge about how RCA use affects the durability of concrete. This is due to contradictory research results and studies focused only on the properties of RCA containing concrete not durability [Salem 2003]. RCA containing concrete performed in a comparable manner to virgin concrete in terms of strength and durability [Shayan 2003, Olorunsogo 2002]. In general, concrete durability is reduced as RCA content is increased [Olorunsogo 2002]. The increased absorption of the RCA leads to larger amounts of shrinkage and cracking in RCA containing concrete [Mesbah 1999]. However, durability properties can be improved with longer curing periods [Olorunsogo 2002].

2.3.4.1 Workability

Concrete workability is defined as the effort required to manipulate a freshly mixed quantity of concrete with minimum loss of homogeneity [Mehta 2006]. After five to ten minutes, RCA mixes are stiffer and lose workability at a faster rate than mixes containing virgin aggregate [Salem 2003].

2.3.4.2 Slump

Slump is defined as the "measure of the consistency of freshly mixed concrete, equal to the immediate subsidence of a specimen molded with a standard slump cone" [CAC 2002]. Admixtures in the RCA had no significant impact on the slump of the new RCA concrete [Hansen 1984]. The more RCA that is used in cement mix, the higher the w/c ratio that is needed. This will result in a higher slump [Lin 2004]. However, assuming a constant w/c ratio, RCA concrete mixes have a decrease in slump compared to virgin concrete mixes. RCA has a higher absorption and an angular texture that increases the internal friction [Rashwan 1997]. As the amount of RCA increases at a constant w/c ratio, the workability decreases [Topcu 2003]. The moisture state of the RCA impacts the slump and slump loss of the concrete. Keeping a constant w/c ratio, slump and slump loss was the highest for concrete that contained oven-dried RCA as compared to air-dried or saturated surface dry RCA.

2.3.4.3 Air Content

Air content of freshly mixed concrete is based on a change of volume for a change in pressure. RCA has a higher void content than virgin aggregate. This results in RCA containing concrete having a larger amount of entrapped air compared to virgin aggregate [Salem 2003]. The air content of RCA containing concrete is higher than the concrete from which the RCA was made since the new concrete contains both the air entrapped in the concrete and the air in the RCA [Katz 2003]. Admixtures in the original concrete that is made into RCA had no significant impact on the air content of the new RCA concrete [Hansen 1984].

2.3.4.4 Initial Set Time

The time required for the cement paste to cease being fluid and plastic is the initial set time [CAC 2002]. Admixtures in the original concrete had no significant impact on the initial set time of the new RCA concrete [Hansen 1984].

2.3.4.5 Final Set Time

The final set time is the time required for the cement paste to develop a certain degree of strength [CAC 2002]. There was no significant difference in final set time for RCA containing concrete when the RCA was made from a concrete containing an admixture [Hansen 1984].

2.3.4.6 Compressive Strength

Compressive strength is the ability to resist compression loads [CAC 2002]. In general, using RCA in the concrete mix decreases compressive strength compared to virgin aggregate. However, at 28 days, all mix designs usually exceed 50 MPa compressive strength [Shayan 2003]. One study showed the compressive strength of virgin concrete was 58.6 MPa, and the RCA concrete ranged from 50.9 to 62.1 MPa. There were higher values for concrete made with 50% RCA compared to 100% RCA [Poon 2002]. The loss of compressive strength is in the range of 30-40% for the concrete made with RCA at 28-days [Katz 2003]. There was a minor reduction in 28- and 56-day compressive strength when virgin aggregate was partially replaced with RCA and a much greater reduction when RCA was used in full [Abou-Zeid 2005]. The most influential parameter affecting compressive strength is the w/c ratio [Lin 2004]. Other influential parameters include fine RCA content, cleanness of aggregate, interaction between fine RCA content and crushed brick content, and interaction between w/c ratio and coarse RCA content [Lin 2004]. Keeping a constant w/c ratio, air-dried RCA containing concrete had the highest compressive strength compared to oven-dried and saturated surface dry RCA [Poon 2003]. Using unwashed RCA reduces compressive strength particularly at lower w/c ratios. Compressive strength is 60% of virgin concrete at 0.38 w/c and 75% at 0.6 w/c [Chen 2002].

There seems to be a strong interaction between maximum aggregate size and water-cement ratio when compared with compressive strength development [Tavakoli 1996a]. Compressive strength may increase for RCA due to a lower w/c ratio compared to virgin aggregate, 14% and 34% respectively. However, compressive strength may decrease for RCA since it has a higher air entrainment, 25%, compared to virgin aggregate 23% [Salem 2003]. The majority of strength loss for RCA concrete can be attributed to material smaller than 2 mm because natural sand has greater strength than RCA fines [ACPA 1993]. It is recommended to keep RCA fines less than 50% of the sand content [Shayan 2003]. Bonding between the RCA and the cement can be affected by loose particles created during the crushing process. Treating the RCA by impregnation of silica fume resulted in an increase in compressive strength of approximately at 30% at 7-days and 15% at 28-days. Exposing the RCA to ultrasound resulted in a uniform increase of 7%

compressive strength over time [Katz 2004]. The age at which the RCA is crushed has a significant impact on the compressive strength of the final concrete. For example, crushing concrete into RCA after three days compared to one day resulted in a seven percent increase in compressive strength of the new RCA concrete at 7 days. The difference in compressive strength of the new RCA concrete increased to 13% when measured at 90 days [Katz 2003]. The compressive strength of the original crushed concrete influences the compressive strength of the RCA concrete [Tavakoli 1996a]. However, it has been reported that RCA concrete can produce higher compressive strengths than the original concrete [Ajdukiewicz 2002]. For example, an 80+ MPa concrete was created from an original 60MPa concrete [Ajdukiewicz 2002]. When comparing laboratory-made RCA and field demolished RCA, there was the same basic trend in all strength development [Tavakoli 1996a]. Admixtures in the original concrete had no significant impact on the compressive strength of the new RCA concrete [Hansen 1984]. When slag is added to the RCA concrete, it develops strength over a longer period of time compared to normal concrete [Sagoe-Crentsil 2001]. Some research suggests that compressive strength is dependent on the amount of time the RCA spent in the stockpile after crushing [Rashwan 1997]. For example, concrete made with RCA that was in the stockpile one day had a 25% higher compressive strength than concrete made with RCA that was in the stockpile 28 days. Concrete made with RCA that was in the stockpile seven days had a seven percent lower compressive strength than concrete that was in the stockpile 28 days [Rashwan 1997]. RCA concrete showed good performance when exposed to temperatures up to600° C with a loss in compressive strength of 20-25% [Abou-Zeid 2005]. When RCA concrete fails it is usually because cracks passed through the RCA: however, when virgin concrete fails it is usually due to bond failure at the aggregate-paste interface [Salem 2003].

2.3.4.7 Flexural Strength

Flexural strength or modulus of rupture is the ability to resist tension resulting from bending [CAC 2002]. There are conflicting results about how RCA use affects flexural strength. The results range from RCA decreasing flexural strength [Zaharieva 2004, Katz 2003, and Salem 2003] to RCA increasing flexural strength [Poon 2002]. One study showed a decrease in flexural strength between 10-20% [Zaharieva 2004]. Other studies found comparable flexural strength results between RCA concrete and the control mixes [Tavakoli 1996a, Abou-Zeid 2005]. And yet another study showed that flexural strength increased with the amount of RCA used. Virgin concrete had a flexural strength of 3.31 MPa, and RCA concrete ranged from 3.74 to 3.89 MPa with 100% RCA concrete having higher values than 50% RCA concrete [Poon 2002]. The parameters that influence flexural strength are not completely clear. However, minor decreases in strength can be attributed to material smaller than 2 mm resulting from natural sand having greater strength than RCA fines [ACPA 1993]. One study suggested that flexural strength was comparable to the w/c ratio [Tavakoli 1996a].

2.3.4.8 Permeability

The permeability of concrete is measured using several standard methods. However, the rapid chloride permeability test (RCPT) is the most widely used, It was originally developed for the Federal Highway Administration (FHWA) by the portland cement association to provide a rapid test method for determining the chloride permeability of concrete (Whiting, 1981). The test is performed using 2 in. (51 mm) long, 3.75 in (95 mm) diameter cylindrical specimens. After the curved surface of a test specimen is coated with epoxy, the specimen is vacuum submerged in water and then soaked in the same water for 18 hours ASTM (C1202, 2010). The specimens are then placed in the testing apparatus where one end of the specimen is exposed to a solution containing 3% sodium chloride (NaCL) solution and the other end is exposed to a solution containing 0.3N sodium hydroxide (NaOH) solution ASTM (C 1202, 2010). A DC voltage (60 V) is applied over the cell with the negative terminal connected to the cell containing NaCL solution and the positive to the NaOH solution, causing the negatively charged chloride ions to migrate towards the positive terminal. The current across the specimen is measured at least every 30 minutes during the 6-hour test ASTM (C 1202, 2010). The test results are interpolated based on the charges transferred during the test. High coulombs, means high diffusion of chloride ions in the concrete (i.e. high permeability) thus the concrete is less durable.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

The main aim of this chapter is to perform experimental study to investigate the properties of concretes produced with recycled aggregates and comparison of them with normal concrete. During the experimental work, different concrete samples with various concrete mix designs were investigated by different ages. For casting normal concrete samples, cement with class C was used. Crushed limestone aggregates and Local sand was used as fine and coarse. Drinkable water was used as mixing water. For casting recycled concrete samples, same cement of class of C was used. Recycled concretes with different strength levels (20-30 MPa) were crushed by jaw crusher and were separated according to their size distributions.

3.2 EXPERMENTAL PROGRAM

A total of 20 concrete mixtures were prepared and tested, five of which are designed as control mixtures made with 100% Portland cement and different RCA content (0, 25, 50, 75, and 100%). The w/cm ratio was fixed for all mixtures at 0.38. The remaining mixtures were divided into 5 groups; the first of which has no RCA, the RCA replaced the coarse aggregate by 25, 50, 75, and 100% in the second, third, fourth, and fifth groups, respectively. All mixtures were proportioned to achieve acceptable flowability (i.e. slump flow value between 500 ± 10 to 750 ± 10 mm (19.7 ± 0.4 to 29.52 ± 0.4 in) as well as high resistance to segregation and bleeding). The ratio of the coarse aggregate to fine aggregate (CA/FA) was kept constant for all mixtures. Table 3.1 lists the proportions of all concrete mixtures considered. The properties of fresh concrete such as: flowability, passing ability and segregation resistance of all prepared mixtures were evaluated. The flowability of SCC mixtures was measured using the slump-flow and T_{50} tests. Concrete deformability and filling capacity were measured using the slump-flow and T_{50} tests with the J-Ring, and concrete resistance to segregation was evaluated using the segregation index test. Hardened properties such as, compressive strength, tensile strength are evaluated using the compressive strength test, the split tension test, and durability properties like unrestrained shrinkage, permeability are evaluated by the drying shrinkage test and RCPT test respectively. All concrete specimens used in the above mentioned tests were prepared in accordance with ASTM C 192-00 (ASTM C192, 2007).

Table 3.1: Proportion of concrete mixtures

Mixes	Percentage of SCM	% RCA	Cementitious Materials (kg/ m^3)				Water (kg/ m^3)		Aggregates (kg)			SP ml/m^3
			CM	C	FA	SL	W/CM	W	RCA	CA	FA	
Mix1	Control Mix	0%	375	375	0	0	0.38	143	0	865	880	592
Mix2	50%FA	0%	375	187.5	187.5	0	0.38	143	0	865	880	632
Mix3	50%SL	0%	375	187.5	0	187.5	0.38	143	0	865	880	796
Mix4	25%FAC+25%SL	0%	375	187.5	93.75	93.75	0.38	143	0	865	880	756
Mix5	Control Mix	25%	375	375	0	0	0.38	143	216	649	880	671
Mix6	50%FA	25%	375	187.5	187.5	0	0.38	143	216	649	880	592
Mix7	50%SL	25%	375	187.5	0	187.5	0.38	143	216	649	880	717
Mix8	25%FAC+25%SL	25%	375	187.5	93.75	93.75	0.38	143	216	649	880	790
Mix9	Control Mix	50%	375	375	0	0	0.38	143	432.5	432.5	880	677
Mix10	50%FA	50%	375	187.5	187.5	0	0.38	143	432.5	432.5	880	796
Mix11	50%SL	50%	375	187.5	0	187.5	0.38	143	432.5	432.5	880	716
Mix12	25%FAC+25%SL	50%	375	187.5	93.75	93.75	0.38	143	432.5	432.5	880	890
Mix13	Control Mix	75%	375	375	0	0	0.38	143	648.75	216.25	880	720
Mix14	50%FA	75%	375	187.5	187.5	0	0.38	143	648.75	216.25	880	870
Mix15	50%SL	75%	375	187.5	0	187.5	0.38	143	648.75	216.25	880	845
Mix16	25%FAC+25%SL	75%	375	187.5	93.75	93.75	0.38	143	648.75	216.25	880	921
Mix17	Control Mix	100%	375	375	0	0	0.38	143	865	0	880	847
Mix18	50%FA	100%	375	187.5	187.5	0	0.38	143	865	0	880	923
Mix19	50%SL	100%	375	187.5	0	187.5	0.38	143	865	0	880	884
Mix20	25%FAC+25%SL	100%	375	187.5	93.75	93.75	0.38	143	865	0	880	1142

A total of nine 100 x 200 mm (3.94 x 7.88 in) concrete cylinders were prepared from each concrete mixture and cured in the curing room at room temperature and at a relative humidity larger than 95% until the day of testing, were used to measure the

Compressive strength at 3, 14, and 28 days and one cylinder of 200 x 400 mm (7.88 x 15.76 in) was used to measure concrete tensile strength. An additional 76.2 x 76.2 x 254 mm (3.002 x 3.002 x 10.007 in) concrete prism was prepared from each of the five groups of the concrete mixtures. They were moist-cured at room temperature of 25^{o}C and at a relative humidity larger than 95% as shown in figure 3.1 for the first 7 days and air-cured for the remaining of the test up to 90 days or until the free shrinkage became constant.

Figure 3.1: Concrete samples being cured in the curing room

3.3 MATERIALS AND MIXTURE PROPORTIONS

Crushed limestone aggregate with nominal maximum aggregate size of 19 mm (0.75 in) and well-graded local sand were used as coarse and fine aggregates, respectively. The fine and coarse aggregate gradation used is shown in Table 2. The relative specific gravity and absorption at saturated surface dry condition of coarse aggregate (CA) were 2.68 and 1.2%, respectively, whereas fine aggregate (FA) had a relative specific gravity of 2.67, absorption at saturated surface dry condition of 2.50%, and a fineness modulus of 3.08. Type I Portland cement having a specific gravity and surface area of 3.15 and 400

m^2/kg(1952.98 ft^2/lb), respectively and conforming to the requirements of ASTM C 150 was used in the development of all concrete mixtures. Different binders including ASTM C 150 Type I cement and a combination of one or more SCMs such as, ground granulated blast furnace slag (S), class C fly-ash (FA) were also used in mixtures other than the control mixes. All SCMs including FA and S confirm to ASTM standards and have specific gravity values of 2.6 and 2.94 respectively. The FA and S have a surface area of 350 and 500 m^2/kg (1708.86 and 2441.23 ft^2/lb.), respectively. A highly efficient new generation of polycarboxylic based High-range Water Reducer Admixture (HRWRA) having a density of 1.1 g/cm^3 (0.635 oz/$in^{3)}$ was used in the mixtures. This type of HRWRA contains a viscosity-modifying agent that enhances concrete viscosity. Therefore, VMA was not used in the mixtures. The recommended dosage for the HRWRA varies between 200-780 mL/100 kg (6.7-26 fl.oz/220.462 lb) of the cementitious materials. The HRWRA for all mixtures was added during the mixing directly to freshly mixed concrete in the concrete mixer at the end of the batching cycle for best results. To optimize the super-plasticizing effect, after the addition of the HRWRA, the combined materials were mixed for nearly 100 revolutions, in the concrete mixer according to the guidelines of the HRWRA manufacturer. The slump flow is measured immediately after the 100 revolutions were reached. Table 3.1 shows the actual dosages used in the design mixtures conducted in this study. RCA materials were obtained from a local provider in Peoria, Illinois. The RCA materials were sieved and separated into different sieve sizes and then recombined in proportions equal to the coarse aggregate gradation. The fine and coarse aggregate gradation used in this study is shown in Table 3.2 and figure 3.2.This ensured a constant gradation regardless of the RCA content. The relative specific gravity of RCA was 2.58.

Table 3.2 - Aggregate Gradation

Fine Aggregate		Coarse Aggregate	
Sieve Size (mm)	**%Passing**	**Sieve Size (mm)**	**%Passing**
9.5	100	25	100
4.75	98	19	97
2.36	84	12.5	30
1.18	68	9.5	10
0.6	54	4.75	3
0.3	21	2.36	0
0.15	5	1.18	0
0.075	1	0.3	0

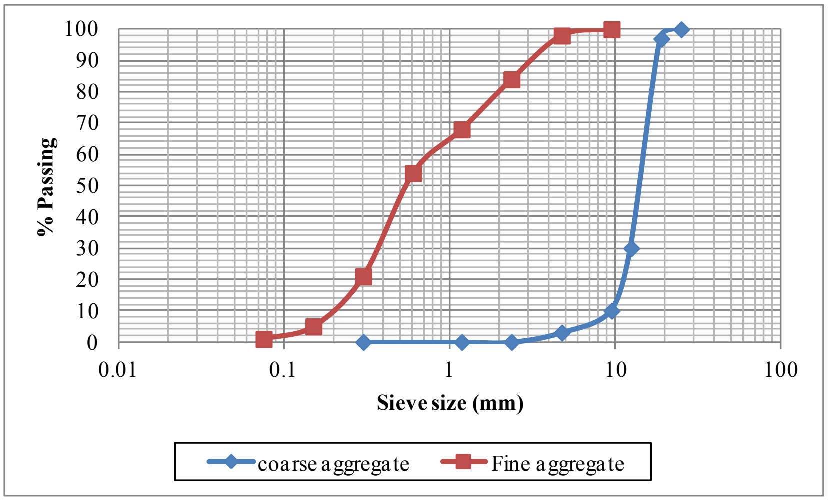


Figure 3.2: Coarse and Fine Aggregate Gradation

3.4 TESTING PROCEDURE OF SCC MIXTURES

3.4.1 Testing Procedures

Testing includes three different categories: 1) the fresh properties of all concrete mixtures were assessed to ensure that the concrete is flowable, deformable and has met the minimum requirements of SCC. The slump flow test and T_{50} tests with and without the J-Ring and the segregation index (SI) test were used during this process, 2) The hardened properties of SCC were evaluated by measuring the compressive strength of all specimens at various ages (3, 14, and 28 days) using nine 100 x 200 mm (3.94 x 7.88 in) concrete cylinders prepared from each concrete mixture and cured in the curing room at room temperature and at a relative humidity larger than 95% until the day of testing, and the split tensile strength at 28 days using one cylinder of 200 x 400 mm (7.88 x 15.76 in), and 3) the durability characteristics were determined by measuring the unrestrained shrinkage up to 90 days for all concrete mixtures using a 76.2 x 76.2 x 254 mm (3.002 x 3.002 x 10.007 in) concrete prism prepared from each concrete mixture. The prisms were moist-cured at room temperature of 25^{o}C and at a relative humidity larger than 95% for the first 7 days and air-cured for the remaining of the test up to 90 days or until the free shrinkage became constant and the permeability of SCC mixtures was evaluated using the rapid chloride permeability test (RCPT) according AASHTO T277, ASTM C1202.

3.4.2 Slump-Flow and T50

The slump flow and T_{50} tests were used to estimate the rate of deformability and flowability of all concrete mixtures. The slump flow test was performed as per ASTM C 1611, where an inverted slump cone was filled with SCC without vibration. The cone was then lifted and the measure of the spread of concrete was recorded. The slump flow value was calculated as the average of two perpendicular diameters of the concrete spread after lifting the cone. Additionally, the T_{50} test was conducted to measure the rate of concrete deformability, which consists of measuring the time needed for the SCC mix to reach a 500 mm spread during the slump flow test. A slump flow value that ranges between 500 and 750 mm and a value of T_{50} less than 7 s are acceptable limits for the design of SCC concrete mixtures (EFNARC 2005). Figure 3.3 shows a typical slump flow and T_{50} tests.

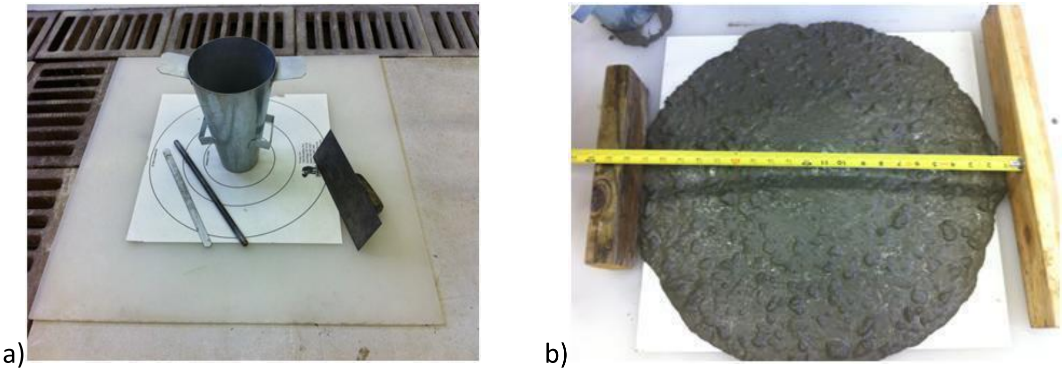


Figure 3.3: (a) Slump flow test set-up, (b) measuring slump flow of SCC mixture

3.4.3 J-Ring Test

The J Ring test was performed for all SCC mixtures to measure the passing ability of the concrete through obstacles. The test was performed in accordance with ASTM (C 1621/ C 1621M-09) "Standard Test Method for Passing Ability of Self Consolidating Concrete by J Ring". Similar to the slump flow test, the J-Ring test consists of measuring the average diameter of the concrete spread after lifting the inverted concrete cone and the time needed for the concrete to reach a circle of a 50 cm (20 in) diameter. Steps followed in conducting the test are as follows: 1) the inverted slump cone was placed in the centre of the J-Ring (a ring attached to steel rods 10 cm (4 in) apart as obstacles); 2) The inverted cone was filled with SCC without rodding or vibration; 3) the cone was lifted vertically and the concrete was allowed to flow freely between the steel rods; 4) The diameter of the concrete spread after concrete reaches a full stop was measured and the average value of two perpendicular diameters was recorded as the slump flow value with the J-Ring; The time needed for the concrete spread to reach a circle of 50 cm (20 in) diameter was also recorded as the $T50$ value with the J-Ring. For SCC mixtures to have an acceptable passing ability, the slump flow value measured using the J- Ring should not more than 10 cm (4 in) less than that measured using the slump flow test. The difference between the $T50$ values measured using the J-Ring test and the slump flow test should not be more than 2 – 4 seconds. Figure 3.4 shows the J-ring test set-up and a typical concrete spread using the J-Ring.

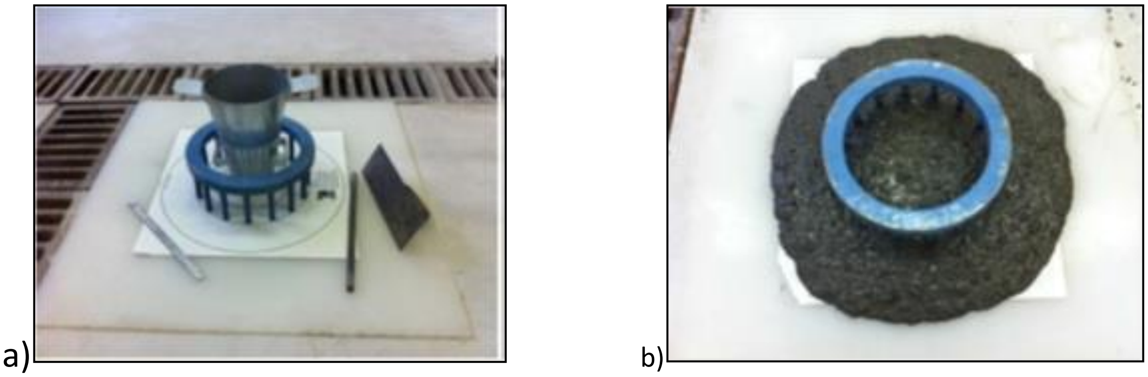


Figure 3.4: J-ring set-up and typical spread using the J ring.

3.4.4 Segregation Index (SI)

Flowability in SCC has always been a concern since the addition of improper amounts of Super plasticizer may result in segregation of the SCC mixture where the coarse aggregate is separated from the SCC mix. The ability of concrete to resist segregation was determined by visually inspecting the concrete mix during the slump-flow test and by assigning a Segregation Index (SI) value to each concrete mix. If there is no clear accumulation of coarse aggregate particles/mortar at the center of the concrete spread and no free water flowing around its perimeter, the mixture is assigned a $SI = 0$ and it means that concrete is not subjected to any segregation. If the concrete mixture experienced an apparent accumulation of coarse aggregate particles/mortar at the center of the concrete spread or a trace of free water flowing around its perimeter, the concrete is assumed to have adequate resistance to segregation and $SI = 1$. In the case of clear accumulation of coarse aggregate particles/mortar or free water, the segregation index is set to 2 and the concrete is likely to segregate.

3.4.5 Compressive Strength Test

The compressive strength of all concrete mixtures prepared in this study was determined using a 10x20 cm (4x8 in) concrete cylinders at 3 ,14 and 28 days. The cylinders were prepared and tested in accordance with ASTM (C39/ C 39M-09) “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens”. All cylinders were moist cured in the curing room at room temperature and at 95 % humidity until the day of testing. An hour prior to testing, cylinders were removed from the curing room and surface dried. Cylinders were then capped using Neoprene caps and tested using a compression machine with 1800 KN (400 kip) capacity. During testing, load was applied continuously and without chock at a loading rate of 138 kPa/s to 335 kPa/s (20 psi/sec to 50 psi/sec) until failure. The compressive strength of each concrete mixture is determined based on the average compressive strength of 3 concrete cylinders made from the same concrete batch. Figure 3.5 shows the compressive strength test set-up.

Figure 3.5: Compressive strength test set-up of a concrete cylinder under axial compression

3.4.6 Splitting Tensile Strength

The splitting tensile strength of all concrete mixtures was determined using a 15x30 cm (6 x 12 in) concrete cylinder at 28 days. The test was performed in accordance with ASTM (C 496/ C 496M-04) “Standard Test for Splitting Tensile Strength of Cylindrical Concrete Specimens”. For this test, concrete cylinders were all cured in the curing room at room temperature and 95 % humidity until the day of testing. An hour before testing, concrete cylinders were removed from the curing room, surface dried, and set-up on the loading machine used in the compression test. A plywood strip was placed along the center of the lower bearing block of the loading machine and the concrete specimen was placed on top of it. A similar plywood strip was placed on top of the concrete specimen and centered over the bottom strip. Load was applied continuously at a loading rate of 100 to 200 psi/min (689 to 1380 kPa/min) splitting tensile strength until failure. The tensile strength of concrete was calculated using the following equation. Figure 3.6 shows the splitting tensile strength test setup.

$$T = \frac{2P\,D}{\pi L} \qquad \text{Equation 3.1}$$

Where:

T = splitting tensile strength, psi,

P = maximum applied load, lbs,

L and D = length and diameter of concrete
Specimen, in.

Figure 3.6: (a) Splitting tensile strength test set-up and (b) a typical failure mode of a concrete cylinder under tension.

3.4.7 Unrestrained Shrinkage Test

The unrestrained (free) shrinkage for all concrete mixtures was measured using the Comparator test set-up (Figure 3.7). The test consists of a sturdy upright support with a digital indicator gauge mounted on the top and a calibration (reference) bar. The digital indicator has a range of 12.7 mm (0.5 in) and 0.0025 mm (0.0001 in) divisions. The unrestrained shrinkage of all concrete mixtures was measured using 76.2 x 76.2 x 254 mm mortar prisms. From each concrete mixture, two mortar prisms were prepared as previously described. Both mold prisms were covered and placed in the curing room at room temperature and 95 % humidity for 24 hours right after casting. They were then unmolded and one prism was continuously moist cured in the curing room and the second one was air cured at normal room temperature. The change in length for both (moist and air cured) prisms was measured in accordance with ASTM C (490/ C 490 M-09) "Standard Practice for Use of Apparatus for The Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete". The shrinkage value for each prism was recorded every other day during the first week and once a week thereafter for ninety days. Figure3.9 shows the Comparator test set-up and a mortar specimen being tested.

Figure 3.7: Unrestrained shrinkage test set-up and a mortar prism being tested.

3.4.8 Rapid Chloride Permeability Test (RCPT)

The rapid chloride permeability test is used to evaluate the resistance of concrete to chloride ions ingress through electrical conductivity measurements and it is commonly used due to its simplicity. The test is performed in accordance with ASTM (C 1202-10) " Ability to Resist Chloride Ion Penetration". In this test, a cylindrical plain concrete specimen with a 100 mm (4 in) diameter and a 50 mm (2.0 in) thickness is exposed to a 3 % sodium Chloride (Na CL) on one side and 0.3 N sodium hydroxide (Na OH) solutions on the other side. A 60-volt current is passed through the specimen for 6 hours and the current integrated over time is measured in coulombs. The permeability of concrete is assessed based on the results obtained from this test according to the interpretation shown in Table 3.3.

Table 3.3: Chloride Ion Permeability Based on Charge Passed through a concrete specimen (ASTM C 1202-10)

Charge Passed (Coulombs)	Chloride Ion Permeability
>4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
< 100	Negligible

Concrete specimen with more than 4000 coulombs passing through it has high chloride ion permeability and it is considered as a non-durable concrete. On the other hand, concrete specimen with 100 – 1000 coulombs passing through it has very low chloride ion permeability and it is classified as a very durable concrete.

3.4.8.1 Procedure for Conducting Rapid Chloride Permeability Test

Preparation of Concrete Specimens

1- For all concrete mixtures prepared in this study, a 10x20 cm (4x8 in) concrete cylinder was prepared as previously mentioned and moist cured in the curing room at normal room temperature and 95 % humidity until two days before testing (90 days).

2- Two days before the test, the concrete cylinder was taken out of the curing room and the top 5 cm (2 in) from the rough end of the concrete cylinder was cut using a concrete and masonry saw to prepare a sample disc.

3- The top (rough end) of the 5 cm (2 in) sample disc was clearly marked and the top and bottom were covered using a duct tape to make sure that the entire surface on both ends is clear and exposed.

4- To ensure that chloride ions ingress through the end of the sample disc only, the one side surface of the concrete disc was covered with epoxy

5- The disc was then kept in room temperature to let the epoxy dry after which the duct tape was removed.

6- The sample disc was then de-aerated in accordance with ASTM C 1202 10 for 3 hours as shown in figure 3.8.

7- After the de-aeration process, the sample disc was kept in air tight container until the time of testing.

Testing Procedure

Concrete disc samples were tested at 90± 2 days and testing was performed as follows:

1- The concrete discs were placed in an applied voltage cells and the cells were tightened using four screws, one at each corner. Discs were placed so that the rough end of the discs should be in contact with the side of the cells that contains the sodium chloride (NaCL) solution and the other end of the disc will be in contact with the side of the cells that contains the sodium hydroxide (NaOH) solution.

2- The joints between the sample discs and the cells sides were then completely sealed with a sealant

3- The voltage cell having the top side (rough concrete surface) of the sample disc was filled with 3 % sodium chloride (NaCL) solution and the other end of the cell having contact with the bottom side (cut concrete surface) of the sample disc was filled with 0.3 N sodium hydroxide (NaOH) solution.

4- All electrical wiring were then connected in accordance with ASTM C1202 and a 60 Volts current was applied to the cells as shown in figure 3.9

5- The value in coulombs of the integrated current through the concrete disc was recorded every 30 minutes and the final value after 6 hours is considered for interoperation as shown in Table 3.3.

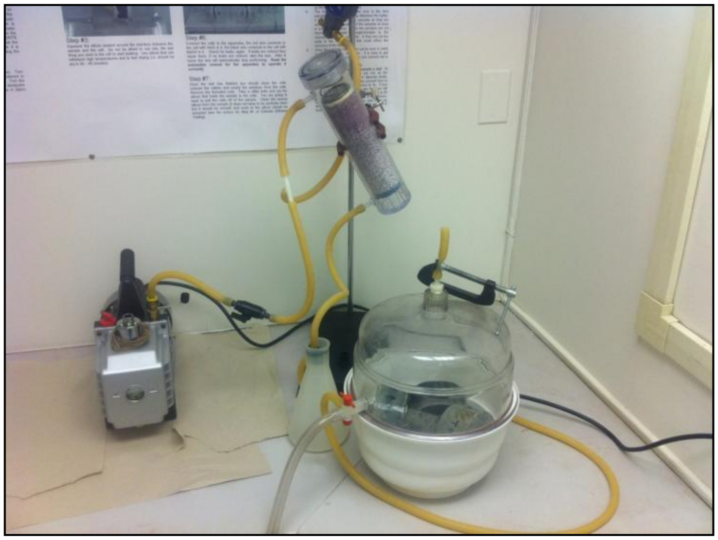


Figure 3.8: Sample discs being de-aerated.

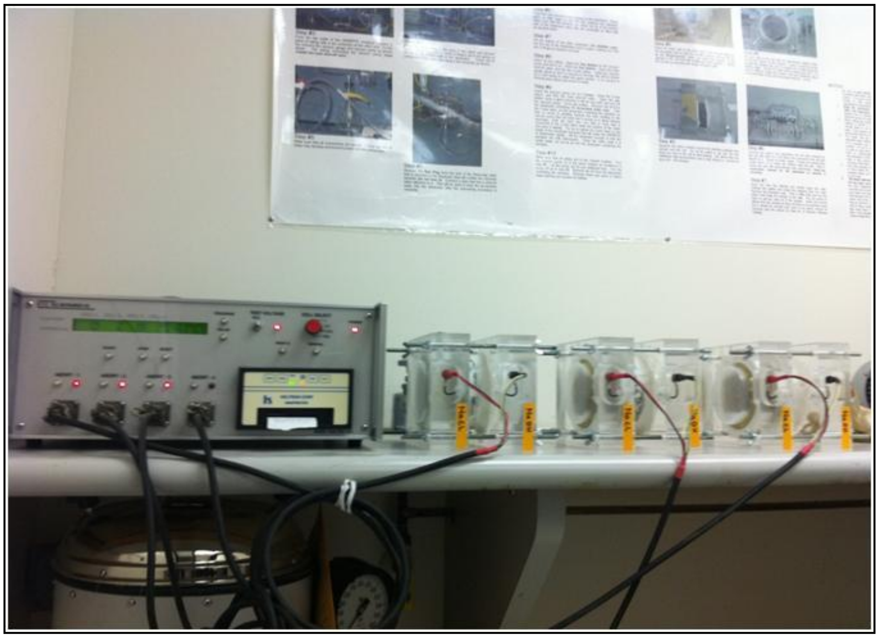


Figure 3.9: Rapid Chloride Permeability test set-up with all electrical wiring connected and test being performed.

CHAPTER 4

RESULTS AND DISCUSSION

4. 1INTRODUCTION

The objective of this research is to investigate the effect of Recycled Concrete Aggregate (RCA) with self-consolidating concrete with high content of supplementary cementitious materials as partial replacement of Portland cement. Concrete properties investigated in this study were explained in chapter three, and they include the compressive strength at 3, 14, and 28 days, the tensile strength at 28 days, the unrestrained (free) shrinkage up to 90 days, and concrete resistance to chloride permeability at 90 days. The properties of fresh SCC mixtures were also measured. These mixtures were intentionally designed to be self-consolidating and achieve acceptable flowability and deformability, and adequate resistance to segregation. Hence, the properties of fresh SCC mixtures were only measured for validation purposes, and they are listed in Table 4.1. In addition, the effect of high content of SCM on the properties of SCC mixtures was also investigated so that the optimum amount of such materials that can be used in SCC is quantified. Finally, the usage of the investigated SCC with RCA mixtures as a concrete sustainable material is discussed in this chapter.

4.2 Effect of Recycled Concrete Aggregate on the Fresh Properties

The fresh properties of all concrete mixtures were measured to ensure that the concrete is flowable, stable, and meets certain requirements from current standards to be classified as SCC. They were assessed using the slump flow; T_{50} tests with and without the J-Ring, and the segregation index test. In general, a slump flow value between 500 and 750 mm and a value of T50\7 s are considered acceptable for SCC design (EFNARC 2005).

Another important aspect of SCC is the passing ability of concrete through obstacles, which was assessed by measuring the slump flow and T_{50} values using the J-Ring test. The difference between the slump flow and J-Ring flow is an indication of the passing ability of concrete. A difference less than 50 to 100 mm is considered acceptable. The difference between the T_{50} values measured using the J-Ring test and the slump flow test should not be more than 2 – 4 seconds (SCC Workability). Finally, segregation is a major problem and should be avoided during the production of SCC. Table 4.1 shows the fresh properties of all concrete mixtures. The results showed that in general, fly ash and slag increase the workability of concrete for all mixtures including those incorporating RCA. It is clear that Mix 16, Mix 18, and Mix 20 required the highest dosage of HRWRA to achieve the targeted slump flow values (543, 572, and 602 mm). This indicates that replacing the coarse aggregate with high percentages of RCA reduces the workability of the SCC mix. Figure 4.1 shows the slump flow values and slump flow with J-Ring for all concrete mixtures conducted in this study. It is clear that almost all mixtures achieved the minimum requirements for self-consolidating concrete. The slump flow values were changed with the incorporation of RCA into the concrete mixtures. The substitution of coarse aggregate by 25, 50, and 100% RCA, decreased the hang stream regard by 0.8, 5.8, and 9.9%, independently, while it was essentially the same for the 75% RCA substitution mixture in light of high flowability in the concrete mixture contrasted with different substitutions. The use of (25% FA + 25% SL) in lieu of cement increased the magnitudes of the slump flow values in almost each mixture group. Table 4.1, shows that the use of 50% FA in replacement of cement increased the slump flow in the mixtures with 75, and 100% RCA replacement, whereas the slump flow values were almost identical for the remaining design mixes with 0, 25, and 50% RCA replacement. This is presumably because of high utilization of HRWRA on account of high water absorption due to high RCA content. Moreover, the use of 50% SL instead of cement did not have any significant change on the slump flow values in the different mixture groups. The lowest slump flow value was monitored when the coarse aggregate was replaced with 75% RCA and the cement by (25% FA + 25% S) where the flowability of concrete very nearly achieves segregation. Furthermore, binary mixtures made with high content of FA and S required a greater amount of HRWRA than that of the control mixture by 6.8, 34.5, and 27.7% for the cases of 25% FA, 25% SL, and (25% FA + 25% SL) with no RCA, respectively. The amount of HRWRA needed for the control mixtures of the five groups of mixtures (0, 25, 50, 75, and 100% RCA) increased by 13.3, 14.4, 21.6, and 43.1%, respectively. Additionally, the same trend was observed for the mixtures incorporating FA and/or S, which indicates that replacing the CA by RCA required greater amounts of HRWRA. The amount of HRWRA required for Mix1 (0% RCA) was 69.9% of that of the amount required for Mix 17 (100% RCA) which shows the adverse effect that replacing the CA by RCA has on flowability of the SCC mixes. Additionally, all of SCC mixtures showed high deformability indicated by the high slump flow values, and the smaller T_{50} tests values. The mixtures also showed moderate viscosity because the HRWRA used in this study contains a viscosity-modifying agent in its production and using high dosages of such an admixture to achieve a slump flow value higher than 500 mm enhances concrete viscosity. Table 4.1 shows that the largest amount of HRWA of 1142 ml/m^3 (29.1 fl. Oz/yd^3) was used for the case of 100% RCA using (25% FA + 25% SL). This is due to the high absorption of water in RCA compared to the CA. It is well known that there is very limited data related to the amount of HRWRA needed for any concrete mix. Figure 4.1, shows a typical slump flow and slump flow with the J-ring for the mixtures tested. All mixtures have exceeded the minimum requirements for the formation of SCC (slump flow values between 500 and 750 mm and $T_{50} < 7$ seconds.

Table 4.1: Properties of fresh concrete mixtures

Mix No.	Segregation Ratio	Fresh Properties			
		Slump flow(mm)	T_{50} (sec.)	Slump flow with J-Ring (mm)	SP ml/m3
Mix 1	0-1	607	4	557	592
Mix 2	0	558	3	521	632
Mix 3	0	585	4	543	796
Mix 4	0	621	2	574	756
Mix 5	0	602	4	562	671
Mix 6	0-1	558	5	512	592
Mix 7	0	576	6	524	717
Mix 8	0	597	5	552	790
Mix 9	0	572	4	535	677
Mix 10	0-1	555	3	506	796
Mix 11	0-1	586	4	543	716
Mix12	0	624	2	587	890
Mix13	0	610	3	570	720
Mix14	0-1	579	2	525	870
Mix15	0	588	4	540	845
Mix16	0-2	543	5	497	921
Mix17	1	547	2	504	847
Mix18	0	572	2	527	923
Mix19	0-2	585	7	538	884
Mix20	0-1	602	3	567	1142

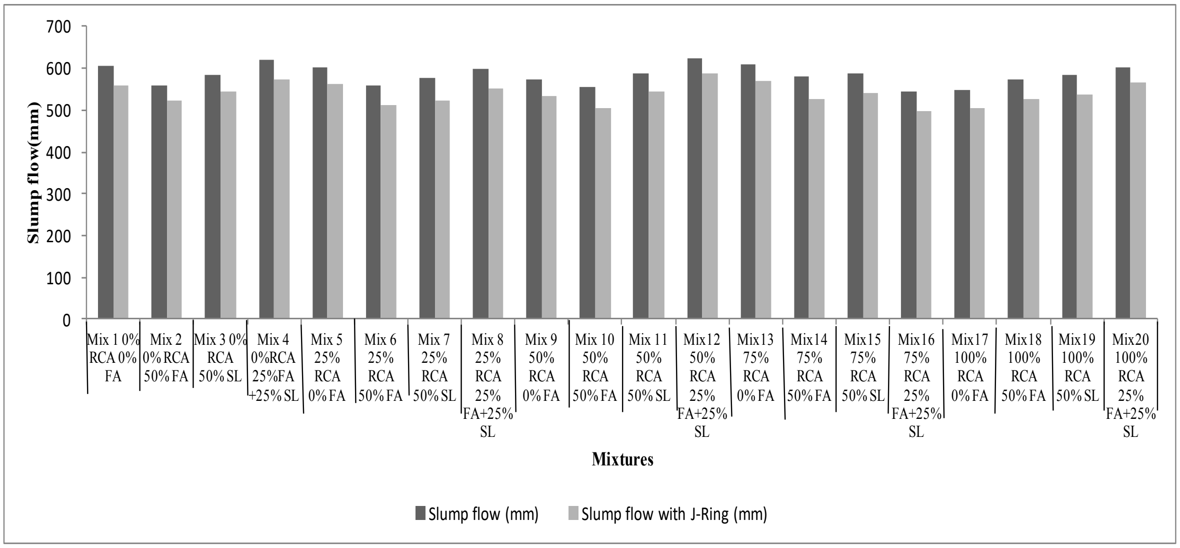
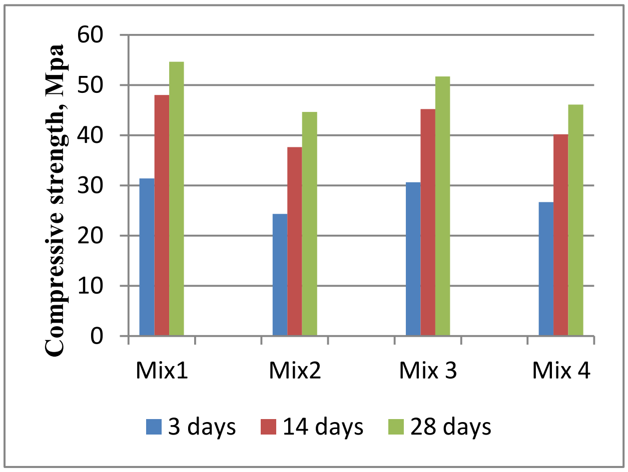


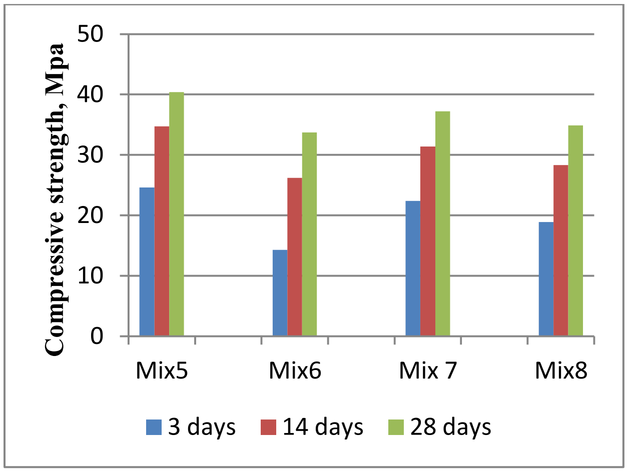
Figure 4.1-Slump flow of all mixtures

4.3 Effect of High Content of SCMs on the Compressive Strength

The effect of the addition of SCMs including fly ash, slag, and both fly ash and slag to the SCC concrete mixtures is illustrated in Figures 4.2 and 4.3. The addition of FA and S to mixtures has resulted in the reduction of the compressive strength at 3, 14 and 28-days compressive strength. However, the decrease in the compressive strength of the mixtures containing FA was more than those containing S or FA and S. The 28-days compressive strength for Mixes 2, 3, and 4 were less than that of Mix 1 (control mix) by 18.32, 5.3, and 15.6%, respectively as shown in Figure 4.2. The same trend was observed for mixes containing 25, 50, 75, and 100% RCA. The inclusion of slag to mixtures had the minimal effect on the 3, 14, and 28-days compressive strength. The 3-days compressive strength was less than that of the control mixture by 2.55%, where the 14 and 28-days compressive strengths were less by 5.833% and 5.3%, respectively. However, the compressive strengths of the mixes containing fly ash were the least among all mixes, where the reduction was 22.61, 21.7, and 18.32% compared to the control mix (0% RCA) after 3, 14, and 28 days respectively. A similar trend was observed for the cases of 25, 50, 75, and 100% RCA for the 3, 14, and 28 days mixes. Mixes with both 25% fly ash and 25% slag had an intermediate strength between those with 50% fly ash only and 50 % slag only as shown in Figure 4.3.



a)



b)

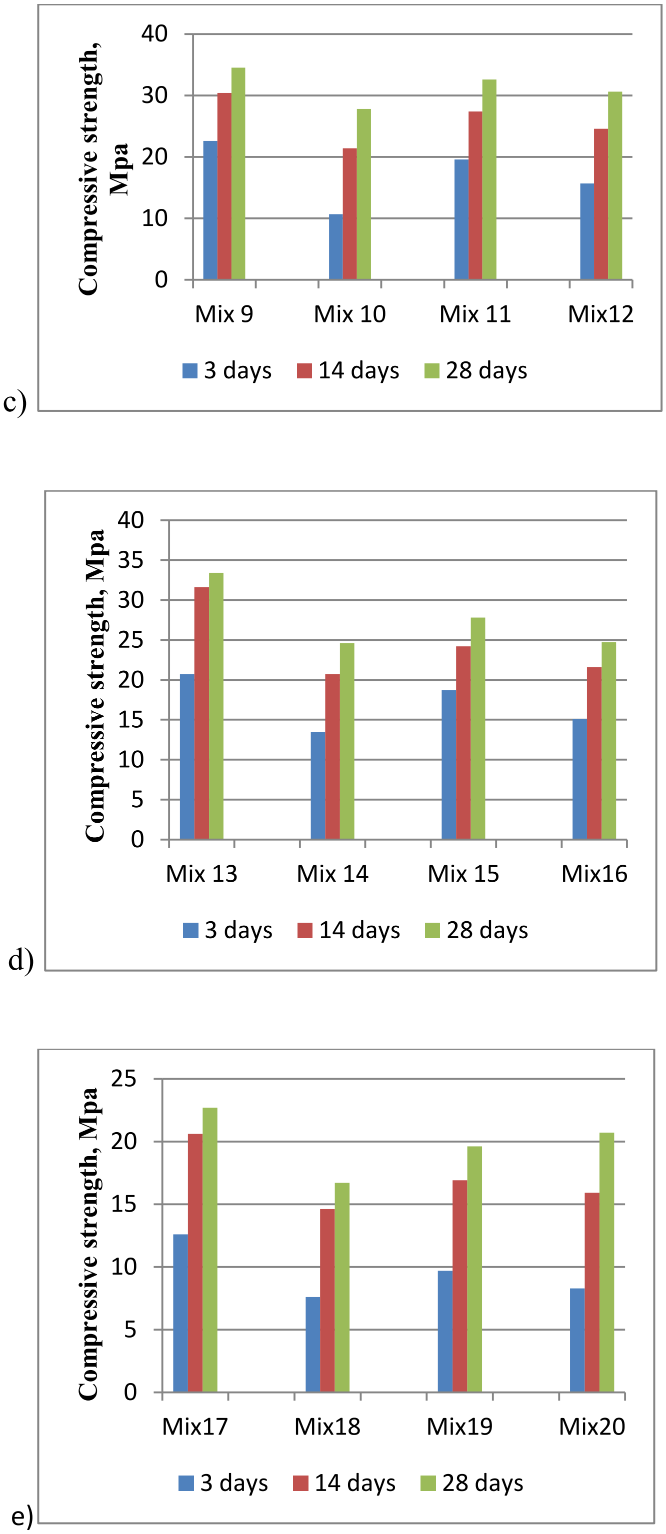
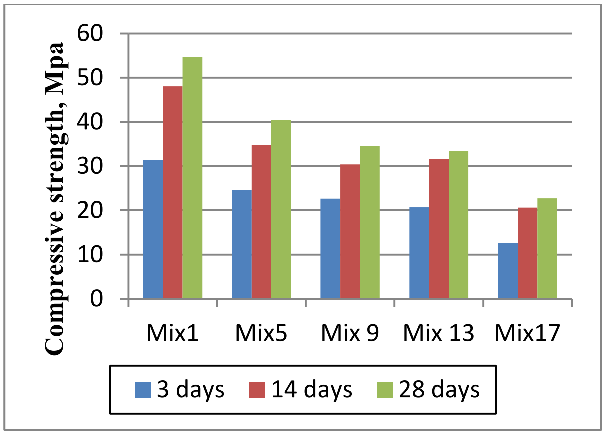
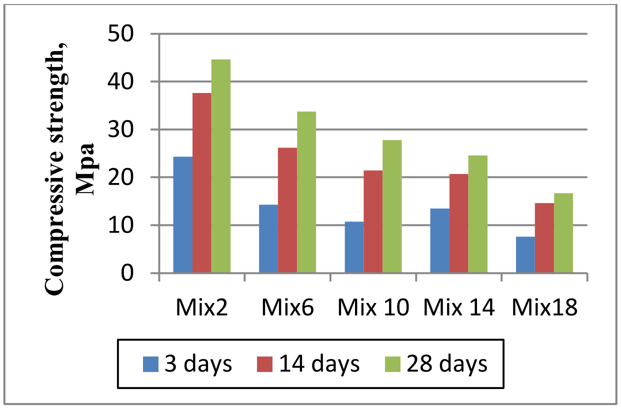


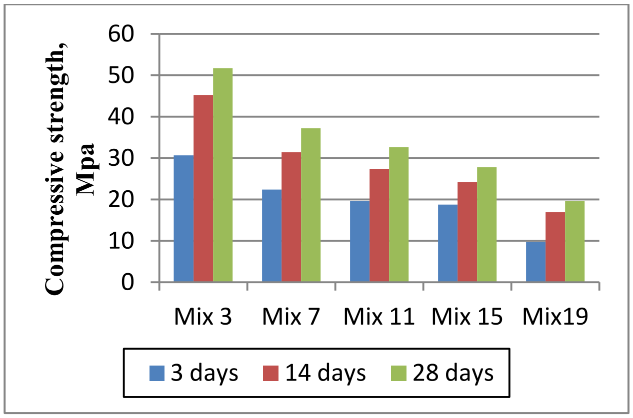
Figure 4.2: SCC compressive strength: a) 0 % RCA content, b) 25 % RCA content, c) 50 % RCA content, d) 75% RCA content, e) 100% RCA content.


Compressive strength, Mpa
60
50
40
30
20
10
0
Mix1
Mix5
Mix 9
Mix 13
Mix17
3 days
14 days
28 days

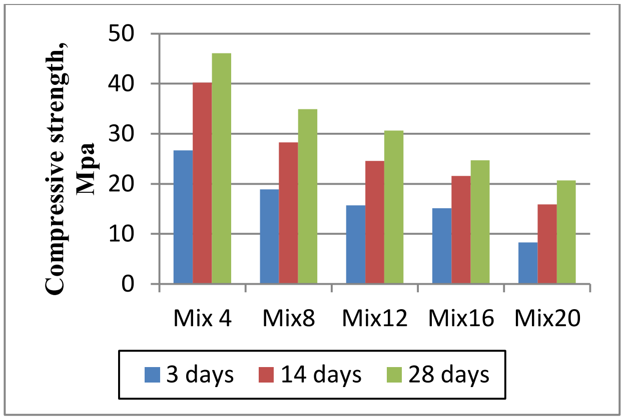
a)


Compressive strength, Mpa
50
40
30
20
10
0
Mix2
Mix6
Mix 10
Mix 14
Mix18
3 days
14 days
28 days

b)


Compressive strength, Mpa
60
50
40
30
20
10
0
Mix 3
Mix 7
Mix 11
Mix 15
Mix19
3 days
14 days
28 days

c)



d)

Figure 4.3: SCC compressive strength: a) SCC-control, b) SCC-fly ash, c) SCC-slag, d) SCC-fly ash & slag.

4.4 Effect of RCA Content on the Compressive Strength

Figure 4.2 summarizes the effect of replacing the CA by 0, 25, 50, 75, and 100% RCA with different percentages on the compressive strength. It is clear from the results that as the percentage of RCA increases, the compressive strength decreases for all different combinations of CA and RCA. Figure 4.3a shows the compressive strength of all control mixtures at 3, 14, and 28 days. It is observed that the 28-days compressive strength has decreased by 26, 36.8, 38.83, and 58.42 % for the cases of 25, 50, 75, and 100% RCA compared to Mix1. A similar reduction was observed at 3, and 14 days. Figure 4.3b, shows the compressive strength of all mixtures prepared using, 50% fly ash at 3, 14, and 28 days for all the different percentages of RCA. In this case, the compressive strength has decreased by 24.4, 37.7, 44.8, and 62.6 % at 28 days compared to Mix2. Figure 4.3c, shows the compressive strength of all mixtures prepared using, 50% slag at 3, 14, and 28 days for all the different percentages of RCA, where the compressive strength has decreased by 28, 36.9, 46.2, and 62.1% at 28 days compared to Mix 3. A similar trend was observed for the case of 25% FA and 25 % slag, where the reduction in the 28-days compressive strengths were reduced by 24.3, 33.6, 46.4, and 55.1% compared to Mix 4. The results show that as the percentage of RCA replacing the CA increases in the mix, the greater the reduction in the magnitudes of the compressive strength. Additionally, the same trend was observed for the mixtures incorporating FA and/or S, which indicates that as the percentage of RCA replacing the CA increases in the mix, the greater the reduction in the magnitudes of the compressive strength.

Despite the reduction in the compressive strength that was reported in some of the studied mixes, what is really essential is the target compressive strength and whether it has been achieved or not. The Illinois Department of Transportation (IDOT) minimum compressive strength for different engineering applications will be adopted to determine the applicability of using SCCRCA. IDOT mandates a minimum of 27.5 MPa 14-days compressive strength for concrete used in bridge superstructures, 24.0 MPa 14-days compressive strength for concrete used in pavements, and 22.1 MPa 14-days compressive strength for concrete used in pavement and bridge patching applications. The results of the 14-days compressive strength of the 20 mixtures conducted in this study against IDOT criteria are shown in Figure 4.5 the results indicate that 13 mixes have exceeded the bridge patching application requirement, 13 mixes have exceeded the pavement requirement, and 9 mixes have exceeded the bridge superstructures requirement. Among the mixes that have exceeded the requirement for bridge superstructures, mixes with 0, 25, 50, and 75% RCA (Mixes 1, 5, 9, and 13) with 100% cement, the remaining mixes included 50% SCMs content (Mixes 2, 3, 4, 7, and 8).

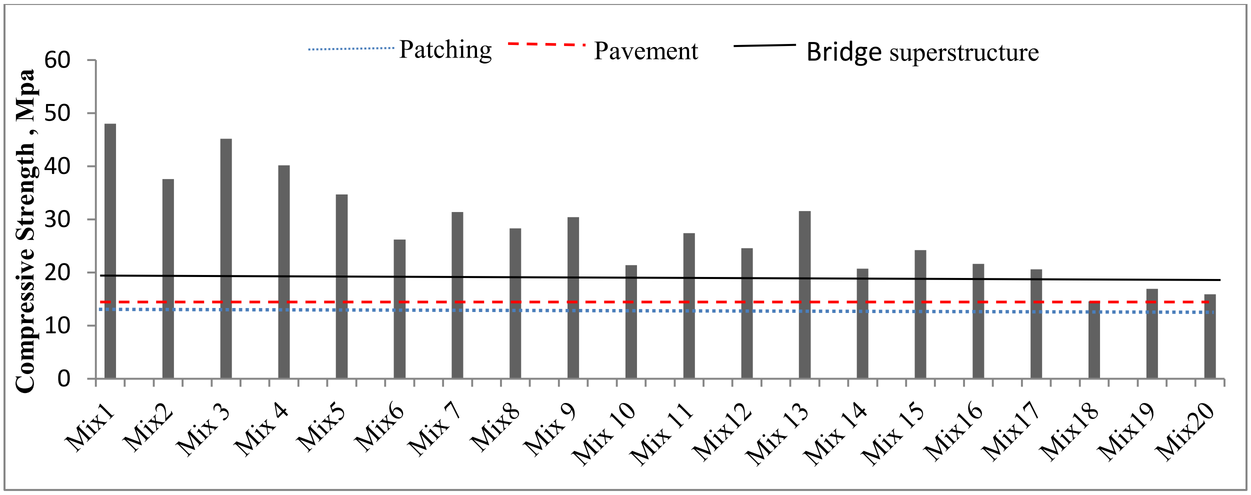


Figure 4.4: Compressive strength of all mixture at 14 days

A linear regression model has been developed along with analysis of variance (ANOVA) which was used to study the effect of RCA content, fly ash content, slag content, and mixture age on SCC compressive strength.

Compressive strength = Constant + (a x RCA content) + (b x Fly ash) + (c x Slag) + (d x age)

The statistical analysis, shown in Table 4.2 clearly shows that all the factors are significant since they have a p-value less than 0.05 for all the factors considered with an R-squared value of 90.32%. The examination also indicates that the addition of RCA has a more negative effect on the compressive strength when compared to FA and S, as indicated by a higher negative value of its standardized multiplier (-0.725) compared to -0.323 and -0.127 for RCA and slag respectively. As anticipated the age of the mixtures had a positive coefficient of 0.544. The standardized multipliers were used because they show the effect of each variable based on equal standard deviations. A comparison between the laboratory measured compressive strength values to the estimated values from the regression model. A highly relevant relationship is predicted by the model as shown in Figure 4.5, where all the points are very close to the equality line. This model could be used to estimate the compressive strength for any combination of RCA, fly ash, and slag at any concrete age, provided that the predicted value is within the experimental limits, i.e. prediction within ages (0-28 days), and RCA content from (0-100%).

Table 4.2: Linear regression model parameters

Factor	Multiplier Estimate	Standard Error	t-stat	Standardized Coefficients	P-value
(Constant)	33.730	1.288	26.115		9.8E-33
FA	-.043	.007	-6.926	-.323	2.073E-8
SL	-.018	.007	-2.716	-.127	0.0080259
RAC	-.026	.001	-17.439	-.725	2.784E-24
Age	.558	.044	13.070	.544	6.526E-18

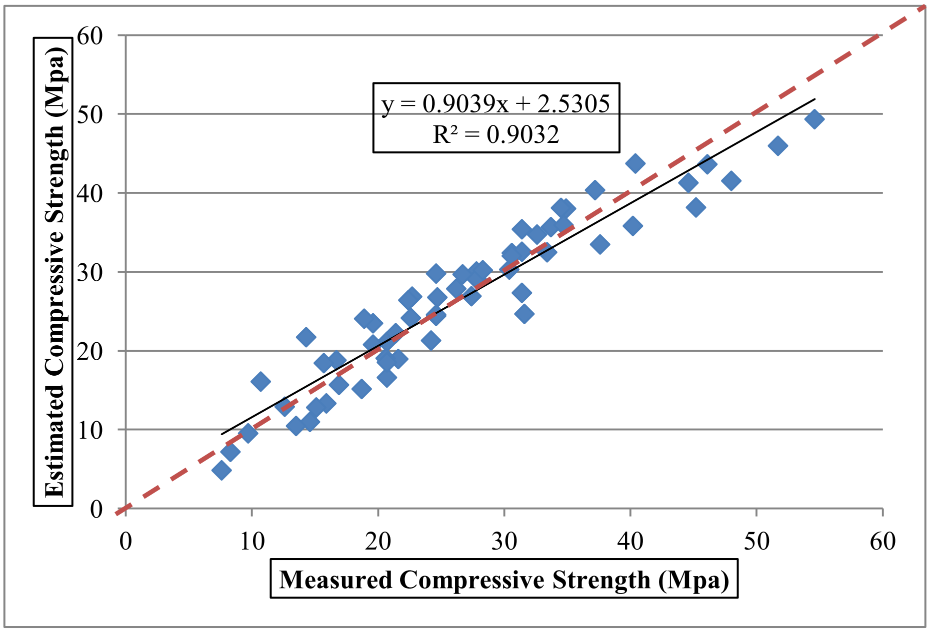
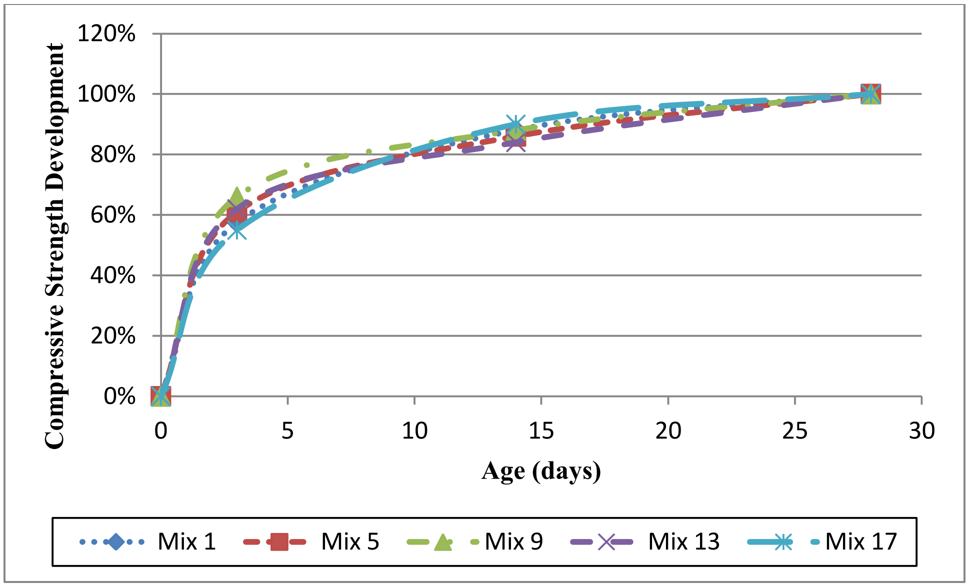
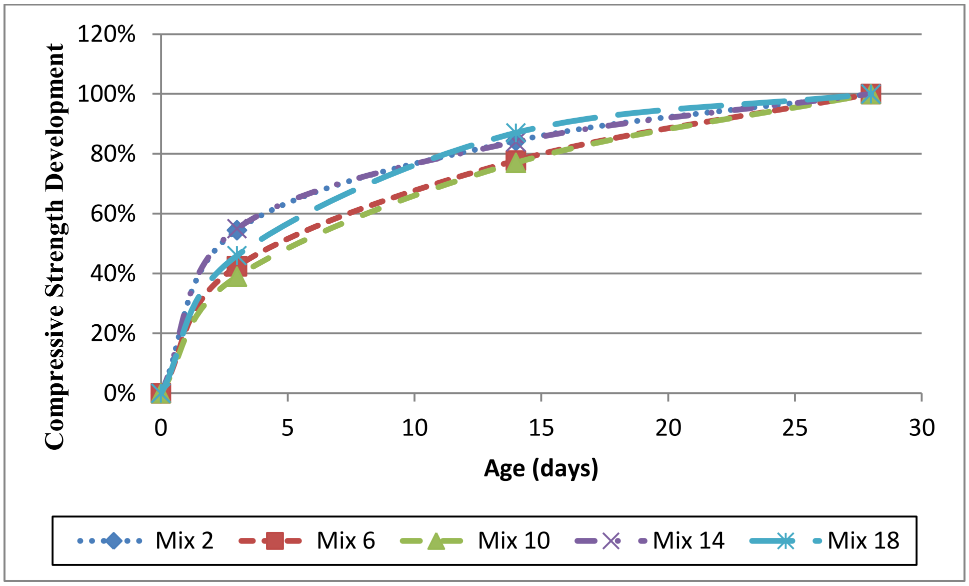


Figure 4.5: Estimated versus measured compressive strength

In addition to the importance of ultimate compressive strength of concrete, another important measure of concrete strength is the rate of compressive strength development. Figure 4.6 depicts the compressive strength development of the 20 mixes in this study over the 28 days. The results are arranged to allow for studying the effect of adding RCA to a control SCC, SCC-fly ash, SCC-slag, and SCC-fly ash and slag mixture. It is very important to note that this analysis is based on the 28 days compressive strength of each mix. So, even though the compressive strength development rate is important, it is only relevant if the mix satisfy target strength required by specifications. As shown in Fig. 4.6a, the addition of RCA to control SCC mixtures increased the first 3 days strength development rate, while 3–14 days rate decreased, however, in all cases almost more than 85% of the 28 days strength was developed within the first 14 days. The control SCC-fly ash mix develop about 84% of its strength within 14 days, the addition of 25%,50%,75% RCA dropped that value to about 78 %,77%,84%, however 87 % of the 28 days strength is developed within the first 14 days when 100 % RCA content is used as shown in Fig.4.6b. As illustrated in Fig. 4.6c SCC-slag mixes develop around 84% of its full strength in the first 14 days, this percent almost remains constant to about 85 % with the addition of RCA. Finally the SCC mixes with both slag and fly ash results showed a different trend as shown in Fig. 4.6d, in all cases more than 80 % of the 28 days strength was developed within the first 14 days when compared to other percentile adding.

a) 
Compressive Strength Development
120%
100%
80%
60%
40%
20%
0%
0
5
10
15
20
25
30
Age (days)
Mix 1
Mix 5
Mix 9
Mix 13
Mix 17

b) 
Compressive Strength Development
120%
100%
80%
60%
40%
20%
0%
0
5
10
15
20
25
30
Age (days)
Mix 2
Mix 6
Mix 10
Mix 14
Mix 18

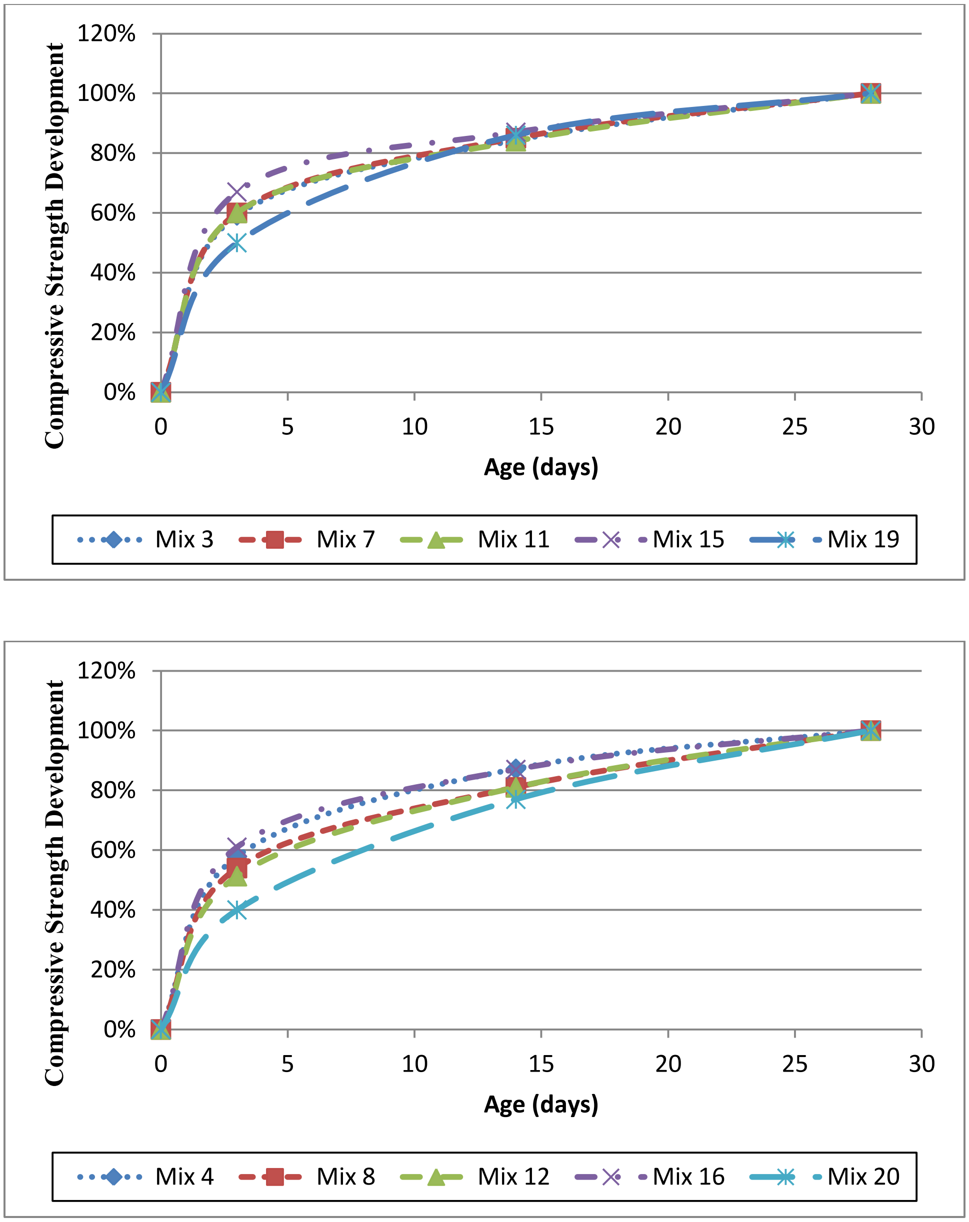


Figure 4.6 SCC compressive strength development: a) SCC-control, b) SCC-fly ash, c) SCC-slag, d) SCC-fly ash & slag.

4.5Effect of RCA Content on the Tensile Strength

Figure 4.7 shows the split tensile strength of all tested mixtures at 28 days. The results are configured to illustrate the effect of replacing the CA by different percentages of RCA in

SCC-control, SCC-fly ash, SCC-slag, and SCC-fly ash & slag as shown in Figure 4.8a-d respectively. As the RCA content increased from 0 to 100% the split tensile strength of all mixtures decreased accordingly. The maximum tensile strength recorded was 6.2 MPa (899 psi) which corresponds to the control mixture (Mix1) of 100% cement and 0% RCA, while the minimum recorded was 1.8 MPa (261 psi) which corresponds to (Mix 18) of 50% fly ash and 100% RCA. Replacing the cement by 50% slag increased the tensile strength for all different RCA contents compared to replacing it by 50% fly ash and 25% fly ash and 25% slag.

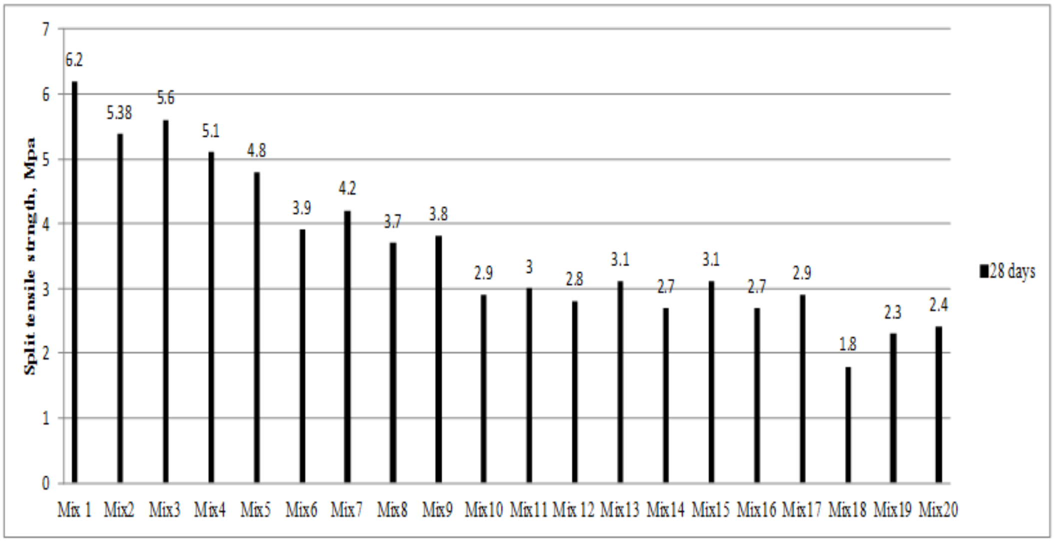
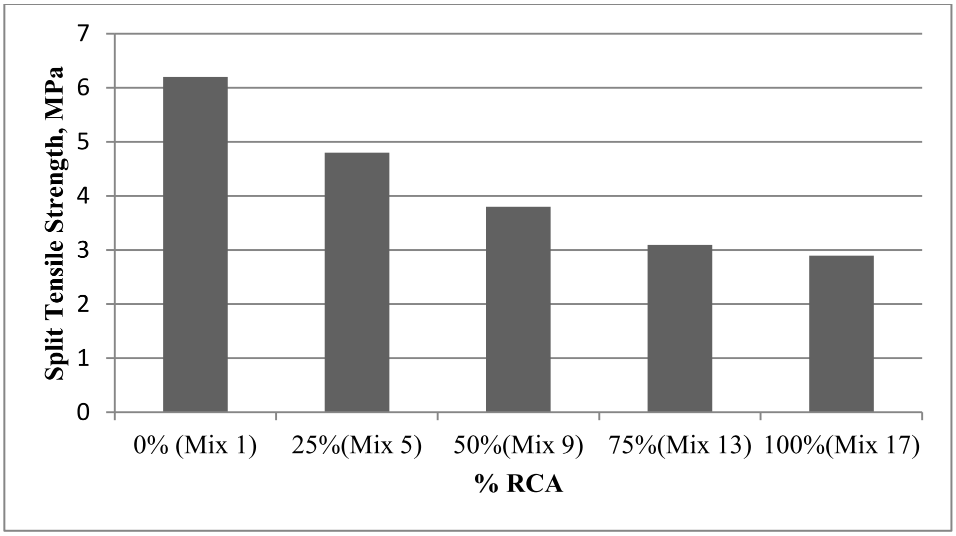
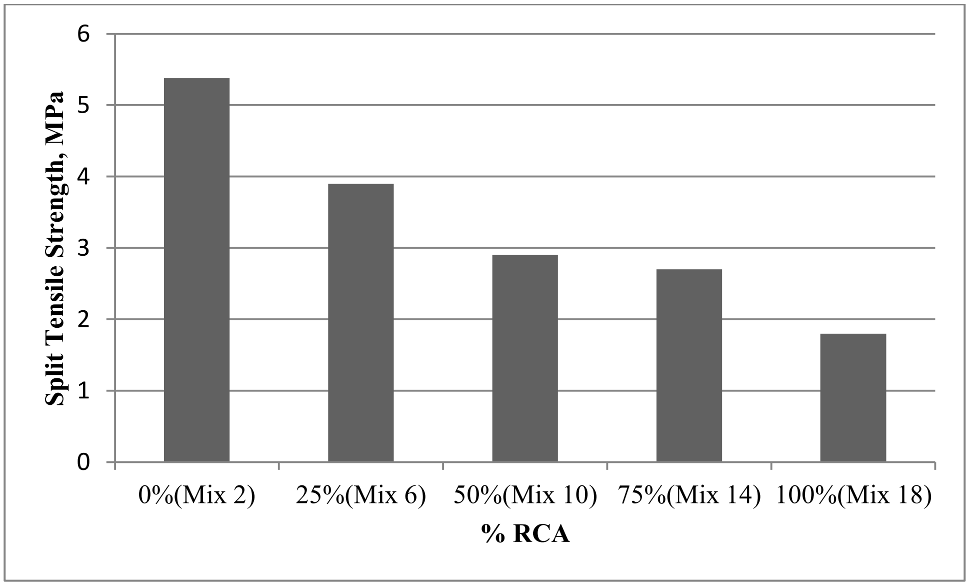


Figure 4.7: Split Tensile strength of all mixtures


Split Tensile Strength, MPa
7
6
5
4
3
2
1
0
0% (Mix 1)
25%(Mix 5)
50%(Mix 9)
75%(Mix 13)
100%(Mix 17)
% RCA

a)


Split Tensile Strength, MPa
6
5
4
3
2
1
0
0%(Mix 2)
25%(Mix 6)
50%(Mix 10)
75%(Mix 14)
100%(Mix 18)
% RCA

b)

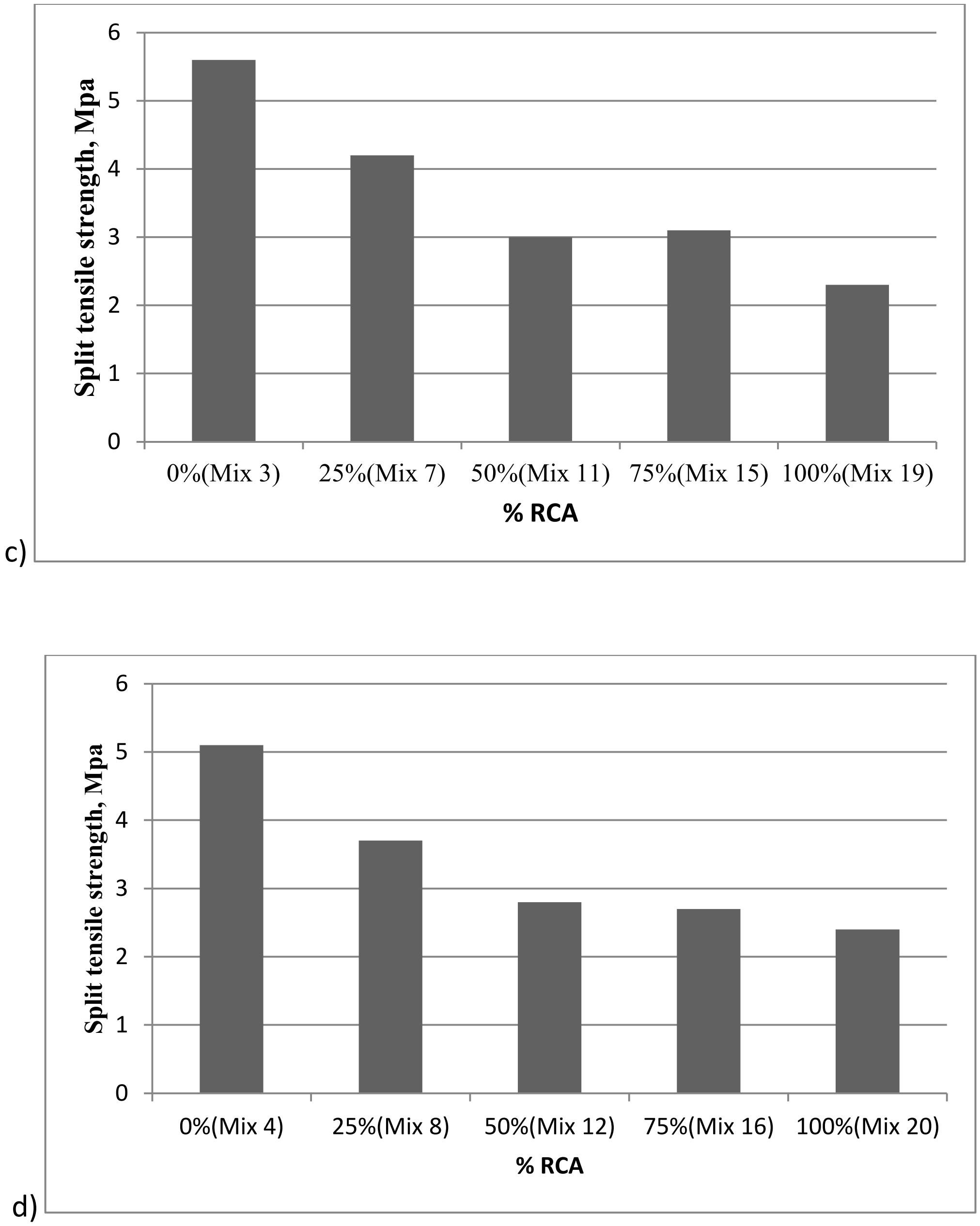


Figure 4.8. SCC split tensile strength: a) SCC-control, b) SCC-fly ash, c) SCC-slag d) SCC-fly ash & slag.

In general, it is observed that the tensile strength of SCC mixture is around 10-15% of compressive strength. ACI-318 (2011) provides a relationship between the tensile and compressive strength of conventional concrete and proposed that the tensile strength is proportional to the square root of the compressive strength (ACI equation 9-10).

$$f_r = 7.5\lambda\sqrt{f_c'} \qquad \text{Equation 4.1}$$

$$f_r = 0.6228\lambda\sqrt{f_c'} \quad \text{In SI units} \qquad \text{Equation 4.1(a)}$$

Where $\lambda = 1.0$ for normal weight concrete and f'_c is the concrete compressive strength.

Figure 4.9, shows a relationship between the compressive and tensile strength of all SCC mixtures considered in this study. From the results, it is clear that the relationship provided by ACI 9-10 is not applicable for SCCRCA mixtures made with high volume SCMs and RCA. A new relationship is proposed and it also assumes that the tensile strength of SCCRCA is proportional to its compressive strength but to the power of 0.9871 instead of 0.5 as shown in Figure 4.9. The new equation better represents the relationship between the tensile and compressive strength of SCCRCA and it is expressed as follows:

$$y = 0.1144x^{0.9871} \qquad \text{Equation 4.2}$$

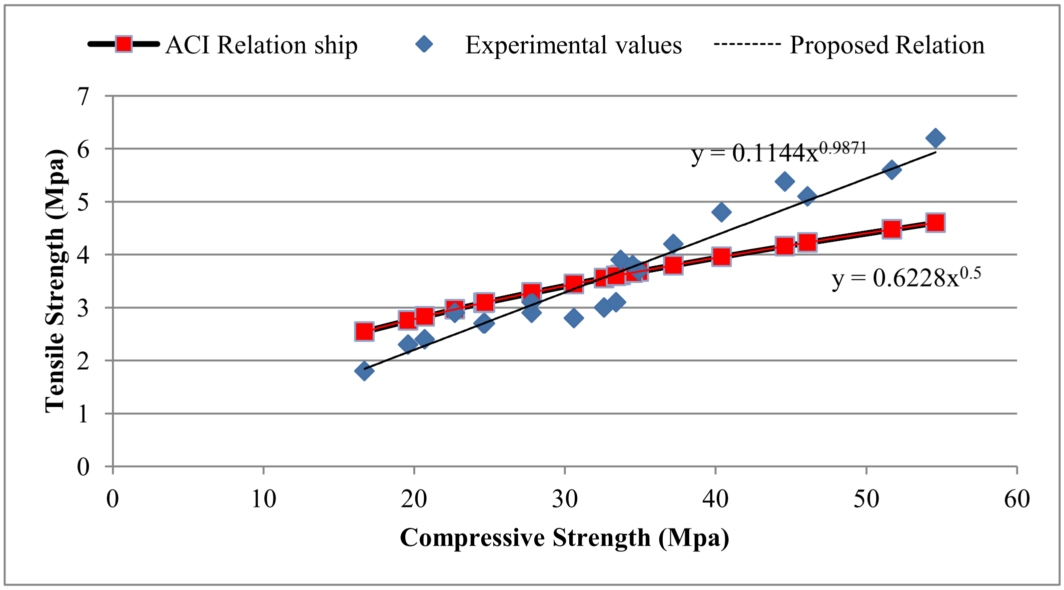


Figure 4.9. Relationship between the compressive strength and the tensile strength of Self Consolidating Concrete mixtures made with high content of Supplementary

4.6 PERMEABILITY OF SCC MIXTURES WITH HIGH CONTENT OF SCMs

The permeability of SCC mixtures considered in this study was evaluated using the rapid chloride permeability test (RCPT) explained in chapter 3. Due to the slow hydration of SCMs, RCA and to allow time for such materials to hydrate so that results could be representative, the test was performed at 90 days instead of 28 days. It is clear that all SCC mixtures incorporating high content of SCMs outperformed the control mixture and showed a significantly higher resistance to chloride penetration. Additionally, as the percentage of RCA replacing the CA increased, the resistance to chloride penetration increased as well. It has been well documented in the literature that the permeability of concrete in general depends on the w/cm ratio. Increasing the w/cm ratio usually leads to an increase in concrete permeability. It is also known that the permeability of concrete depends on its compressive strength and concrete with high compressive strength is usually less permeable. It is important to note that the w/cm ratio for all SCC mixtures considered in this study was kept constant to eliminate the effect of w/cm ratio and be able to quantify the effect of SCM on the permeability of concrete. Results shown in Figure 4.10 reveal that the permeability of HPSCC mixtures at 90 days is independent of concrete compressive strength. More experimental testing is required in this area. Furthermore it also observed from the results that the SCMs contents are affecting permeability of the SCC mixture rather than the RCA content. So, it is concluded that SCMs were the major contributor for low permeability of the SCC mixtures with a constant W/Cm ratio and also this is probably due to air voids present because of RCA addition through which the diffusion of chloride is delayed.

For example, the 28-day compressive strength of all SCC mixtures is equal to or less than that of the control mixture, whereas the number of coulombs for the control mixture was the highest at 958 coulombs compared to other SCC mixtures. Additionally, as the percentage of RCA replacing the CA increased, the resistance to chloride penetration increased as well.

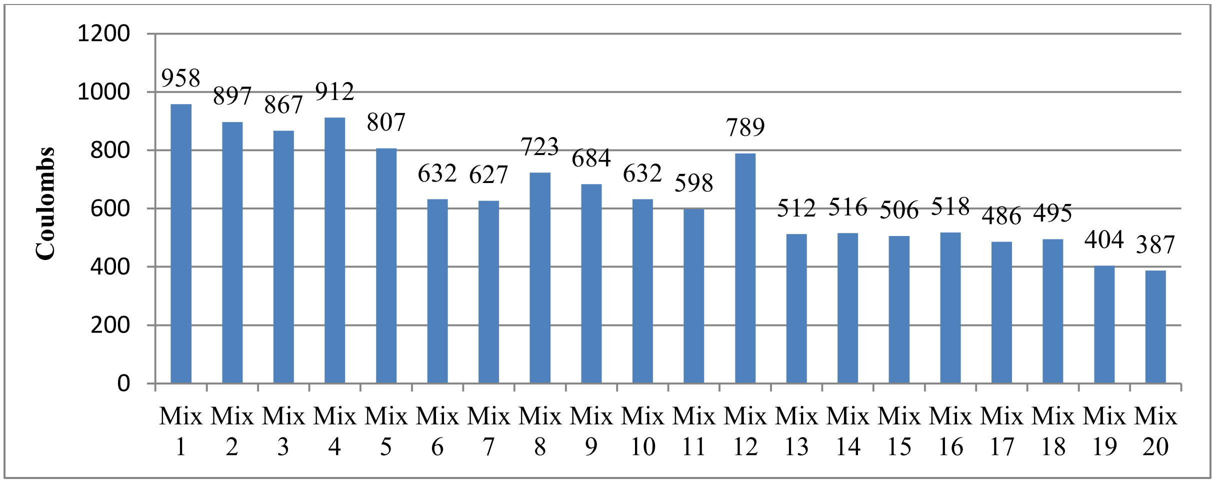


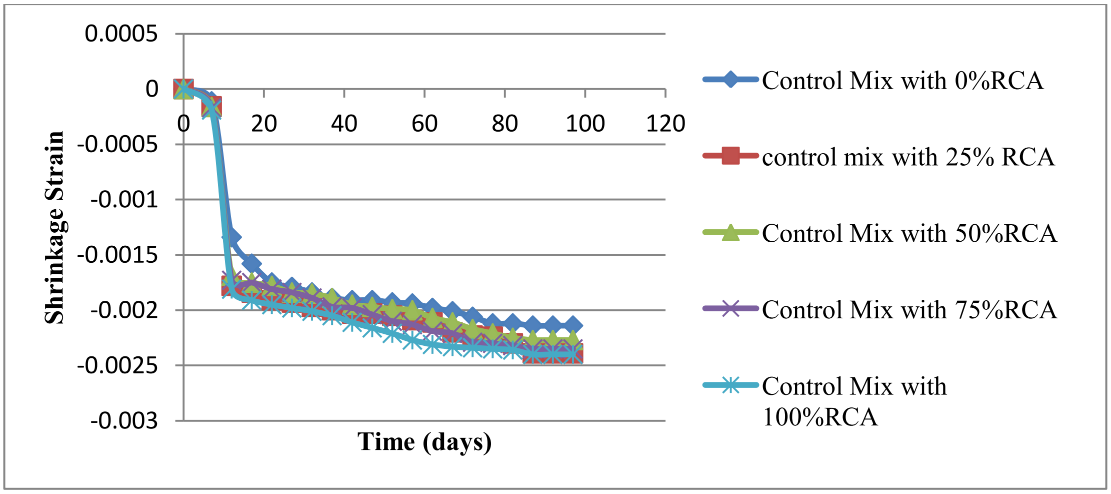
Figure 4.10: Chloride Diffusion in all Self Consolidating Concrete mixtures using the Rapid Chloride Permeability Test

4. 7 FREE SHRINKAGE OF SCC MIXTURES WITH HIGH CONTENT OF SCM AND RCA

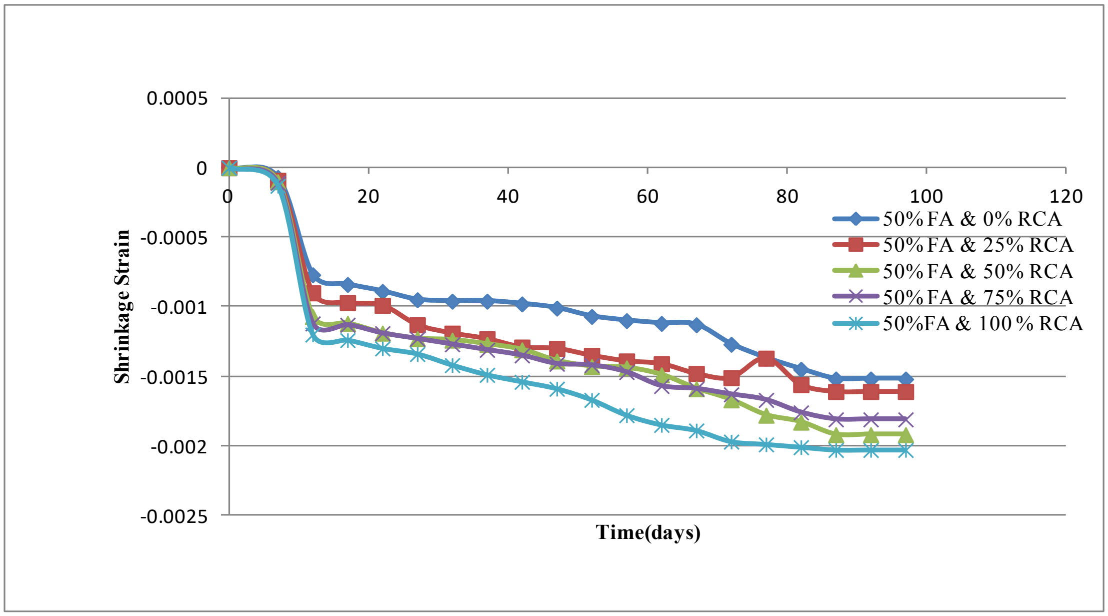
A single concrete prism was used from each mixture to study the unrestrained shrinkage. The specimens remained in the curing room for the first 7-days and then removed to be exposed to room temperature. The unrestrained shrinkage of concrete was measured consistently every 5 days up to 90 days. Figure 4.11a shows the effect of using 100% cement with (0, 25, 50, 75, and 100% RCA) on the free shrinkage of concrete. The shrinkage strain was very small during the first 7 days, however, a drastic jump in its magnitude was observed following the 7th day as the specimens were exposed to normal room temperature, followed by an almost linear change in the magnitude of its values until it was almost constant after 90 days. The same trend was observed for the specimens containing both class C fly-ash and slag as shown in Figure 4.11d; however, the magnitude of the shrinkage strain of the specimens containing 50% FA, 50% S, and 25% FA and 25% S was smaller in magnitude than that of the mixes containing 100% cement which indicates that replacing the cement by high volume SCMs reduces the shrinkage strain. The results show that the total shrinkage strain measured using concrete prisms made from concrete mixtures having 100% cement with 25%, 50%, 75%, and 100% RCA replacement is 11.68%, 6.1%, 9.81%, and 12.1% more than that of the control mixture (0% RCA and 100% cement). Therefore, it is obvious that increasing the content of RCA in the mixtures results in bigger shrinkage strain magnitudes for all mixtures.

It is clear that replacing the cement by 50% FA has the most significant effect in reducing the free shrinkage strain. The free shrinkage strain of Mix2 (0% RCA and 50% FA) is 28.97 % less than its corresponding control mixture. The same trend was observed for Mixes 6, 10, 14 and 18 (25% RCA and 50% FA, 50% RCA and 50% FA, 75% RCA and 50% FA, and 100% RCA, and 50% FA) where the free shrinkage strain values were less than their corresponding control mixtures by 32.64%, 15.42%, 2.49%, and 15.42% respectively. The results show that the total shrinkage strain measured using concrete prisms made from concrete mixtures having 50% cement replaced by FA and 25%, 50%, 75%, and 100% RCA replacement is 32.6%, 15.4%, 23%, and 15.4% less than that of their corresponding control mixtures, respectively. Figure 4.12, shows a sample of the concrete prisms that were used to measure the unrestrained shrinkage. The maximum total shrinkage strain recorded was -0.00249 in (-0.063 mm) for Mix 8 (25% RCA with 25% fly ash and 25% slag), and the minimum was -0.00152in (-0.038mm) for Mix 2 (0% RCA and 50% fly ash) as shown in Figure 4.11b.

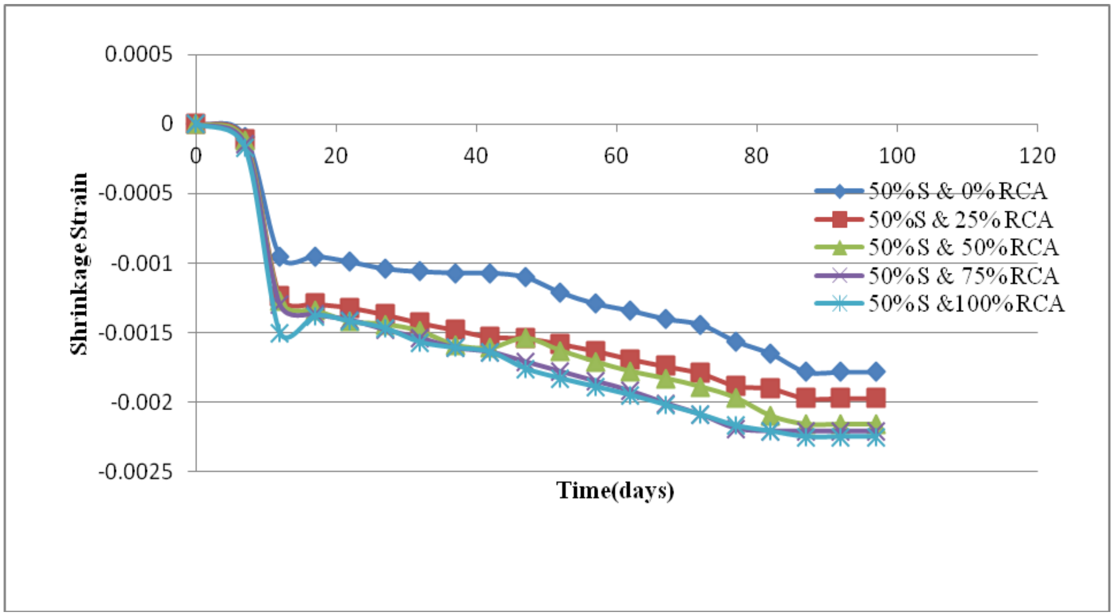
It is clear that replacing the cement by 50% SL decreases the free shrinkage strain. The free shrinkage strain of Mix3 (0% RCA and 50% SL) is 16.8 % less than its corresponding control mixture. The same trend was observed for Mixes 7, 11, and 15 (25% RCA and 50% SL, 50% RCA and 50% SL, 75% RCA and 50% SL) where the free shrinkage strain values were less than their corresponding control mixtures by 17.5%, 4.8%, and 5.9%, respectively. The reduction in the free shrinkage of such mixtures can be attributed to the denser paste matrix generated by using slag, which is finer than Portland cement.



a)


0.0005
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
0
20
40
60
80
100
120
Shrinkage Strain
Time(days)
50% FA & 0% RCA
50% FA & 25% RCA
50% FA & 50% RCA
50% FA & 75% RCA
50%FA & 100% RCA

b)


0.0005
0
-0.0005
-0.001
-0.0015
-0.002
-0.0025
0
20
40
60
80
100
120
Shrinkage Strain
Time(days)
50%S & 0%RCA
50%S & 25%RCA
50%S & 50%RCA
50%S & 75%RCA
50%S &100%RCA

c)

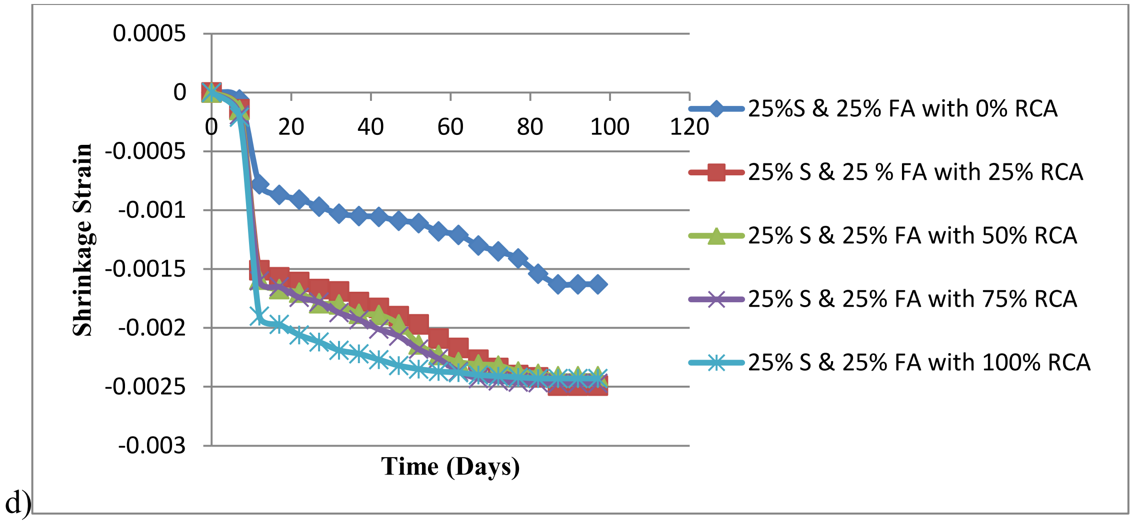


Figure 4.11. SCC Shrinkage: a) SCC-control, b) SCC-50%fly ash c) SCC-50%slag d). SCC-25%fly ash &25% slag

Figure 4.12 Unrestrained shrinkage test specimen sample

4.8 Sustainability Construction

Recycling concrete provides sustainability several different ways. The simple act of recycling the concrete reduces the amount of material that must be land filled. The concrete itself becomes aggregate and any embedded metals can be removed and recycled as well. As space for landfills becomes premium, this not only helps reduce the need for landfills, but also reduces the economic impact of the project. Moreover, using recycled concrete aggregates reduces the need for virgin aggregates. This in turn reduces the environmental impact of the aggregate extraction process. By removing both the waste disposal and new material production needs, transportation requirements for the project are significantly reduced. In addition to the resource management aspect, recycled concrete aggregates absorb a large amount of carbon dioxide from the surrounding environment. The natural process of carbonation occurs in all concrete from the surface inward. In the process of crushing concrete to create recycled concrete aggregates, areas of the concrete that have not carbonated are exposed to atmospheric carbon dioxide.

The LEED Green Building Rating System recognizes recycled concrete in its point system. Credit 4 (Materials and Resources) states, “specify a minimum of 25 percent of building materials that contain in aggregate a minimum weighted average of 20 percent post-consumer recycled content material, OR, a minimum weighted average of 40 percent post-industrial recycled content material.” Using recycled aggregates instead of extracted aggregates would qualify as post-consumer. Because concrete is an assembly, its recycled content should be calculated as a percentage of recycled material on a mass basis. Credit can also be obtained for Construction Waste Management. It is awarded based on diverting at least 50 percent by mass of construction, demolition, and land clearing waste from landfill disposal. Concrete is a relatively heavy construction material and is frequently recycled into aggregate for road bases or construction fill.

The objective of this research is to develop more environmental friendly self- Consolidating concrete not only by incorporating SCMs as partial replacement of Portland cement, but also by replacing the coarse aggregate with RCA up to100%. If successful, the use of SCMs and RCA will help in reducing the industrial waste dumped in the landfill and conserving the natural resources like limestone, clay, gravel and sand.

4.8.1. Benefits of SCMs and RCA

As discussed above and in previous chapters the main problem with concrete not being a sustainable material is the excessive use of cement and the amount of CO_2 emission due to its production. Replacing 50% of cement in concrete will definitely lead to lesser cement production, which in turn leads to lesser use of natural materials such as lime and clay, and most importantly less emission of CO_2 and harmful gasses. More than 2800 million tons of cement was produced in 2009 and for each ton of cement, one ton of CO_2 is released in the atmosphere. Replacing 50% of cement with materials like slag, fly ash or silica fumes means a 2000 million tons reduction in the amount of CO_2 released in the atmosphere worldwide per year. It is reasonable to expect that reducing the amount of CO_2 by 2000 million tons a year will definitely ease global warming without jeopardizing the properties of concrete.

Results obtained from concrete mixtures incorporating high content of SCM as partial replacement of cement showed that concrete properties were not compromised by using high content of SCM. All mixtures with high content of SCM revealed a better durability than mixtures made with 100% cement. This concludes that sustainable quality concretes can be produced with a minimum amount of cement leading to a very environmentally friendly material. All mixtures with high content of SCMs and RCA revealed a better durability than mixtures made with 100% cement. The horizontal lines indicated in Figure 4.4 speak to the Illinois Department of Transportation (IDOT) particular for compressive strength for extension superstructure, pavements and patches. Table 4.3 conclude the consequences of checking the 14 days compressive strength of the 20 mixes in this study.

Table 4.3. 14-Days compressive strength IDOT criteria.

MIX	14-Days compressive strength	Application		
		Pavement and bridge deck patching(>22.1Mpa)	Pavement and structures (>24Mpa)	Bridge superstructure
1	48	Satisfactory	Satisfactory	Satisfactory
2	37.6	Satisfactory	Satisfactory	Satisfactory
3	45.2	Satisfactory	Satisfactory	Satisfactory
4	40.2	Satisfactory	Satisfactory	Satisfactory
5	34.7	Satisfactory	Satisfactory	Satisfactory
6	26.2	Satisfactory	Satisfactory	Not Satisfactory
7	31.4	Satisfactory	Satisfactory	Satisfactory
8	28.3	Satisfactory	Satisfactory	Satisfactory
9	30.4	Satisfactory	Satisfactory	Satisfactory
10	21.4	Not Satisfactory	Not Satisfactory	Not Satisfactory
11	27.4	Satisfactory	Satisfactory	Not Satisfactory
12	24.6	Satisfactory	Satisfactory	Not Satisfactory
13	31.6	Satisfactory	Satisfactory	Satisfactory
14	20.7	Not Satisfactory	Not Satisfactory	Not Satisfactory
15	24.2	Satisfactory	Satisfactory	Not Satisfactory
16	21.6	Not Satisfactory	Not Satisfactory	Not Satisfactory
17	20.6	Not Satisfactory	Not Satisfactory	Not Satisfactory
18	14.6	Not Satisfactory	Not Satisfactory	Not Satisfactory
19	16.9	Not Satisfactory	Not Satisfactory	Not Satisfactory
20	15.9	Not Satisfactory	Not Satisfactory	Not Satisfactory

The results demonstrate that 13 mixes have surpassed the bridge patching application necessity, 13 mixes have surpassed the pavement prerequisite, and 9 blends have surpassed the bridge superstructures necessity. Among the mixes that have surpassed the prerequisite for bridge superstructures, mixes with 0, 25, 50, and 75% RCA (Mixes 1, 5, 9, and 13) with 100% cement, the remaining mixes incorporated 50% SCMs content (Mixes 2, 3, 4, 7, and 8).

4.8.2 Durability

Another important aspect of the economical sustainability is durability. Building our infrastructures from non-durable materials means high maintenance cost, shorter service life, and such infrastructures must be demolished and replaced by new structures sooner than expected, which affects financial and natural resources? A significant amount of material and energy flow is required for construction and demolishing of infrastructure. In addition, new structures require the use of new materials and waste from demolished ones need to be disposed in landfills. All such activities increase the overall life cycle cost of the structure. The structure built from a durable concrete serves more life than one built from a non-durable one and saves significant amounts of money and resources.

The results obtained from free shrinkage and RCPT tests showed less shrinkage and higher resistance to chloride ion penetration when compared to control mixtures. This indicates that using such concrete in the construction industry will reduce the overall life cycle cost of concrete structures and therefore significantly enhance concrete contribution to economical sustainability.

In conclusion the self-consolidating concrete with inclusion of RCA and SCMs developed in this study will enhance concrete sustainability from several perspectives.

It helps in reducing the greenhouse gases by reducing the cement production and preserves the natural resources. Furthermore it helps in reducing the need of landfills to dispose industrial by product wastes and recycled aggregates from building demolition. Finally, it is important to mention other influential factors that also contribute to the sustainability of concrete, such as reducing the noise levels during construction by eliminating the vibration process, significant reduction in construction labors and energy to mix, place and finish concrete, reducing the adverse effect on labors health due to reduction in noise level and the equipment required.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

In order to fulfill its commitment to sustainable development, the concrete of tomorrow should not only be more durable, but should also be developed to satisfy socioeconomic needs at the lowest environmental impact (Aitcin, 2000). The development and use of self-consolidating concrete, SCC is believed to help reduce both waste and energy consumption. However, due to lack of available data on its long term performance, there have been concerns regarding its structural performance and its ability to sustain harsh environmental conditions. In addition, global warming is a major problem for todays and future development and most industries are shifting towards sustainable and green practices.

Sustainable technologies such as supplementary cementitious materials and RCA can overcome the shortage of NCA, eliminate the harvesting cost of NCA, and reduce the construction and demolition wastes in landfill site. In addition, it will eliminate the transportation cost for gathering NCA to construction site, and for disposing the construction and demolition wastes to landfill site. RCA was used in the present study as partial and full replacements of NCA to produce high-workability concretes. The effects of RCA on the workability, compressive strength, splitting tensile strength, Permeability, and Unrestrained Shrinkage of concrete were investigated. A total of 20 concrete mixtures were prepared and tested. The properties of fresh concrete, such as flowability, deformability, filling capacity, and resistance to segregation are discussed. The properties of hardened concrete, such as compressive strength at 3, 14, and 28 days, and durability characteristics such as, free shrinkage up to 90 days and resistance to chloride permeability are also presented.

Results obtained from this research are presented and discussed in chapter four. Based on the properties investigated and results obtained, the following general observations are summarized below

5.1.1FRESH PROPERTIES

The effect of a relatively low content of SCM on the properties of fresh self-consolidating concrete is well documented (EFNARC, 2005) and it has been shown that while fly-ash and slag increase the workability of concrete, similar observation can be made for using high content of SCMs in the concrete developed in this study. Furthermore, similar effects were observed with incorporating RCA in SCC mixtures. It is important to note that the binary mixtures made with 25% fly ash and 25% slag required an average of 24% more HRWRA for mixes with 25%, 50%, 75% and 100% RCA replacement compared to the control mixture. Most of the specimens satisfied the target value of T_{50}.It was also observed that the replacement of CA with RCA almost reduced the slump flow values with J-Ring for control mixtures.

5.1.2 COMPRESSIVE STRENGTH

Results obtained from this study for the compressive strength of concrete show that high content of supplementary cementitious materials and RCA can be used in SCC mixtures as partial replacement of cement and coarse aggregate respectively without jeopardizing its mechanical properties. The addition of slag to mixtures had minimum effect on the 14 and 28 days compressive strength. Mixes with fly ash exhibited the most reduction in strength and the SCC mixtures with both fly ash and slag showed intermediate strength between fly ash only and slag only mixes after 14 and 28 days. It is clear from the results that as the percentage of RCA increases, the compressive strength decreases for all different combinations of CA and RCA. Despite the reduction in the compressive strength that was reported in some of the studied mixes, what is really essential is the target compressive strength and whether it has been achieved or not. The Illinois Department of Transportation (IDOT) minimum compressive strength for different engineering applications will be considered to determine the applicability of using SCCRCA. The results of the 14-days compressive strength of the 20 mixtures conducted in this study against IDOT criteria indicate that 13 mixes have exceeded the bridge patching application requirement, 13 mixes have exceeded the pavement requirement, and 9 mixes have exceeded the bridge superstructures requirement.

The linear regression model along with analysis of variance indicates that the addition of RCA has more negative impact on compressive strength when compared to fly ash and slag. Furthermore, this model could be used to estimate the compressive strength for any combination of RCA, fly ash, and slag at any concrete age, as long as the prediction is within the experimental limits, i.e. extrapolation to ages more than 28 days, and RCA content from (0-100%).

5.1.3 SPLIT TENSILE STRENGTH

The results clearly indicated that the split tensile strength dropped due to addition of RCA. Replacing the cement by 50% slag increased the tensile strength for all different RCA contents compared to replacing it by 50% fly ash and 25% fly ash and 25% slag. The maximum tensile strength recorded was 6.2 MPa (899 psi) which corresponds to the control mixture (Mix1) of 100% cement and 0% RCA, while the minimum recorded was 1.8 MPa (261 psi) which corresponds to (Mix 18) of 50% fly ash and 100% RCA. From the results it is clear that the relationship provided by ACI 9-10 is not applicable for SCCRCA mixtures made with high volume SCMs and RCA. A new relationship is proposed and it also assumes that the tensile strength of SCCRCA is proportional to its compressive strength but to the power of 0.9871 instead of 0.5.

5.1.4 UNRESTRAINED SHRINKAGE

Results obtained in this study regarding the unrestrained shrinkage of the proposed concrete showed that using RCA and SCMs in SCC mixtures generally leads to a significant reduction in the unrestrained shrinkage of concrete. In the first 10 days there is a change in the shrinkage strain on the mixtures with no RCA and a greater jump on days 5 to day 10 in the mixtures which has 0-100% RCA substitution. It is also clear that replacing the cement by 50% FA and 50% S reduces the free shrinkage strain regardless of the w/cm ratio.

5.1.5 PERMEABILITY

The permeability of concrete mixtures developed and tested in this study was evaluated using the rapid chloride permeability test; RCPT. Due to the fact that the hydration process of cementitious materials with RCA is slower than that of cement, the RCPT was performed at 90 days instead of 28 days in order to achieve more representative results to the effect of high content of such materials. Regardless of the type or amount of the SCM used, results from the RCPT at 90 days clearly showed that using SCMs as partial replacement of cement in concrete mixtures significantly reduces chloride ions diffusion in the concrete and thus enhances concrete permeability. All SCC mixtures incorporating high content of SCM and RCA outperformed the control SCC mixtures and showed a significantly higher resistance to chloride penetration.

5.2 CONCLUSIONS

The following conclusions can be drawn based on the findings of the experimental investigation:

1- About 50% fly ash(FA) and 50% Ground Granulated Blast Furnace Slag (GGBFS) can be used in concrete mixtures as partial replacement of portland cement and still develop a workable, strong, durable and cost-effective SCC.

2- Using RCA as a replacement for CA with 25, 50, 75, and 100% resulted in SCC mixtures with an average slump flow and slump flow with J-Ring of 581 and 537 mm, respectively, while they were 593, and 549 mm for the case of 100% CA. All mixtures had values above the minimum limit of SCC.

3- Using 25, 50, 75, and 100% RCA has decreased the 28-days compressive strength of SCCRCA mixtures by 26%, 36.8%, 38.8%, and 58.42%, compared with the control mix for the case of 0% RCA content.

4- SCC mixes with both 25% fly ash and 25% slag had transitional 28-days compressive strength between those having 50% fly ash and 50 % slag only.

5- As the percentage of RCA replacing CA increased (0-100%), the split tensile strength decreased accordingly appropriately.

6- The use of 50% S as a replacement to cement has resulted in the least reduction in the split tensile strength of all mixes when compared to 50% FA and 25% FA and 25% S.

7- Concrete mixtures containing 50% FA had the lowest total free shrinkage values when compared with all other mixes including those with 100% cement, 50% S, and 25% FA and 25% S.

8- The test results showed that ACI formula (ACI 9-10) used for predicting the tensile strength of concrete does not accurately estimate the tensile strength of SCCRCA mixes. A new formula has been developed that better evaluates the tensile strength of SCCRCA mixes.

9- SCC mixtures including high content of SCMs outperformed their corresponding control mixtures and showed higher resistance to chloride penetration.

10- SCC mixes with 0%, 25%, 50% RCA replacing CA can be used for bridge superstructures, while those with 75% and 100% RCA can be used for pavement and patching applications.

5.3 RECOMMENDATIONS FOR FUTURE RESEARCH

a. For RCA to become widely used material, consistent and predictable results need to be obtained when using as a substitute for virgin aggregate in concrete. To achieve this, further study is required in the areas of aggregate properties, mixture design and proportioning, performance, testing, and modeling.

b. Perform petrographic analysis on the RCA samples to better understand their composition, quality, and how much deleterious material that can be included without affecting the performance of the concrete.

c. Comparing concrete mixes with different sources of RCA including sources of RCA that are clean, contaminated, and cured differently.

d. Compare concrete mixes with a variety of coarse RCA content to find the optimal amount that can be added without sacrificing performance.

e. Investigating other durability issues, such as freeze-thaw, acid attacks, and carbonation for SCC mixtures made with high content of SCM.

f. Studying the long term performance of HPSCC with RCA mixtures.

g. Public awareness should be raised by educational campaigns in order to demonstrate and clarify the concept of recycling construction and demolition concrete benefits.

5.4 Incentives and Tactics to Promote the Use of Recycled Aggregates

5.4.1Aggregate Producers

- Waive tipping fees for higher quality rubble at crushing operations

Reduced or waived tipping fees will offset the expense of hauling. The resulting increase in rubble delivered to the crushing operations could alleviate the problems of steady material supply at the crusher.

- Provide income tax credits

Tax credits for the purchase of crushing equipment that will be used to produce recycled aggregates was identified by those interviewed as potentially the biggest incentive to aggregate producers interested in manufacturing recycled aggregate.

- Create demand from project owners

Tax credits or other incentives for the use of recycled aggregates would encourage project owners to select recycled aggregates over virgin materials at their project site.

- Create more stationary/permanent crushers

While many companies have invested in mobile crushers, the stationary units can be better tuned to produce consistently graded material that would be preferable for production of concrete.

5.4.2Concrete Producers

- Explore potential products

Concrete producers may feel most comfortable with routine use of recycled aggregates if mixtures were designed for specific lower strength uses such as footings. Producers interviewed expressed comfort with mixes containing up to 50% replacement of virgin aggregates with RA as long as material finer than 9.5 mm is removed.

- Consolidate operations

Due to greater industry consolidation, some aggregate producers also operate concrete batching plants. If a single facility could receive and crush demolition waste, quarry virgin aggregates, and batch concrete, it would be possible to tailor mix materials that contain appropriate quantities of recycled aggregates.

- Engineers submit their own quality control plan

In order for recycled aggregates to be used in concrete on niche projects, it may be necessary for engineers to provide more specific specifications regarding source material and handling, prequalification tests for mixes, and additional testing requirements.

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