5-1-2014

Influence of limestone powder content and size on transport properties of self-consolidating concrete

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Repository Citation
Spitek, Rebecca Kendal, "Influence of limestone powder content and size on transport properties of self-consolidating concrete" (2014). *UNLV Theses, Dissertations, Professional Papers, and Capstones*. 2149.
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INFLUENCE OF LIMESTONE POWDER CONTENT AND SIZE ON TRANSPORT PROPERTIES OF SELF-CONSOLIDATING CONCRETE

by

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Bachelor of Science in Civil Engineering
University of Nevada, Reno
2011

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Engineering-Civil Engineering

Department of Civil and Environmental Engineering and Construction
Howard R. Hughes College of Engineering
The Graduate College

University of Nevada, Las Vegas
May 2014

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

THE GRADUATE COLLEGE

We recommend the thesis prepared under our supervision by

Rebecca Spitek

entitled

Influence of Limestone Powder Content and Size on Transport Properties of Self-Consolidating Concrete

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Engineering -- Civil and Environmental Engineering
Department of Civil and Environmental Engineering and Construction

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May 2014

ABSTRACT

Influence of Limestone Powder Content and Size on Transport Properties of Self-Consolidating Concrete

by

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Self-consolidating concrete (SCC) requires higher cementitious materials content than conventional vibratory-placed concrete. This requirement leads to higher time-dependent properties (i.e., shrinkage (drying and autogeneous) and creep), increases formwork pressure, and results in a higher production cost. One alternative to alleviate excess creep and shrinkage, and to reduce cost, is to replace a portion of cementitious materials with mineral additives. The objective of this study was to examine the role of limestone powder, as a partial replacement of cementitious materials, on transport properties of self-consolidating concrete (SCC). A total of 10 different SCCs, including a control concrete, was prepared and test specimens were cured for 28 and 90 days. A constant powder content of 475 kg/m^3(800 lb/yd^3), constant coarse-to-fine aggregate ratio of 0.43, and uniform water-to-cementitious materials ratio of 0.45 were used. A high-range water reducing admixture was utilized and its dosage varied in order to achieve uniform target flow properties. The target flow properties were: slump flow of 625 mm ±

25mm (25 inches ± 1 inch), a visual stability index of 0 (highly stable) to 1 (stable), and J-Ring less than 50 mm (2 inches). The flow properties examined were slump flow, visual stability index (VSI), T_{50} flow time, and J-Ring. The evaluation of bulk properties included compressive strength and demolded unit weight. The transport properties of the studied SCCs consisted of absorption, capillary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion.

For the first part of the study, limestone powder with an average size gradation of 8 microns, designated as L8, replaced a portion of cementitious materials (Portland cement and fly ash) at the levels of 5, 10, 15, 20, 25, and 30% by weight. It was found that the inclusion of L8 type limestone powder improved absorption, water penetration, capillary absorption, and rapid chloride penetration of the studied SCCs, in comparison with those of the control SCC, for both curing ages. While chloride diffusion and rapid migration coefficients did not improve at 28-day curing as compared to those obtained for the control SCC, a longer curing age (i.e. 90 days) provided for marginal (5%) to sizeable (30%) improvements in chloride diffusion and rapid migration coefficients, respectively. Improvements with each increasing 5% increment of limestone powder replacing a portion of cementitious materials were observed for rapid chloride penetration, capillary absorption, and absorption at 28- and 90-day curing. The 28-day cured limestone powder contained SCCs produced water penetration depths, rapid migration coefficients, and chloride diffusion coefficients which remained unaffected with increases in limestone powder content. All transport properties of the studied SCCs improved with increasing curing age from 28 to 90 days.

For the second part of the study, limestone powder, designated as L3, which had an average particle size of 3 microns, was used to substitute a portion of cementitious materials at the levels of 10, 15, and 20% by weight. It was observed that the finer limestone powder contained SCCs generally improved absorption, water penetration, rapid chloride penetration, and rapid migration as compared to those obtained for the coarser limestone powder contained SCCs. When higher limestone powder content (i.e., 20% by weight of cementitious materials) and longer curing age (i.e., 90 days) were used, the two limestone powder types had similar water penetration, rapid chloride penetration, and rapid migration results. Moreover, when 3 micron size limestone powder was used, with the exception of absorption test results, the remaining transport properties of the studied SCCs improved with an increase of curing age from 28 to 90 days.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my academic advisor, Dr. Nader Ghafoori, for his patience, guidance, suggestions, and assistance throughout this investigation. Because of his dedication, this master's thesis and milestone in my life were achieved. I would also extend my gratitude towards my examination committee members, Dr. Samaan Ladkany, Dr. Mohamed Kaseko, and Samir Moujaes for their assistance and guidance.

I would also like to thank Mr. Peter Faught and Mr. Jon Becker for providing technical support and limitless assistance throughout the duration of the experimental program. I wish to extend my appreciation to my teammates, Mr. Borhan Moradi and Mr. Meysam Najimi, for their guidance and assistance.

Finally, but not least, I wish to extend my eternal gratitude to my fiancé Matthew Diggins, my mother Barbara Spitek, my aunt Sandra Gajkowski, and all my family and friends. Without their support and love, I would not have been able to accomplish this life achievement.

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CHAPTER 1

INTRODUCTION

The purpose of this chapter is to introduce the thesis's objective and scope, to present background information on the topic, and to examine present relevant literature.

1.1 Introduction

Self-consolidating concrete (SCC) is a recently developed concrete that easily flows under its own weight and requires little or no mechanical vibration to consolidate. It is particularly beneficial in the areas where heavy and closely-spaced reinforcements are needed. SCC differs from traditional concrete in that SCC requires a balance between the concrete's flow and cohesion, in order to prevent segregation or bleeding, enabling it to fill the form work easily. The balance is achieved by a relatively low yield value that guarantees high flow ability and a moderate viscosity that prevents segregation and bleeding. The concrete's moderate viscosity allows for homogeneity during transportation, placing, and curing, and to uphold the structural integrity and durability of the concrete.

SCC offers several advantages when compared with vibratory-placed concrete including higher flow ability; lesser screeding and better self-leveling; shorter construction period; lower labor costs; higher construction quality and productivity; and a better work environment through construction site noise reduction. On the other hand, unlike vibratory-placed concrete, SCC's specific rheological characteristics to produce proper consolidation require a higher paste volume. As such, self-consolidating concrete is susceptible to more drying and autogenous shrinkage and creep due to its high cementitious materials content. SCC also induces additional formwork pressure when compared to traditional concrete. The need for a higher cementitious materials content and consideration for extra formwork pressure result in a higher production cost of SCC for which it can be mostly compensated with elimination of densification effort.

A possible solution to SCC's higher cost is to substitute a portion of Portland cement with mineral admixtures. Mineral admixtures are finely graded minerals added to concrete to enhance its workability or hardened durability properties (American Concrete Pavement Association 2013). These mineral admixtures are classified as nominally inert materials, pozzolanic materials, cementitious materials, or a combination of pozzolanic/cementitious (American Concrete Pavement Association 2013). These mineral admixtures have the ability to improve concrete's pore structure through physical and/or chemical means, resulting in improved transport properties and long-term durability of concrete (Chan et. al. 1999)

The primary objective of this research study is to examine transport properties of self-consolidating concretes containing different dosages of limestone powder as a partial replacement of cementitious materials. The influence of limestone powder size gradations on transport properties of SCC is also investigated. Past research and relevant literature examining the effect of inert mineral fillers on fresh, mechanical, and transport properties of self-consolidating concretes are also presented. The significance of this study and results of the experimental program for the studied limestone contained self-consolidating concretes are discussed in details.

1.2 History of Self-Consolidating Concrete

In the 1980's, Japan reduced the number of skilled workers in their construction industry which adversely affected concrete construction, producing many under and over consolidated structures. Two disadvantages of under-consolidation are an increase of entrapped air and surface flaws, resulting in reduction of concrete strength. The defects caused by excessive vibration are segregation, external and internal bleeding, and the damage of the air void system which affects strength and durability (ACI 2007).

Okamura, a Japanese professor, proposed a solution to this challenge with the idea of durable concrete structures independent of the quality of the construction work. The idea assumed a concrete compacted into every angle of the formwork under its own weight without requiring mechanical vibrating compaction. After its development and rapid spread in Japan, Europe began to frequently use self-consolidating concrete (ACI 2007). Self-consolidating concrete has become greatly considered for precast/prestressed implementation in the United States. State departments of transportation have also become more active in research regarding SCC (Vachon 2002).

1.3 Characterization of Self-Consolidating Concrete Mixtures

Self-consolidating concrete is characterized by its fresh and hardened properties. Concrete fresh properties are defined by the workability of the SCC which varies for different applications. The workability can further be classified by specific field requirements and rheological properties. They are discussed in Section 1.3.1. The mechanical properties, also referred to as hardened properties, incorporate many factors which are discussed in more details in Section 1.3.2. Transport properties, categorized as mechanical concrete properties, are discussed in Section 1.3.2.2.

1.3.1 Fresh Properties

EFNARC, the European federation of national trade association representing producers and applicators of specialist building products, established three properties to describe the workability of SCC as the passing ability, filling ability, and segregation resistance. The passing ability of SCC is the capability of SCC to flow through restricted sections, such as the narrow clear spacing of reinforcement in congested areas. Tests to measure passing ability are the concrete acceptance test, filling vessel test, J-Ring, L-box, and U-box tests (EFNARC 2002).

Filling ability is concrete's capacity to flow under its own weight and entirely fill reinforced formwork. Empirical tests that measure the filling ability are L-box, U-box test, slump flow test including T_{50} and VSI, and the V-funnel test. The last workability description is segregation resistance and is the concrete's ability to maintain a homogenous composition during placing and curing. Tests to evaluate segregation resistance are column segregation test, electrical conductivity test, penetration tests, segregation test, settlement column segregation test, surface settlement test, and sieve stability test (EFNARC 2002).

Rheology is the scientific investigation of the flow and deformation of a material (Koehler 2004). It is implemented to describe SCC flow properties and considers freshly-mixed concrete as a fluid (Ferraris 1999). The difference between the solid behavior and fluid behavior under stress is that a solid undergoes a recoverable deformation while a fluid is constantly under shear stress and is unrecoverable from the deformation impacted to the fluid. The relationship between the shear stress and shear rate is used to characterize the flow properties of a concrete fluid (Hackley and Ferraris 2001).

The Bingham model is the most commonly employed method to demonstrate the relationship between shear stress and shear rate. For the majority of cases, it accurately characterizes the concrete flow. It is simple and only requires the calculation of two factors; the yield stress and plastic viscosity. The yield stress is the required amount of stress to start or support flow. The plastic viscosity is the opposition to flow and occurs once the yield stress has been surpassed. The Bingham model is demonstrated below:

$$\tau = \tau_0 + \mu\gamma \qquad \text{(Eq. 1.1)}$$

where τ is the shear stress, γ is the shear rate, τ_0 is the yield stress, and μ is the plastic viscosity. The evident viscosity is equivalent to the shear stress divided by the shear rate. The shear rate increasing will cause the viscosity of the concrete to decrease (Ferraris 1999).

1.3.2 Hardened Properties

The difference between the hardened properties of traditional concrete and those of SCC can be attributed to three reasons; an altered mixture proportions, better microstructure and conformity, and absence of vibration. The altered mixture proportions may incorporate greater paste volume, higher powder contents, reduced water to cementitious and powder ratios, and lower coarse aggregate volume. The smaller maximum size aggregate and the implementation of chemical and mineral admixtures also affect the hardened properties differently than regular concrete. The microstructure is improved due to the higher packing density of the paste (Klug and Holschemacher 2003). The lower water-to-cementitious material ratio may, but not always, lead to equal or better hardened properties (EFNARC 2002). Hardened properties include the microstructure, strength, stiffness, dimensional stability, transport properties, and durability (Koehler and Fowler 2007).

SCC microstructure is frequently better than traditional concrete. The enhanced microstructure is due to the higher packing density of the paste and the decrease in the size and porosity of the interfacial transition zone. Improvement in the microstructure is also attributed to the low water-to-powder ratios and the use of HRWR (high-range water reducer (superplasticizer)) which effectively diffuses the cement (Koehler and Fowler 2007).

SCC in general should have a higher compressive strength due the absence of vibration. This absence of vibration leads to a stronger bond between the paste and aggregate (EFNARC 2002). The use of mineral fillers can increase the early strength development while secondary cementitious materials can enhance the ultimate strength (Klug and Holschemacher 2003). The flexural strength and tensile strength of SCC also tends to be higher than conventional concrete due to the improved microstructure (Klug and Holshemacher 2003). SCC generally has equal or slightly less moduli of elasticity than traditional concrete because of better paste content and decreased maximum aggregate size (EFNARC 2002).

SCC dimensional stability includes the autogeneous and drying shrinkage. Autogeneous shrinkage decreases with higher water-to-cement ratios, and incorporation of inert mineral fillers such as limestone powder can also decrease the autogeneous shrinkage (Roziere 2005). The autogeneous shrinkage is typically higher for SCC than traditional concrete due to its high cementitious materials content (Tucry and Loukili

2003; Suksawang et. al. 2005). Drying shrinkage is increased by higher paste volumes and higher water content (Kosmatka 2002). SCC will typically have higher drying shrinkage than conventional concrete due to higher paste volumes (EFNARC 2002).

1.3.2.1 Transport Properties

Transport properties in concrete are developed by excess water in the concrete during the hardening process. Once the cement expends the water it requires to hydrate and harden, the excess water escapes and leaves behind a system of thin capillaries and internal pores. These capillaries and pores allow substances such as gases, liquids, and ions to penetrate into the concrete which, with the presence of chloride or sulfate, can be hazardous to concrete's structural integrity. Chloride is potentially hazardous due to its corrosive impact on the reinforcement steel of concrete. Other ingresses may cause durability related issues such as sulfate attack and alkali silica reactivity. Transport properties are a suitable index of concrete's durability as both consider the penetration of hazardous substances into concrete (Basheer 2001).

The transport properties are defined by pore structures of the paste and the paste volume (Zhu 2001). Permeability and diffusivity is associated with the entire porosity and the size and stability of the voids in the concrete. The cement paste's binding capacity is defined by diffusivity. To reduce permeability and diffusivity in concrete, a reduction in volumes, sizes, and connection of pores is required. A reduction in pore characteristics can be achieved by selection appropriate aggregates or paste properties which improves the transition zone of the concrete. Reducing the water-to-cementitious materials or reducing the water content can lead to an improved pore formation. The pore structure is further enhanced by adequately curing the concrete and using supplementary cementitious material. Supplementary cementitious material improves the pore structure with better pore structure packing which leads to less connectivity between the pores (Koehler and Fowler 2007).

With an increase in hydration, there is a decrease in permeability and diffusivity. When concrete specimens are cured in higher temperatures, the hydration may accelerate which produces a rougher structure. This rougher structure leads to higher long term permeability (Koehler and Fowler 2007). The paste has been found to not be the main cause of permeability in well-cured concrete. The only reason the paste could contribute to permeability is if it has a water to cement ratio greater than 0.7. This signifies the transition zone is more influential in regards to permeability (Mehta and Monteiro 1993). Cements with higher contents of C_3A and the incorporation of supplementary cementitious material assist in binding the ions to the paste (Mehta and Monteiro 1993). SCC diffusivity and chloride permeability may be greater or lesser than traditional concrete and is highly dependent on the mixture proportions of the SCC in question (Koehler and Fowler 2007). The use of secondary cementitious materials and lower water-to-cementitious materials ratio may improve the permeability and diffusivity of self-consolidating concrete (Koehler and Fowler 2007).

Transport mechanisms into concrete include diffusion, absorption, and permeability (Basheer et. al. 2001). Diffusion relates to how substances such as ions move through the concrete from higher concentration to lower concentration areas , meaning, when the chloride concentration on concrete’s outside is greater than the inside of concrete, the chloride ions will migrate into the concrete towards the lower chloride concentration (Hamilton et. al. 2007). Diffusions tests are categorized as gas diffusion, water vapor diffusion, and ionic diffusion test (Bashher et. al. 2001). Water absorption is the migration of liquid into the pore structure of concrete due to surface tension in the capillaries of concrete. The two methods of water absorption are the effective porosity, the mass of water which will fully saturate the specimen, and sorptivity, the rate infiltration of the capillary rise (Bashher et. al. 2001). The mechanism of permeability relates to the transport of liquid due to hydraulic pressure on one side concrete forcing the liquid through the concrete medium (Hamilton et. al. 2007).

1.4 Materials

1.4.1 Portland Cement

The use of cement dates back to 7000 BC in Israel where lime concrete was used to build a floor (Auburn University 2000; Brown 1996). Cement was also used to construct the Great Pyramid of Giza around 2500 BC. The use of cement continued through the Greek and Roman empires and into the 1800's. It was not until 1824 when Joseph Aspdin obtained a patent for Portland cement and proposed a formula for his product. He named it Portland cement due to the color of the set concrete resembling limestone quarries on the Isle of Portland in the English Channel. The first documented shipment of Portland cement to the United States was in 1868 and the first recorded manufacturing of Portland cement was in 1871 in Pennsylvania (Kosmatka et. al. 2002).

Portland cement is hydraulic cement consisting mostly of hydraulic calcium silicates. Hydraulic cements react chemically with water, and the cement then sets and hardens. This chemical reaction is called hydration. When the cement mixes with the water, paste is formed. When aggregates, which consist of sand and gravel of granular material, are included in the paste, concrete is formed. The paste acts as glue and joins the aggregates together (Kosmatka et. al. 2002).

The hydration process results from cement particles developing a fibrous growth on its exterior as soon as the cement particle comes into contact with water. The fibrous growth of one cement particle continues to enlarge until it connects with another cement particle's growth. The interaction between all cement particle's fibrous growth continues while simultaneously stiffening, hardening, and strength occur. Concrete's workability is lost when stiffening begins to occur. Stiffening is dependent on many factors including the cement composition, cement fineness, admixtures used, mixture proportions, and temperature settings (Kosmatka et. al. 2002).

Curing concrete ensures hydration can last longer which increases the strength and hardness of the concrete. Curing consists of ensuring satisfactory moisture conditions and temperature settings while the concrete hardens. Strength development occurs during the first month of curing (Kosmatka et. al. 2002).

The manufacturing of Portland cement consists of grinding material consisting primarily of hydraulic calcium silicates called clinkers. Other substances that can be present in clinkers are calcium aluminates, calcium aluminoferrites, and calcium sulfate. The cement's chemical composition is selected before manufacturing begins. The materials selected to ensure this chemical composition are blended by either a wet or dry process. After blending, the material is processed through a kiln where it forms the clinker. The clinker is then ground to produce Portland cement (Kosmatka et. al. 2002).

Different variations of Portland cement exist to perform certain purposes. Each of the variations is manufactured and has distinct chemical and physical properties. All

Portland cements are required to meet the specifications stated by ASTM C 150, AASHTO M 85, or ASTM C 1157. The ASTM C 150 uses Roman numerals to designate the cement and includes Type I to Type V. AASHTO M 85 also uses Roman numerals Type I to Type V. The two specifications are almost identical. The ASTM C 150 designation types are shown in Table 1.1. (Kosmatka 2002)

Table 1.1: ASTM C 150 Types of Cement (Kosmatka et. al. 2002)

ASTM C 150 Designation	Description
Type I	Normal
Type IA	Normal, air-entraining
Type II	Moderate sulfate resistance
Type IIA	Moderate sulfate resistance, air-entraining
Type III	High early strength
Type IIIA	High early strength, air-entraining
Type IV	Low heat of hydration
Type V	High sulfate resistance

The chemical composition for each type of Portland cement differs. Also, even within the same type, different manufacturing plants may use different chemical compositions than others. The potential chemical compositions averages for each type of cement are shown in Table 1.2 (Kosmatka et. al. 2002).

Table 1.2: Chemical Composition of Cement by Type (Kosmatka et. al. 2002)

Chemical Composition	Type I	Type II	Type III	Type IV	Type V
SiO_2	20.5	21.2	20.6	22.2	21.9
Al_2O_3	5.4	4.6	4.9	4.6	3.9
Fe_2O_3	2.6	3.5	2.8	5	4.2
CaO	63.9	63.8	63.4	62.5	63.8
MgO	2.1	2.1	2.2	1.9	2.2
SO_3	3	2.1	3.5	2.2	2.3

The physical properties of Portland cement discussed in this section are the particle size, fineness, density, and relative density. In regards to the particle size of Portland cement, approximately 95% are smaller than 45 micrometers with an average size of 15 micrometers. Portland cement's fineness refers to the overall particle size distribution. This aspect affects the rate of hydration and heat released. It is found that the strength development can be increased by the use of greater cement fineness, or smaller particle size of the cement. Fineness can be measured by the Blaine air-permeability test. The particle density and relative density (specific gravity) of Portland cement averages 3.15 Mg/m^3 and 3.15 respectively (Kosmatka et. al. 2002).

When using Portland cement in self-consolidating concrete, it is recommended by Grace Construction Products to use cements that conform to ASTM C150, C595, C845, or C1157. The type of cement used may drastically affect the self-consolidating properties, and therefore it is recommended that testing be performed on SCC specimens before any production for worksites be performed (W.R. Grace & Co.-Conn 2005)).

1.4.2 Aggregates

In conventional concrete mixes, the fine and coarse aggregates occupy 60 to 70 % of the total concrete volume (Kosmatka et. al. 2002). In self-consolidating concrete, the coarse aggregate volume is typically in the range of 28% to 32% (W.R. Grace & Co.-Conn 2005). An initial fine-to-coarse aggregate ratio of 0.50 is recommended by Grace Construction with adjustments made to achieve workability. The coarse and fine aggregates selection, as well as the separate and combined gradation greatly impacts the performance of the SCC (W.R. Grace & Co.-Conn 2005).

Aggregate gradation is defined by the particle size distribution. This distribution is evaluated by a sieve analysis where square openings of wire-mesh sieves determine the aggregate particle size (Kosmatka et. al. 2002). The coarse and fine aggregate gradations are explained in the following sections.

1.4.2.1 Coarse Aggregates

Coarse aggregates are composed of crushed stone or gravel. The particles are normally larger than 5 mm and are between 9.5 mm and 37.5 mm. Coarse aggregate gradation uses 13 standard sieves for the sieve analysis and opening sizes range from 1.18 mm to 100 mm. A large amount of variety is allowed for the grading and grading sizes of coarse aggregates. This variety in coarse aggregate gradation affects the mix's water requirement and workability. Since these variations are hard to predict, gradations with uniformity between the sieves are usually incorporated rather than adjusting variations (Kosmatka et. al. 2002).

The maximum size aggregate is the sieve number in which a hundred percent of the coarse aggregate content must pass. The maximum size is reliant on the shape and size of the concrete member as well as the reinforcement clear spacing. The recommended requirements for determining the maximum size is that the size should not surpass either one-fifth the narrowest dimension of the concrete member, three-quarters of the clear spacing of reinforcing bars, and one third the slab depth. The nominal maximum size of the coarse aggregate is the sieve size where the greater part of the coarse aggregate passes. The retained value on this sieve normally ranges from 5 to 15 % (Kosmatka et. al. 2002).

When using coarse aggregates in self-consolidating concrete, the maximum size is selected in regards to its passing ability and stability of the SCC. Standard nominal maximum sizes used in SCC are 19 mm, but can extend to 25mm. Grace Construction Products recommends not using coarse aggregates with a nominal maximum size larger than 25 mm in SCC (W.R. Grace & Co.-Conn 2005). The use of larger sizes will create sensitivity to blocking and will require higher powder content or higher use of a viscosity modifying agent than normally required (W.R. Grace & Co.-Conn 2005).

Coarse aggregates should also be selected to achieve lower water demands provide adequate stability. The selection can be based off a void content, where a lower void content is desirable due to less mortar required to occupy the voids. Well-rounded aggregates will provide a better void content. This will provided lower mortar and lower powder content which will enhance the stability of the SCC. Angular and crushed aggregate can also produce quality SCC, but will require more powder or VMA to achieve flowability requirements (W.R. Grace & Co.-Conn 2005)

1.4.2.2 Fine Aggregates

Fine aggregates used in SCC should meet the requirements of ASTM C 33 or AASHTO M 6/M 43. The grading limits for ASTM C 33 are shown in Table 1.3 (Kosmatka et. al. 2002).

Table 1.3: Grading Limits for ASTM C 33 (Kosmatka et. al. 2002)

Sieve Size	Percent passing by mass
9.5 mm (3/8 in)	100
4.75 mm (No.4)	95 to 100
2.36 mm (No. 8)	80 to 100
1.18 mm (No. 16)	50 to 85
600 µm (No. 30)	25 to 60
300 µm (No.50)	5 to 30
150 µm (No. 100)	0 to 10

The requirements set forth by ASTM C 33 are that the fine aggregate cannot have more than 45% retained on any two consecutive sieves. Also the fineness modulus must not be less than 2.3 but not greater than 3.1. The fineness modulus cannot vary more than 0.2 from the value of the aggregate source. The material passing the 300 µm and 150 µm is vital to the mix because it improves the workability, surface texture, air content, and bleeding of the concrete. Typically values of 5 to 30% are allowed to pass 300 µm (Kosmatka et. al. 2002).

The fineness modulus is the cumulative percentage by mass retained on each of a stipulated sequence of sieves and divided by 100. The designated sieves for the fineness modulus are 150 µm, 300 µm, 600 µm, 1.18 mm, 2.36 mm, 4.75 mm, 9.5 mm, 19.0 mm, 37.5, 75 mm, and 150 mm. When the value of the fineness modulus is higher, the fine aggregate is much coarser. The fineness modulus is helpful in determining fine and coarse aggregate proportions of concrete **(**Kosmatka et. al. 2002).

1.4.2.3 Combined Aggregate Gradation

Combined aggregate gradation is beneficial to analyze how aggregates will function in a concrete mixture. Combined gradation can be implemented to regulate pumpability, workability, shrinkage, and other properties. Shilstone(1990) and Abrams (1918) validated the advantages of using combined aggregate gradation. It was proven that an optimum aggregate combination exists for constant cement content and consistency and provides the most efficient water-to-cement ratio which will produce a higher strength. This optimum combination also has the least particle obstruction (Kosmatka et. al. 2002).

Shilstone (1990) used a coarseness factor and workability factor to quantify combined aggregate gradation. Three fractions of gradation were established; coarse, intermediate, and fine. Coarse fraction, designated as Q, is all material retained on the 9.5 mm sieve. Intermediate fraction, I, is all material passing the 9.5 mm sieve but retained on the 2.36 mm sieve. The last fraction is the fine, W, and is the all material passing 2.36 mm sieve but retained on the 75 µm sieve (Shilstone 1990).

The coarseness factor is calculated as (Q / Q + I) x 100, or as the percent retained above the 9.5 mm sieve divided by the percent retained above the 2.36 mm sieve multiplied by 100. The workability factor is the percent passing the 2.36 mm sieve. A concrete mix design optimum aggregate relationship graph was composed that plotted the workability factor versus the coarseness factor as shown in Figure 1.1. A trend bar across the graph designates a reference for the mixture gradations. Above the trend is denoted as sandy and below is rocky (Shilstone 1990). The numeric sections shown in Figure 1.1 each represent a zone, and describe the chosen gradation/mixture which lies in the zone. Zone I has a mixture that will tend to segregate and is described as gap-graded and coarse. Zone II is ideal for daily applications and categorized as well-graded. The remaining zones are III, IV, and V and are designated as finer, over-sanded, and rocky respectively (Shilstone and Shilstone Jr. 1999). Grace Construction Products recommends that for successful SCC mixes, the workability factor should be greater than 40 and the coarse factor should be less than 40 (W.R. Grace & Co.-Conn 2005).

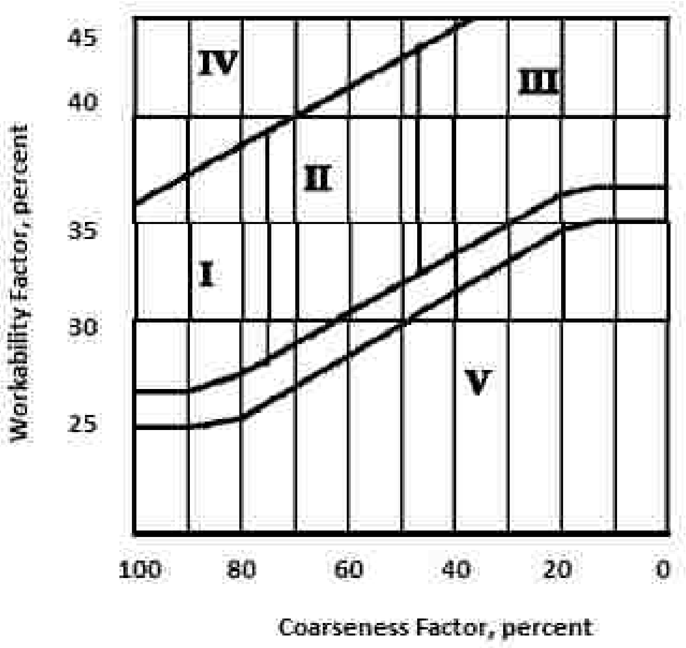

Figure 1.1: Shilstone Combined Aggregate Gradation Chart (FHWA 2005)

1.4.3 Admixtures

Admixtures are ingredients added to concrete other than Portland cement, water, and aggregates. The functions of concrete's admixtures can be classified as the following; air-entraining, water reducing, plasticizer, accelerating, retarding, hydration-control, corrosion inhibitors, coloring, and miscellaneous. The concrete's performance should be obtained firstly by the selection and proportioning of materials. Admixtures should be added when the desired performance cannot be obtained by selection or proportioning (Kosmatka et. al. 2002).

The principal motives to include admixtures in the concrete mixture are to lessen the concrete's construction cost, obtain certain properties in concrete more efficiently, sustain the quality during the processes of mixing, transporting, placing and curing in different weather conditions, and avoid dangers during concrete operations. The admixtures' efficiency depends largely on cement content; water content; aggregate shape and gradation; mixture proportion; mixing time; slump; and the concrete's temperature. Admixtures are classified as chemical or mineral (Kosmatka et. al. 2002).

1.4.3.1 Chemical Admixtures

According to the American Concrete Institute (ACI), a chemical admixture is a material added to the concrete mixture generally in proportion by mass to the cement or cementitious materials. These admixtures then react either chemically or physically with the hydrating cement. This will enhance one or more properties of the concrete in the fresh or hardened state. There are many varieties of chemical admixtures that can improve many different aspects of concrete design (American Concrete Educational Bullentin 2003). Typical chemical admixtures used in self-consolidating concrete are high range water reducing admixtures (HRWRA) and viscosity modifying admixture (VMA) (W.R. Grace & Co.-Conn 2005). Other chemical admixtures such as air-entrainers can be used as well, but this research will focus on the possible incorporation of these two admixtures.

1.4.3.1.1 High-Range Water Reducing Admixtures (HRWRA)

High-range water reducers create the same effect as regular water reducers in concrete but more effectively and potently. The admixtures reduce the water demand and the cement content. They also lower the water-to-cement ratio and produce higher strength and durability for concrete. The workability of the concrete is also improved by the incorporation of high range water reducers (Kosmatka et. al. 2002).

A sufficiently reduced water content provided by HRWRA creates concretes that can have an ultimate compressive strength in excess of 70 MPa, increased early strength gain, and reduced chloride-ion penetration. Also a reduction in bleeding is associated with the use of HRWRA. Disadvantages of using HRWRAs include larger entrained air voids and higher void-spacing factors. These factors will reduce the resistance to freezing and thawing than normal concrete. Plasticizers and superplasticizers are chemical admixtures that use the same chemicals as HRWRA but are used to make flowing concrete (Kosmatka et. al. 2002). Since SCC is mostly defined by its highly flowable nature, the incorporation of an HRWRA is generally required (W.R. Grace & Co.-Conn 2005).

1.4.3.1.2 Viscosity Modifying Admixtures (VMA)

Viscosity Modifying Admixtures (VMA) is a chemical admixture that target improving the rheology of the concrete mix. VMAs are also known as Viscosity Enhancing Admixtures (VEA), Stabilizers, and Water Retaining Admixtures. As noted before, the rheology is defined in terms of yield point and plastic viscosity. The yield point is the force required to make the concrete flow. The plastic viscosity refers to concrete’s resistance to flow acted on by any external stress. VMAs increase the plastic viscosity while only causing a small increase in the yield point (EFNARC 2006).

VMAs assist in the design of self-consolidating concrete by reducing the segregation of materials and reducing the powder content. The main objective of VMA is to make the SCC mix more tolerant to variations in water content, without adversely affecting the plastic viscosity. There are three types of self-compacting concrete in regards to enhancing the overall viscosity. The first type is the powder type which uses large amounts of powder to prevent segregation and maintain rheology. The second utilizes a VMA with lower powder content. The third type is a combination of the two, and uses moderate powder content with the use of a VMA. All three types control the yield point with the use of a superplasticizer (EFNARC 2006).

1.4.3.2 Mineral Admixtures

Mineral admixtures are the finely graded material added to the mixture to attain particular engineering characteristics of cement mortar and concrete. Other advantages of using mineral admixtures in concrete are economic benefits by replacing a portion of cement and by reduction of environmentally hazards associated with their disposal. Such cases are in the production of marble, where the powder left behind have no other function and are difficult to dispose of (Uysal and Yimaz 2011). Mineral admixtures are used as replacements of cement or fine aggregates in concrete, whereas chemical admixtures are used in addition to either and are used as needed to improve the desired property. Mineral admixtures can either be considered supplementary cementitious material or inert filler (material of low or no reactivity) (ACPA 2013).

1.4.3.2.1 Supplementary Cementitious Material

Supplementary cementitious material is either pozzolanic or latent hydraulic powder can provide extra workability, increased strength, and lessen the permeability of the SCC (W.R. Grace & Co.-Conn 2005). This material is added to the concrete as an amount of the total cementitious system. It is used as replacement for Portland cement depending on the required properties of the concrete (Kosmatka et. al. 2002).

Fly ash is used generally as a supplementary cementitious material. It is the by-product of the combustion of coal in electric power generating plants. Fly ash particle sizes can differ from 1 μm to greater than 100 μm. The average particle size is under 20 μm. The surface area of a fly ash particle is usually around 300 to 500 m^2/kg. The bulk density and closed pack storage density vary from 540 to 860 kg/m^3 and 1120 to 1500 kg/m^3 respectively. Coal combustion fly ash is divided into two classes by ASTM C 618. These two classes are Class F and Class C. Class F typically has low-calcium content and carbon contents less than 5%. Class C fly ash has high-calcium content between (10% and 30% CaO) with carbon contents less than 2%. Class F fly ash can replace the cementitious material by mass at dosages of generally 15 to 25%, while Class C fly ash can replace larger portions of the cement at 15 to 40%. The dosages will vary due to the reactivity of the fly ash and the required properties of the concrete (Kosmatka et. al. 2002). For the purpose of this study, class F fly ash was utilized throughout this research.

1.4.3.2.2 Limestone Powder

Inert powder is defined by W.R. Grace & Co.-Conn (2005) as limestone, dolomite, or granite dust finer than 0.150 (No.100) sieve. The addition of mineral fillers improves the total powder content's (cement and mineral fillers) packing density, and reduces segregation, bleeding, hydration heat, thermal shrinking, and improves cohesion (W.R. Grace & Co.-Conn 2005). Additionally, mineral fillers are also generally less expensive than Portland cement. This provides an economically beneficial alternative to regular self-consolidating concrete mixes and decreases environmental pollution due to the utilization of by-products and waste materials (Uysal and Yimaz 2011).

Limestone powder, which was used in the research study, is used commonly in regions of Europe as mineral filler but has not been as greatly incorporated in the United States' concrete production (Tsivillis et. al. 1999). Limestone powder's particle size distribution and fineness vary by source and are dependent on the grinding methods used. The powder is composed principally of calcium carbonate (Zhu and Bartos 2003). The economy of SCC can be improved by replacing the cement levels of up to 50 percent. This is achieved by reducing the Portland cement and HRWRA amount (Ghezal and Khayat 2002). The water demand and superplasticizer demand is also reduced due to the improved workability with the addition of limestone powder because of its enhanced particle size distribution (Nehdi et.al. 1998). The static stability and a reduction in bleeding can occur with the addition of limestone powder (Ghezal and Khayat 2002).

The rheological properties are also affected by the addition of limestone powder. The yield stress and plastic viscosity can both decrease with the increase of limestone powder (Ghezal and Khayat 2002). There is a critical amount of limestone powder that can be added where the limestone powder addition will increase the concrete's viscosity considerably. The critical amount is associated with the available space in the mix, and when the critical amount is surpassed the particle size distribution is not enhanced and instead increases the inter-particle friction (Yahia et. al. 2005). The transport properties in the interfacial transition zone are improved by increasing paste density from the addition of limestone powder. The concrete's strength may also be improved with the enhanced workability attributed by the addition of limestone powder. This enhanced workability allows for a decrease in the water amount which may improve the overall strength of the concrete (Ghezal and Khayat 2002).

Limestone powder, considered mostly as a low-reactivity mineral admixture, may affect self-consolidating concrete in four ways (De Schutter 2011). The first is through physical means where the limestone powder acts as nucleation sites for hydration products, especially the C_3S phase, which leads to accelerated cement hydration (De Weerdt et. al. 2010). The limestone powder also acts as filler between cement's coarser particles due to limestone powder's smaller particle size which can optimize the packing density and lead to improved SCC mechanical and transport properties (De Schutter 2011). Due to limestone powder's mostly inactive role in hydration, it provides a dilution effect which allows most of the water to be used for cement hydration (De Schutter 2011). Lastly, though for the most part chemically inert, limestone powder does have the potential to slightly modify SCC's hydration phases (De Schutter 2011). Bonavetti et. al. found limestone powder altered Portland cement's hydration due to the formation of the compound mono-carboaluminate, which is related to cement's C_3A phase (Bonavetti et. al. 2001). Mono or hemi-carboaluminate is formed, along with additional ettringite, due to the transformation of the monosulphoaluminate hydrate when small amounts of limestone powder are present. The addition of mono or hemi-carboaluminate and extra ettringites may lead to a slight increase in hydration products volume (Hiaro et. al 2007; Lothenbach et. al 2008; Matschei et. al. 2007). The increase in hydration products volume may in turn increase concrete's strength and decrease its permeability (De Weerdt et. al. 2010).

1.5 Mixture Proportions

The mixture proportion for self-consolidating concrete differs significantly from traditional concrete. SCC Mixture proportions are greatly defined by the fresh properties requirements. The hardened properties may be either improved or reduced depending on the mixture proportion used. In general, SCC mixes will have higher powder contents, lower water-to-cementitious material ratio, lower coarse aggregate content, and the use of secondary cementitious material (ACI 2007). Two organizations that have established a basis for SCC mixture proportions are ACI (2007) and EFNARC (2002). .

1.5.1 ACI Mixture Proportions

The mixture proportioning established by ACI was chosen on its ability to select aggregates that offer the required passing ability of SCC, cementitious materials-to-water ratio, and mortar/ paste fraction ratio previously confirmed to create SCC with the desired stability and slump flow. The steps provided by ACI are listed below (ACI 2007).

Step 1. Determine the slump flow performance

Step 2. Select the coarse aggregate and proportion

Step 3. Approximate the required cementitious materials and water content

Step 4. Calculate the paste and mortar volume.

Step 5. Select admixture

Step 6. Batch trial mixture

Step 7. Test the flowability requirements of SCC (filling ability, passing ability, segregation)

Step 8. Adjust the mixture proportions

The passing ability is the main concern when selecting aggregate nominal maximum size and the coarse aggregate content. The nominal maximum size should be selected based reinforcement clearing space, the aggregate surface texture, and the aggregate gradation. The coarse aggregate content selection is separated into two categories: Category I and Category II. Category I is defined as coarse aggregate with a nominal maximum size of ½ inch or greater. Category II is all coarse aggregate with nominal maximum size smaller than ½ inch. Category I should have an absolute volume of coarse aggregate compared to total volume of 28% to 32%. Category II should have an initial proportion of coarse-to-fine aggregates of 50 % to 50% (ACI 2007).

The powder content includes cement, ground granulated blast-furnace slag (GGBFS), fly ash, limestone powder, and any other powders crushed to 0.125mm or smaller. Suitable initial powder content is 385 to 475 kg/m^3 (650 to 800 lb/yd^3). Increasing the powder content, water content, or both may increase the slump flow and minimize segregation. Water-to-powder ratio may remain constant but the volume of powder and water will increase (ACI 2007).

ACI (2007) defines paste as the volume of cement, secondary cementitious material, mineral powder, water, air, and chemical admixtures. Mortar is the paste volume with the addition of fine aggregate which is all material passing the No. 8 sieve. The paste volume for SCC is typically in the range of 34 % to 40% of the total concrete volume. Mortar volume is generally 68 % to 72% of the total mixture volume (ACI 2007).

1.5.2 EFNARC Mixture Proportions

EFNARC (2002) recommends using proportions by volume rather than mass. The initial ranges for proportions are as follows; water-to-powder ratio by volume of 0.8 to 1.10, a total powder content of 160 to 240 liters, a coarse aggregate content of 28 to 35 percent by volume of the mix, a water content that does not exceed 200 liters/ m^3, and a sand content to account for the remainder of the total volume (EFNARC 2002).

These proportions are adjusted to meet the requirements for self-compactability. If the self-compactability requirements cannot be met from the specified proportioning, then the following can be implemented to achieve self-compactability; the use of additional or different filler, modifying the proportion of coarse aggregate-to-fine aggregate, using a VMA, adjusting chemical admixture dosage, using different chemical admixtures, or adjusting the water to powder ratio (EFNARC 2002).

1.6 Literature Review on Transport Properties of Self-Consolidating Concretes

This section discusses the literature in regards to the role of limestone powder's effect on self-consolidating concrete's flow, hardened, and transport properties. The attached Appendix A summarizes additional studies that examined the use of limestone powder and other mineral admixtures on traditional and self-consolidating concrete's properties.

1.6.1 Flow Properties

Zhu and Gibbs (2005) assessed self-consolidating concrete mixtures with the use of limestone and chalk powders as fillers. These fillers were examined for their effect on the superplasticizer demand to achieve proper flowability and the strength properties of the concrete mixtures. Three types of limestone powder and two types of chalk were used in the mixtures with all different fineness of the powders. Two types of superplasticizer were implemented, namely, Glenium 27 and Glenium C315, which are both a modified polycarboxylic ether (Zhu and Gibbs 2005).

The first part of the study examined paste mixtures. The water-to-powder ratio was fixed at 0.30 by mass and a mini slump flow was used to evaluate the flowability. The limestone/chalk powders partially replaced the Portland cement 40% by mass. The results demonstrated that the flowability was less sensitive to the different powders and more to the variation of the superplasticizers (Zhu and Gibbs 2005).

The next part of the study examined self-consolidating concretes that had levels of limestone/chalk filler replacement of 55, 44, and 25% for each type of filler used. The total powder content was 540 kg/m^3 and the water content was 170 kg/m^3. The water-to-cement ratio for these replacement levels was 0.69, 0.57, and 0.42, respectively. Three reference traditional concretes with the same water-to-cement ratio were mixed to compare to the self-consolidating concrete mixtures. A slump flow test and a J-Ring test were used to evaluate the properties of the concrete mixtures (Zhu and Gibbs 2005).

All studied SCC's achieved 600-650 mm of flow and had a good passing ability with little segregation. The mixtures with limestone powder required less superplasticizer than the chalk-contained mixtures did. It was observed that the powder type rather than the fineness of the powder had a greater effect on the superplasticizer demand. There was no observed difference between the particle shapes of the limestone powder and of the chalk powder. The superplasticizer demand increased for lower addition levels of the filler replacement of total powder content due to a lower water-to-cement ratio (Zhu and Gibbs 2005).

Sahmaran et. al. (2006) examined the effects of chemical admixtures and mineral additives on self-compacting mortars. The mineral additives used in the study were fly ash, brick powder, limestone powder, and kaolinite. The chemical admixtures included three superplasticizers: SP1 (polycarboxylic ether), SP2 (modified polycarboxylate), and SP3 (melamine formaldehyde). Two viscosity modifying admixtures were also incorporated: VMA 1 (aqueous dispersion of microscopic silica) and VMA 2 (high molecular weight hydroxylated polymer). A total of 43 mixtures were made with a constant powder content (cement and type or combination of mineral additive) of 650 kg/m^3 and water amount of 260 kg/m^3. The self-compacting mortar's fresh properties were tested by a mini V-funnel and mini slump flow test. Limestone powder and fly ash increased the workability of the self-compacting mortar. Of the three superplasticizer types, SP1 and SP2 were found to produce similar results. SP3 was not as effective as the other two superplasticizers (Sahmaran et. al. 2006).

Koehler and Fowler (2007) examined the use of microfines as a partial replacement for both fine aggregate content and cementitious materials content (cement and fly ash) for self-consolidating mortar and concrete mixtures. Microfines have a comparable size to that of cement and fly ash, and can perform as part of the powder content. For the study, microfines were defined as material finer than 75 μm. The types of microfines examined were three samples of limestone powder, dolomitic limestone, granite, and traprock (Koehler and Fowler 2007).

The replacement of microfines accounted for as part of the fine aggregates in mortar was taken as 0, 5, 10, 15, and 20% of the fine aggregate content. When replacing the powder content, microfines were examined at 0 and 15% of the powder content (cement and fly ash). Two control mixes were utilized that examined the w/cm for microfines used as a part of the sand volume and the w/cm for when microfines were used as part of the powder volume. To understand the difference between the mixtures, the HRWRA demand for a 9-inch mini slump flow test and a corresponding mini V-funnel time was examined for each mixture. The compressive strength and drying shrinkage was also evaluated (Koehler and Fowler 2007).

In this study, it was found when the microfines replaced the fine aggregate portion, the demand for HRWRA increased, and the water-to-powder ratio decreased while the water-to-cementitious materials ratio remained unchanged. This was predicted because of the reduction of the water-to-powder ratio, and is partially counteracted by the increase in paste volume. When the microfines replaced the cementitious materials content (cement and fly ash), the water to powder (cement, fly ash, and microfine incorporated) ratio remained constant, while the water-to-cementitious materials ratio increased, and there was less HRWRA demand than when the microfines replaced the fine aggregate portion. In the same study used to evaluate self-consolidating concrete, the percent of replacement for both fine aggregate and powder content were examined at 0 or 15%. The demand for HRWRA and plastic viscosity increased with all mixtures with microfines (Koehler and Fowler 2007).

Bhattacharya et. al. (2008) studied 10 SCC mixtures to evaluate the influence of aggregate size and distribution, mineral admixtures (silica fume, fly ash, and slag), and fillers (limestone powder). Slump-flow, J-ring, column segregation, L-box, and compressive strength were examined for all ten mixtures. The aggregate ratio varied for each of the ten mixtures and incorporated two coarse aggregate sizes of maximum 25 mm size and of maximum 9.5 mm size. The study considered fly ash and slag to be mineral admixtures, silica fume to be pozzolanic material, and limestone powder to be filler material. The HRWRA was adjusted to obtain suitable flow properties (Bhattacharya et. al. 2008).

The aggregate gradation was compared to Shilstone's coarseness and workability factor. Shilstone's work accounted for the slump of normal concrete and therefore the workability factor and coarseness factor of the studied SCCs were above Shilstone's recommended values. The study suggests that the coarseness factor for the mix should be greater than 60 and the workability factor should be above Shilstone's proposed band for acceptable relationships between coarseness factor and workability factor. The target minimum slump flow was set at 650 mm. All mixtures, but one, achieved this slump flow. In regards to the use of the mineral admixtures (slag, silica fume, and fly ash) and filler(limestone powder), limestone powder was shown to produce more slump flow than the slag/silica fume and fly ash/silica fume mixes due to a higher paste volume (Bhattacharya et. al. 2008).

Surabhi et. al. (2009) examined self-consolidating concrete mixtures with various levels of replacement of limestone powder and studied the fresh and hardened properties. The limestone used in this study was passing through the 150 μ sieve and had a specific gravity of 2.7. The study used a modified polycarboxylic ether based superplasticizer and the dosage was kept constant for all investigated mixtures. A control mixture without the use of limestone was also developed. The limestone powder contained SCCs were blended and replaced the cement content at percentages of 10, 20, 25 and 30% with limestone powder (Surabhi et. al.2009).

Mixtures were considered to be self-consolidating concrete if the slump flow was 650 ± 10 mm. The mixes with 25 and 30% replacement of the cement were not considered self-consolidating concrete due to the low slump flows achieved. The replacement level of 20% with limestone powder achieved the highest slump flow (Surabhi et. al. 2009).

Sahmaran et. al. (2009) performed an investigation that used high and low lime fly ash replacing a portion of cement by 30, 40, 50, 60, and 70 % by weight. Limestone powder with an average particle diameter of 5 μm was used in the studied SCCs at a rate of 4.2% of the filler, fine aggregate, and coarse aggregate content. A control mixture with no fly ash was also batched to compare results. The study found that the low lime fly ash had better workability due to its smooth surface and spherical shape compared to the high lime fly ash. Therefore, the low lime fly ash had a lower water demand (Sahmaran et. al. 2009).

Uysal and Yilmaz (2011) used limestone powder, basalt powder, and marble powder at replacement levels of 10, 20, and 30% of the cement content in self-consolidating concrete. Constant water-to-binder ratio of 0.33 was kept. The total powder content was also fixed at 550 kg/m^3. The study examined the workability, air content, compressive strength, ultrasonic pulse velocity, and static and dynamic elastic moduli. The dosage of a polycarboxylate-based high range water reducing admixture (HRWRA) was kept at a constant 1.6% of the binder materials by weight. The concrete's workability was tested using the slump flow test and the L-box test (Uysal and Yilmaz 2011).

All studied mixtures exhibited an adequate slump flow of at least 690 mm. It was believed this was due to the increased packing density of the mixtures caused by the addition of the mineral admixtures. Increasing the packing density decreased the inter-particle friction of the concrete which decreased the flow resistance. The SCCs that contained limestone powder had the highest slump flow compared to the basalt and marble mixes. It was reasoned that the surface area of the particles may cause this effect because there was an increase in water demand for those mixtures (Uysal and Yimaz 2011).

1.6.2 Hardened Properties

Zhu and Gibbs, whose methodology was discussed in section 1.6.1, found SCC's with filler had a higher compressive strength gain than the reference traditional concretes. The compressive strength gain was higher for mixtures with limestone powder. Among the limestone powder-contained SCCs, the mixtures with a finer blend of limestone had higher strength gains (Zhu and Gibbs 2005).

Sahmaran et. al. (methodology mentioned in section 1.6.1) found the use of superplasticizers increased the compressive strength compared to the control mixture even though it was unexpected to the researchers due to a constant water-to-powder ratio. The compressive strength decreased when mineral admixtures were incorporated. Fly ash and brick powder, both considered pozzolanic, did not contribute to self-compacting mortar's compressive strength due to both minerals having coarser particles. Fineness of the pozzolanic material's particles is a significant factor in their role in pozzolanic activity. Kaolinite and limestone powder generally did not increase compressive strength which was expected as both minerals are considered relatively inert (Sahmaran et. al. 2006).

Koehler and Fowler (discussed in section 1.6.1) observed the microfines had little effect on both compressive strength, modulus of elasticity, modulus of rupture, and flexural strength with a constant water-to-cementitious materials ratio. The drying shrinkage slightly increased when microfines were used as a partial replacement for fine aggregates and increased even less when mircofines were used as a partial replacement of powder. Similar to the observation reported for the mortar study, microfines should be considered a part of the paste volume and not that of the aggregate volume (Koehler and Fowler 2007).

Bhattacharya (discussed in section 1.6.1) observed that limestone powder-contained SCCs produced a higher compressive strength than SCC's containing combinations of slag+ silica fume and fly ash +silica fume due to lower water-to-powder ratio (Bhattacharya 2008). Sahmaran et. al. (discussed in section 1.6.1) examined the compressive strength of the studied SCC's at 7, 28, 90, 180, and 365 days. Fly ash was found to reduce SCC's compressive strength at early ages and contribute to the strength development at later ages. Low-lime fly ash produced higher compressive strength gain due to a lower water-to-cementitious materials ratio used than compared with that of the high-lime fly ash (Sahmaran et. al. 2009).

Surabhi (mentioned in section 1.6.1) found SCC's containing limestone powder had an increase in compressive strength, split tensile strength, flexural strength, and modulus of elasticity with up to 20% partial limestone powder but then decreased for higher levels of replacement (Surabhi 2009). Uysal and Yimaz (discussed in section 1.6.1) reported the use of mineral admixtures decreased the compressive strength compared to the control mix. The marble mixes though exhibited a higher strength gain due to it being finer than the other two powders used in the study (Uysal and Yimaz 2011).

1.6.2.1 Transport Properties

Zhu and Bartos (2003) provided data on SCC water sorptivity and oxygen permeability. The research used two cube strengths of 40 MPa and 60 MPa to characterize the mixtures. The studied SCC's used either filler such as fly ash, limestone powder, or a viscosity modifying agent. The properties examined were the oxygen permeability, absorption, chloride diffusivity, and sorptivity. The SCC mixtures were found to have lower sorptivity and oxygen permeability than the reference concretes have. The chloride diffusivity relied on the type of filler in which the pulverized fly ash produced a lower chloride migration coefficient than limestone powder. The SCC produced with a VMA agent with no mineral admixture had a higher diffusivity than the other two SCCs and the two reference concretes (Zhu and Bartos 2003).

Boel et. al.(2007) examined the transport properties of self-compacting concrete that incorporated either limestone or fly ash filler. The study used one traditional concrete and eight self-consolidating concretes. Considerations for the study included the water-to-cement ratio, cement-to-powder ratio, type of filler, aggregate type, and cement type. The transport properties examined were the water permeability, capillary suction, water vapor diffusion, and gas permeability. The super plasticizer dosage was altered to achieve proper flow ability with no segregation. The transport properties were correlated with the pore structure of the concrete specimen. The pore structure is characterized by the void volume and void network (i.e., void inter-connectivity) (Boel et. al. 2007).

It was found that using fly ash, instead of limestone powder, produced lower transport properties. Also, when the water-to-cement ratio was decreased, the transport properties were discovered to improve. There was not a large effect attributed to the use of two different aggregates. The differences amongst these mixtures were attributed to the difference in their overall pore structure (Boel et. al. 2007).

Sonebi and Ibrahim (2007) studied transport properties of medium strength SCC and compared mineral and chemical admixtures. The mineral admixtures used in the study were pulverized fly ash (PFA) and limestone powder (LSP). The chemical admixture utilized was the viscosity modifying agent diutan gum (VMA). The properties tested were the air permeability, water permeability, capillarity absorption, and in-situ chloride diffusion. These results were compared to two traditional concretes, one made completely with ordinary cement and the other incorporating fly ash. The SCC mixtures that utilized the pulverized fly ash had better transport properties compared to traditional concrete. Limestone powder-contained SCCs also had better transport properties but not as much as the pulverized fly ash mixes. The VMA SCCs had a greater sorptivity, air permeability, and water permeability compared to traditional concrete. The in-situ chloride migration of the SCC including pulverized fly ash was much lower compared to all the other mixtures in-situ migration (Sonebi and Ibrahim 2007)

Koehler and Fowler (discussed in section 1.6.1) found rapid chloride permeability was relatively unaffected when using microfines in replacement of fine aggregates. When replacing for the cementitious materials (cement and fly ash), the rapid chloride permeability decreased an average of 14% for constant water-to-cementitious materials (cement and fly ash) and increased by 65% for a constant water to powder (cement, fly ash, and microfines) ratio (Koehler and Fowler 2007).

De Schutter et. al. (2008) studied the relationship between transport properties and the durability of SCC. The penetration of gases and liquids, freezing and thawing with de-icing salts, and the alkali silica reaction were examined. One traditional concrete and three SCC mixtures were batched to compare results. The investigated SCC incorporated limestone powder as part of the total powder content. The traditional concrete used a higher coarse aggregate volume than the SCCs, while the SCCs used a higher sand volume. The water-to-cement ratio was also altered to understand its impact on the durability of SCC. The superplasticizer was adjusted to achieve suitable flow properties (De Schutter et. al. 2008).

The water permeability for the trial SCCs was slightly less than the traditional concrete. The water absorption was unchanged when the studied SCC and traditional concrete had similar water-to-cementitious materials ratio. The water absorption and the water permeability of the studied SCCs decreased with the reduction in water-to-cementitious materials ratio. The gas permeability of the studied SCCs was much lower than that of the traditional concrete. The trial SCCs and the traditional concrete had similar resistance to freezing and thawing with de-icing salts. However, the SCCs had a much higher alkali silica reaction compared to that exhibited by the traditional concrete. This higher alkali silica reaction may have been due to the addition of the limestone powder. The ASR-induced expansions of the SCCs were found to increase with higher water-to-cementitious materials ratios (De Schutter et. al. 2008).

Sahmaran et. al. (2009) (discussed in section 1.6.1) studied the absorption, sorptivity, and rapid chloride permeability test of SCC's incorporating either low-lime or high-lime fly ash, and limestone powder. Sorptivity and absorption were found to decrease from 28 to 90 days. However, after 90 days, there was no measurable reduction which may be attributed to SCC's high hydration degree. The rapid chloride permeability decreased for all studied SCCs compared to the control mixture regardless of the fly ash incorporated. At 180 and 365 days testing, the total charges passed of the SCCs were nearly identical for the two fly ash types. The volume of penetrable pores had an acceptable linear relationship with the sorptivity (Sahmaran et. al. 2009).

1.7 Research Objectives

The objective of this research was to examine the effect of limestone powder content as a partial replacement of cementitious materials content on SCC's transport properties. Two different size gradations of limestone powder were used. The large size limestone powder with an average size gradation of 8 microns was used to partially replace total cementitious materials content at the levels of 5, 10, 15, 20, 25, and 30% by weight. The smaller size limestone powder with an average size gradation of 3 microns was used to replace a portion of total cementitious materials at the levels of 10, 15, and 20% by weight. The total cementitious materials consisted of Portland cement and fly ash, in which fly ash partially replaced Portland cement at a constant level of 20% by weight. The water-to-cementitious materials ratio was kept constant at 0.45. The amount of chemical admixtures was adjusted to meet the target flow properties requirements of slump flow (635 ± 25 mm), VSI (0 (highly stable) to 1 (stable)), and J-Ring test (less than 50 mm). The evaluation of the hardened properties included compressive strength. The transport properties included rapid chloride penetration (RCPT), rapid migration test (RMT), chloride diffusion, absorption of water after immersion/immersion and boiling, total volume of air voids, water penetration, and capillary absorption.

In order to achieve the above-mentioned objectives, the findings of this investigation are divided into seven chapters.

- Chapter 1 presents information on self-consolidating concrete's background and applications, constituent materials, and recommended guidelines for the self-consolidating concrete mixture proportioning. Also included is a detailed presentation of relevant literature and studies on the effect of limestone powder and fly ash on concrete and self-consolidating concrete's fresh and hardened properties.
- Chapter 2 is devoted to the experimental program of the investigation which includes the preparation and evaluation of raw materials, the mixing procedure, and description of testing equipment and methods.

- Chapter 3 discusses mixture proportion and flow properties of the studied limestone contained self-consolidating concretes. Considerations included in this chapter are the selection of a coarse-to-fine aggregate ratio, selection of constant water-to-cementitious materials ratio (binder ratio), and substitution of a portion of cement or cementitious materials with limestone powder.
- Chapter 4 presents the transport properties of limestone powder contained self-consolidating concrete. The role of the limestone powder content on the transport properties of the studied SCCs is discussed thoroughly.
- Chapter 5 examines the influence of limestone sizes on transport properties of self-consolidating concretes.
- Chapter 6 presents statistical relationships between mixture constituents/proportions and transport properties of limestone powder contained self-consolidating concretes.
- Chapter 7 presents conclusions of the investigation and offers suggestions for future studies in relation to the role of limestone powder on transport properties and long-term durability of self-consolidating concretes.

1.8 Research Significance

In the late 1980’s, the concept of self-consolidating concrete (SCC) was proposed as a solution to achieve durable concrete structures independent of the quality of construction work. SCC offers several advantages when compared with vibratory-placed concrete; including higher flow ability, lesser screeding and better self-leveling, shorter construction period, lower labor costs, higher construction quality and productivity, and better work environment through reduction in construction noise. Despite these advantages, there are some concerns regarding the application of SCC. Unlike vibratory-placed concrete, SCC requires specific rheological characteristics to obtain proper consolidation. Self-consolidating concrete is also susceptible to more shrinkage and creep due to its high cementitious materials content, and higher formwork pressure. Higher cementitious materials also results in higher cost to produce self-consolidating concrete.

One way to address the afore-mentioned concerns and to reduce cost in production of SCC is to utilize mineral admixtures to account for a portion of the paste volume. Inclusion of mineral admixtures may also improve the microstructure of the paste and durability of the concrete. It can also lead to environmental benefits through reduction in cement consumption.

This study was intended to investigate the durability of limestone powder contained SCCs through evaluation of their transport properties. Since durability-related test for Portland cement concrete is time consuming, transport properties serve as valid indices of concrete resistance against harsh environmental and climatic conditions. In fact, the common trend with all deterioration mechanisms of Portland cement concrete is penetration of aggressive medium into concrete from outside or out from inside of concrete.

Previous studies have used limestone powder or fly ash as a partial replacement of Portland cement to examine SCC's transport properties. This research investigation diverges from the past studies in four ways.   It uses ternary mixtures composed of ordinary Portland cement (OPC), Class F fly ash, and limestone powder while past studies used binary mixtures made with OPC and limestone powder. Unlike past investigations, this study utilizes water-to-cementitious materials ratio, as opposed to water-to-powder ratio, in order to properly reflect the role and contribution of cementitious materials to the hydration activities of the studied SCCs. The evaluation of the transport properties under this investigation is far more comprehensive than those presented in the past studies. A portion of this investigation also attempts at finding correlations amongst mixture constituents and proportions, strength, and transport properties of SCCs containing limestone powder.

CHAPTER 2

EXPERIMENTAL PROCEDURE

In order to achieve the intended properties of self-consolidating concrete, special attention must be given to material selection and preparation. Variation in material properties and preparation can greatly impact self-consolidating concrete during production and placement. The moisture content, gradation, and fine content of the aggregates are significant complications that occur during production and are addressed to ensure consistent results. The purpose of this chapter is to introduce the experimental procedure used in this research. The raw material preparation and evaluation are also discussed to ensure testing is not affected by fluctuations in material properties. Additionally, the mixing sequence and testing methods/equipment utilized are discussed in this chapter.

2.1 Material Preparation and Evaluation

Raw materials used in self-consolidating concrete are similar to those used in traditional concrete which include Portland cement, coarse and fine aggregates, water, likely inclusion of chemical admixtures, supplementary cementitious material, and/or inert mineral filler. The chemical admixture used in this study was a high range water reducing admixture (HRWRA). A viscosity modifying agent (VMA) was kept present during mixing in case it was required to attain the target flow properties but was not used. The supplementary cementitious materials and inert mineral filler incorporated in this investigation were fly ash and limestone powder, respectively. The following section presents physical and chemical properties and preparation of the raw materials used in this investigation.

2.1.1 Portland Cement

The cement used in production of self-consolidating concrete should conform to one of the following specifications: ASTM C 595, C 150, or C 1157. For this investigation, Type V Portland cement was employed as it is a statewide cement in Nevada and is generally used when there are special requirements in regards to sulfate resistance for concrete placement. The cement was acquired from a single source, and met the specifications of ASTM C 150. The standard requirements and optional requirements for the cement's physical properties and chemical properties are shown in Table 2.1 and 2.2, respectively. The product information was provided by the cement manufacturer prior to delivery. Upon delivery, Portland cement was stored in 55 gallon metallic drums with liners. The drums were sealed tightly to prevent moisture entry. The drums were stored outside the laboratory facility. Twenty-four hours prior to concrete batching, 5-gallon containers were filled with Portland cement and stored in the laboratory at room temperature of 21 ± 2 °C.

2.1.2 Fly Ash

The same producer who provided the Portland cement also supplied the fly ash used in this study. It was delivered in 55 gallon drums with liners and sealed to avoid moisture intrusion. The fly ash drums were stored outside of the laboratory and were brought in the laboratory in 5 gallon drums twenty four hours prior to batching. The fly ash conforms to ASTM C 618/ AASHTO M295. The fly ash physic-chemical properties are shown in Table 2.3.

Table 2.1: Portland cement physical properties

Item	ASTM Test Method*	Specification Limit	Test Result
Standard Requirements			
Air content of mortar (volume%)	C185	12 max	8
Fineness (cm2/g)			
Air permeability	C204	2600 min	4206
Autoclave expansion (%)	C151	0.80 max	0.02
Compressive Strength			
1 Day	C109	Not applicable	2055
3 Days	C109	1160 min	3493
7 Days	C109	2180 min	4702
28 Days	C109	3050 min	Test results not available
Time of setting (minutes)			
(Vicat)			
Initial: Not less than	C191	45	99
Not more than		375	
Optional Requirements			
False set (%)	C451	50 min	82

*As reported by cement supplier

Table 2.2: Portland cement chemical requirements

Chemical Composition	ASTM Test Method*	Specification Limit	Test Result
Standard Requirements			
SiO_2 (%)	C114	Not applicable	20.42
Al_2O_3 (%)	C114	6.0 max	4.25
Fe_2O_3 (%)	C114	6.0 max	4.05
CaO (%)	C114	Not applicable	63.31
MgO (%)	C114	6.0 max	2
SO_3 (%)	C114	Not exceed 0.02% at 14 days	2.98
Na_2O (%)	C114	Not applicable	0.04
K_2O (%)	C114	Not applicable	0.69
CO_2 (%)	C114	Not applicable	1.53
Loss on ignition (%)	C114	3.0 max	2.5
Insoluble Residue (%)	C114	0.75 max	0.44
Limestone (%)	C114	5.0 max	3.7
$CaCO_3$ in limestone (%)	C114	70 min	94
Potential Compounds (%)			
C_3S	C114	Not applicable	53
C_2S	C114	Not applicable	18
C_3A	C114	5 max	4
C_4AF	C114	Not applicable	12
$C_4AF + 2(C_3A)$	C114	25.0 max	20
Optional Requirements			
$C_3S + C_3A$ (%)	C114	Limit not specified by purchaser	57
Equivalent alkalies (%)	C114	0.6	0.49

*As reported by cement supplier

Table 2.3: Fly ash chemical and physical properties

ASTM C 618/ AASHTO M 295 Testing of Fly Ash				
Chemical Compositions		ASTM/AASHTO Limits		ASTM Test Method*
		Class F	Class C	
Silicon Dioxide (SiO_2)	59.93			
Aluminum Oxide (Al_2O_3)	22.22			
Iron Oxide (Fe_2O_3)	5.16			
Total Constituents	87.31	70% min	50% min	D4326
Sulfur Trioxide (SO_3)	0.38	5% max	5% max	D4326
Calcium Oxide (CaO)	4.67			D4326
Moisture	0.04	3% max	3%max	C311
Loss of Ignition	0.32	6% max	6% max	C311
		5% max	5% max	AASHTO M295
Total Alkalies, as Na_2O	1.29	Not Required		C311
When required by purchaser		1.5% max	1.5% max	AASHTO M295
Physical Properties				
Fineness, % retained on # 325	18.08	34% max	34% max	C311, C430
Strength Activity Index-7 or 28 Day Requirement				C311, C109
7day, % of Control	83	75% min	75% min	
28day, % of Control	79	75% min	75% min	
Water Requirement, % Control	97	105% max	105% max	
Autoclave Soundness	-0.02	0.8% max	0.8% max	C311, C151
Density	2.31			C604

*As reported by fly ash supplier

2.1.3 Aggregates

Aggregate selection is important in the development of the concrete because it occupies a large amount of the concrete volume. Constant aggregate gradation is significant for consistent research results. Both coarse and fine aggregates obtained from the same source were provided by a Southern Nevada quarry. The coarse aggregates conformed to the ASTM C 33 size designation 7. As shown in Table 2.4, the fine aggregates met the gradation requirements set forth by ASTM C 33. The fine aggregate's physical properties including information on deleterious substances and alkali-silica reactivity are shown respectively in Tables 2.5. Aggregate gradation, physical properties, and data on deleterious substances and alkali-silica reactivity are documented in Tables 2.6 and 2.7.

Both coarse and fine aggregates were delivered in 55 gallon metallic drums with liners and stored outside the laboratory. Samples were taken from each drum to test the gradation. The gradation of the fine aggregates was found to be consistent for all samples. However, the gradation for the coarse aggregates varied for each tested sample. To create consistent results, the coarse aggregate was air-dried to less than 0.1% moisture content in horse troughs and then sieved into four size categories. The size designations were denoted as: greater than ½ in, 3/8 to ½ inch, No. 4 sieve to 3/8 inch, and less than No. 4 sieve. The 3/8inch to ½ inch and No.4 to 3/8 inch were stored into 55 gallon metallic drums with liners and labeled, respectively. The greater than ½ inch and less than No. 4 sieve were stored in 5 gallon buckets with lids. The moisture content of the aggregates was measured after the aggregates had been dried. The lids for all the drums and containers were kept tightly sealed to prevent moisture from entering. The moisture content was measured and found to be uniform at about 0.1%. This moisture content was measured before each batching to ensure accurate results.

The fine aggregates were also air-dried in a horse trough to create uniform moisture content. The moisture content of the fine aggregates was found to be 0.1% as well. Once the fine aggregates were dried, they were stored in 5 gallon buckets inside the laboratory. The moisture content was also measured before each SCC batching.

Table 2.4: Fine aggregate gradation

Sieve Analysis and Material Finer than No.200 Sieve ASTM Designation : C117* and C136*		
Sieve Size	Mass Percent Passing	Range
3/8 in	100	100
#4	100	95 to 100
#8	95	80 to 100
#16	65	50 to 85
#30	43	25 to 60
#50	24	5 to 30
#100	9	0 to 10
#200	2.7	0 to 3

*As reported by aggregate producer

2.1.4 Limestone Powder

For the purpose of this study, two different gradations of limestone powder were used. One limestone powder was provided by a local supplier while a second gradation of limestone powder was provided by the same company but from a different location. To identify these limestone powders from one another, the gradations of the limestone powder shall be designated as L8 and L3. Each designation signifies the approximate mean particle size. The L8 limestone powder has 95% of its mass passing the 325 mesh size and has a mean particle size of 8 to 10 microns. The L3 limestone powder refers to the median particle size of the powder which is 3 microns. This powder is finer than the other limestone powder designated as L8. The physical properties of L8 and L3 powders are shown in Table 2.8. The chemical composition of the two limestone powders is shown in Table 2.9. Lastly, the gradations as shown as percent retained above the mesh size is demonstrated in Table 2.10 and the gradations for mass passing in percent is shown in Figure 2.1.

Table 2.5: Fine aggregate physical properties

Laboratory Test	Results	Requirements
Relative Density (Specific Gravity) Oven-Dry,	2.755	
Relative Density (Specific Gravity) Saturated-Surface Dry	2.777	
Apparent Relative Density (Apparent Specific Gravity)	2.818	
Absorption (%)	0.81	
Damp Loose Unit Weight	85 pcf@1.5% moisture	
Organic Impurities	Less than Color Plate No.1	Not Detrimental
Clay Lumps and Friable Particles	0%	3% Max.
Lightweight Particles	0 Specific Gravity 2.0	0.3% Max.
Soundness of Aggregates	Sodium Sulfate 1.7% Loss	10% Max.
Sand Equivalent Value	93	NA
Potential Alkali-Reactivity of Aggregate (Mortar Bar Method)	0.06%	0.1% Max.
Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction	0.03%	0.1% Max.

Table 2.6: Coarse aggregate gradation

Sieve Analysis and Material Finer than No.200 Sieve ASTM Designation : C117* and C136*		
Sieve Size	Mass Percent Passing	Range
3/4 in	100	100
½ in	100	90 to 100
3/8 in	68	40 to 70
#4	4	0 to 15
#8	2	0 to 5
#50	1	-
#100	0.2	-
#200	0.2	0 to 1

*provided by aggregate producer

Table 2.7: Coarse aggregate physical properties

Laboratory Test	Results	Requirements
Relative Density (Specific Gravity) Oven-Dry	2.747	
Relative Density (Specific Gravity) Saturated-Surface Dry	2.768	
Apparent Relative Density (Apparent Specific Gravity)	2.801	
Absorption (%)	0.79	
Dry-Rodded Unit Weight	98 pcf	
Cleanness Value (C.V.) NDOT Test Method NEV. 228B	91	NA
Clay Lumps and Friable Particles	0%	3% Max.
Lightweight Particles	None Specific Gravity 2.0	0.3% Max.
Soundness of Aggregates	Sodium Sulfate 1.4% Loss	12% Max.
Resistance to Degradation Abrasion ASTM C 131	18% Loss	50% Max.
Potential Alkali-Reactivity of Aggregate (Mortar Bar Method)	0.07%	0.1% Max.
Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction	0.03%	0.1% Max.

Table 2.8: Limestone powder physical properties

Designation	L8	L3
Liquid Viscosity	0.7168 cp	0.7166 cp
Analysis Temperature	35.3 °C	35.3 °C
Full Scale Mass	100.00%	100.00%
Sample Density	2.710 g/cm3	2.710 g/cm^3
Liquid Density	0.9939 g/cm3	0.9939 g/cm3
Base/Full Scale	135/96 KCnts/s	136/ 101 KCnts/s
Reynolds Number	1.81	1.81

Table 2.9: Limestone powder chemical composition

Chemical Composition	L8	L3
$CaCO_3$	97.63%	96.94%
$MgCO_3$	0.96%	1.50%
Fe_2O_3	0.13%	0.09%
Al_2O_3	0.32%	0.17%
SiO_2	0.71%	-
S	0.13%	-

Note: - designates information not provided

Table 2.10: Limestone powder gradations

Mesh Size Retained	L8	L3
+ 60 Mesh	0.00%	0.00%
+ 100 Mesh	0.01%	0.00%
+ 200 Mesh	0.17%	1.50%
+ 325 Mesh	4.36%	1.50%

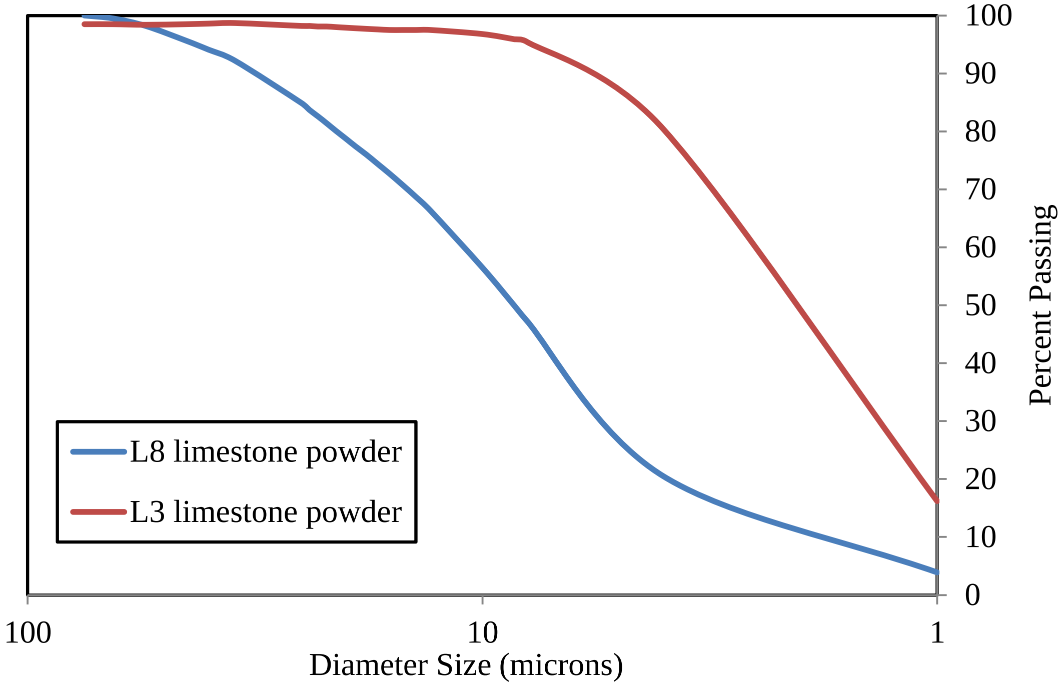

Figure 2.1: Limestone powders mass percent passing versus sieve size (microns)

2.1.5 Chemical Admixtures

Polycarboxylate-based high range water-reducing admixtures (HRWRA) are commonly employed to develop self-consolidating concrete to enhance the fluidity of the concrete. A viscosity modifying admixture (VMA) can also be implemented to improve the segregation resistance of SCC. The VMA is only used if the desired cohesive properties cannot be attained. A HRWRA was used for all SCCs to produce the desired fluidity. For this study, the HRWRA and the VMA were obtained from a single source. They were stored in 5 gallon plastic containers in the laboratory at room temperature of 21 ± 2 °C (70 ± 3°F). The HRWRA was manufactured to comply with Types A & F admixture ASTM C 494, AASHTO M 194, and ASTM C1017. The chemical properties of HRWRA and VMA used in this study are displayed in Table 2.11. This information was attained from the Manufacturer Supplied Product Data (PD) and Material Safety Data Sheet (MSDS).

Table 2.11: Chemical admixture chemical composition

Designation	HRWRA	VMA
Chemical type	Polycarboxylate acid	NS and Welan Gum
Volatiles (%)	59.70%	56.90%
Specific Gravity	1.09	1.207
pH	3 to 8	7.5 to 10.5
Water Reduction Range	up to 40%	-

2.1.6 Water

Tap water that complied with ACI 310 "Specifications for Structural Concrete for Buildings" was used throughout this research.

2.2 Mixing Procedure

The mixing sequence suggested by ASTM C 192 with a slight modification to meet SCC's requirements was used. The adopted mixing procedure will be discussed in details in chapter 3.

2.3 Testing equipment and methods

The objective of this section is to present the testing equipment and methods utilized for this research. The testing methods consist for both freshly-mixed and hardened of the studied SCC's. The slump flow, dynamic segregation resistance (VSI), T_{50}, and J-Ring were used to examine SCC's flow properties. The target flow properties, obtained through alteration in the amount of chemical admixture, will be discussed in Chapter 3. The tests on hardened SCC's were compressive strength, capillary absorption,

absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion. A summary of the evaluated SCC characteristic and the standard used are shown in Table 2.12. The following sections present the test standards and a step by step procedure for each test method used in this investigation.

Table 2.12: Test methods for fresh and hardened properties of SCC

Characteristic	Test method	Specification
Flow ability -Unconfined workability	Slump flow	ASTM C 1611
Flow rate/ plastic viscosity	T_{50}	ASTM C 1611
Passing ability	J-ring	ASTM C 1621
Dynamic Stability	Visual Stability Index (VSI)	ASTM C 1611
Compressive Strength	Compressive Strength	ASTM C 39
Capillary Primary Absorption	Capillary Absorption	ASTM C 1585
Absorption After Immersion	Absorption	ASTM C 642
Absorption After Immersion and Boiling	Absorption	ASTM C 642
Volume of Permeable Voids	Absorption	ASTM C 642
Water Penetration	Water Penetration	EN 12390-8:2000
Rapid Chloride Penetration	Rapid Chloride Penetration Test (RCPT)	ASTM C 1202
Rapid Chloride Migration	Rapid Migration Test (RMT	NT Build 492
Chloride Diffusion	Chloride Diffusion	ASTM C 1556

2.3.1 Slump Flow, Dynamic Segregation Resistance, and T_{50} Tests

The three methods to characterize the flow ability of the investigated self-consolidating concretes were slump flow, $T_{50,}$ and segregations resistance tests in accordance with ASTM C 1611, “Standard Test Method for Slump Flow of Self-Consolidating Concrete.” The tests examined the flow ability, flow time (indication of viscosity), and dynamic stability of the SCC. The slump flow is a measurement of the horizontal flow of SCC and is the mean spread value of two perpendicular concrete spread diameters. The T_{50} flow time was performed simultaneously with the slump flow test, and is the time the concrete takes to spread to a diameter of 508 mm (20 inches). It also signifies the viscosity of SCC by inference. The segregation resistance is evaluated by the visual stability index (VSI) which is rated by a value from 0 to 3 to describe the extent of SCC's segregation and bleeding. The rating system and description of each value are displayed in Table 2.13.

Table 2.13: Visual Stability Index (VSI) criteria

Rating	Criteria
0 Highly stable	No evidence of segregation or bleeding in slump flow, mixer, or sampling vessel.
1 Stable	No mortar halo or coarse aggregate heaping in the slump flow, but some slight bleeding and/or air popping is evident on the surface of the slump flow, concrete mixer, or sampling vessel.
2 Unstable	Slight mortar halo, 10 mm (≤ 0.5 inch) wide, and/or coarse aggregate heaping in the slump flow, and highly evident bleeding in the mixer or sampling vessel.
3 Highly unstable	Visibly segregated by evidence of a large mortar halo, > 10mm, and/or large coarse aggregate pile in the slump flow, and a thick layer of paste on the surface of the concrete sample in mixer and vessel.

The testing equipment used for the three tests were a metallic base plate, a mold, tamping rod, strike off bar, measuring tape, and a stopwatch. The base plate has a plane area of at least 900 x 900 mm (35 x 35 inches) with a center of the plate scribed with a cross and which the lines run parallel to the edges of the plate. There are two circular marks of 200 and 508 mm (8 and 20 inches) diameter in the center of the plate. The mold and tamping rod conformed to the requirements of AASHTO T 119. The strike off bar entailed a flat straight bar of 3 x 20 x 300 mm (0.125 x 0.75 x 12 inches). The measuring tape was used to measure the largest diameter of the spread and the perpendicular diameter. The tape had a minimum degree of 12.5 mm (0.5 inch). To measure the T_{50} flow time, a stop watch was utilized that had a minimum reading of 0.2 second. Figure 2.2 demonstrates the slump flow test apparatus.

Figure 2.2: Slump flow test apparatus

The following steps were utilized to perform the slump flow test:

(1) The base plated was leveled on a flat surface to prevent any interference in the test measurement. The plate was then cleaned and dampened, with any excess water removed to also prevent interference of test recordings.

(2) A 200 mm mark and 500 mm mark were drawn on the base plate. The slump cone was placed with the smaller diameter facing up on the 200 mm diameter marking.

(3) The slump cone was then filled with fresh self-consolidating concrete by means of a scoop. It was placed with no vibration, rodding, or tamping.

(4) Any excess concrete was removed from the top and around the base of the slump cone. The filled cone was not allowed to stand for more than 30 seconds.

(5) The cone then was raised vertically at a distance of 225 ± 75 mm in 3± 1 second. This action was accomplished without any horizontal or torsional movement. The testing process took an estimated time of 2.5 minutes without any interruption.

(6) A stopwatch was immediately started after the slump cone was lifted. It was stopped after the concrete reached the 500-mm circular mark. This recording to the nearest 0.1 second is the T_{50} flow time.

(7) The maximum diameter was measured after the concrete stopped flowing outwards. The diameter perpendicular to the maximum diameter was also measured. The average of these two diameters was the slump flow to the nearest 12.5 mm. If the two readings differed by 50 mm, the test was considered unacceptable and recreated.

(8) The visual stability index (VSI) was performed by visually examining the concrete flow. This examination noted any segregation of the cement paste from the coarse aggregate. This was perceived as a ring of paste spreading past the coarse aggregate. The rating for VSI was recorded from 0 to 3. The descriptions of these ratings are described in Table 2.13. A VSI rating of 0 and 1 were considered only acceptable for this research.

2.3.2 J-Ring Test

To evaluate the passing ability of the concrete, the J-Ring test was utilized. The J-Ring test was used simultaneously with the slump cone. The test measured the difference between the unobstructed diameter (slump flow test) and the obstructed diameter which evaluated the passing ability of the self-consolidating concrete. The test was performed in accordance with ASTM C 1621 "Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring."

The testing equipment for the J-Ring composed of an open steel ring, drilled vertically with holes to accept threaded sections of reinforcing bars, a mold and tamping rod, strike off bar, a base plate, and a measuring tape. The open steel ring had a diameter of 300 mm with a height of 100 mm. The mold and tamping rod were held to the requirements of AASHTO T 119. The base plate was the same plate used in the slump flow test as was the tape measurer. The J-ring testing apparatus is demonstrated in Figure 2.3 and the plane view in Figure 2.4.

Figure 2.3: J-Ring testing apparatus

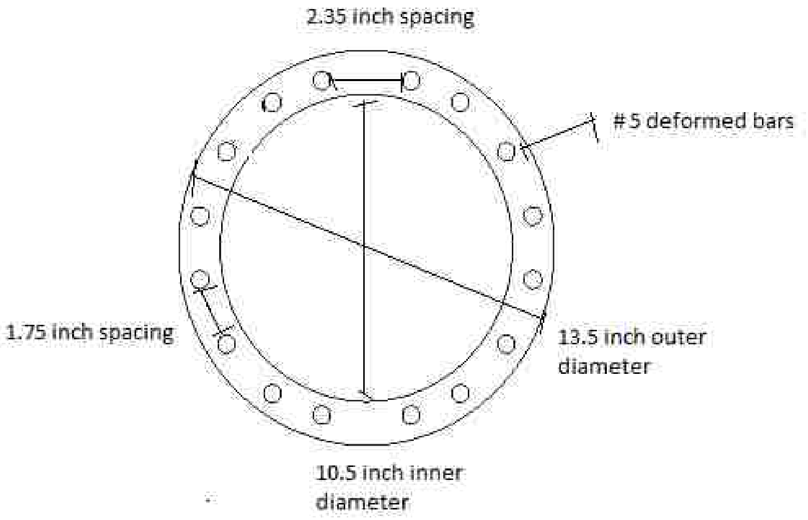

Figure 2.4: J-Ring plane view

The test procedure for the J-ring is as follows:

(1) The J-ring, slump cone, and base plate were washed and dampened.

(2) The base plate was placed on a level surface. The J-ring was placed in the center of the base plate and the slump cone was placed in the middle of the J-ring with the smaller diameter facing up.

(3) Fresh self-consolidating concrete was placed in the cone without any vibration, rodding, or tamping.

(4) The strike off bar was used to level the surface of the concrete once the cone was filled. Any excess concrete was removed from the base plate surface.

(5) The slump cone was lifted vertically to a height of 225 ± 75 mm in 3 ± 1 second without any horizontal or torsional movement. The test from filling the slump cone to the removal of the cone was performed in an elapsed time of 2.5 minutes without any interruption.

(6) As in the slump flow test, the largest diameter was measured and then the diameter perpendicular to the largest diameter. Measurements were recorded to the nearest 12.50 mm. If the two diameters varied by 50 mm or more, the base plate was leveled and the test repeated.

(7) J-ring flow was recorded as the average of the two recorded diameters.

(8) The J-ring value was recorded as the difference between the J-ring flow and the unobstructed slump flow. This unobstructed slump flow was measured in the slump flow test.

(9) The rating of the concrete's passing ability is defined in Table 2.14.

Table 2.14: J-ring Test Criteria

J-Ring value	Passing Ability Rating	Remarks
0-25 mm (0-1 inch)	0	High passing ability
25-50 mm (1-2 inch)	1	Moderate passing ability
> 50 mm (2 inch)	2	Low passing ability

2.3.3 Compressive Strength

The compressive strength test measured the resistance of a concrete specimen to compressive stresses. This test was simulated under a static testing compression machine (Professional Concrete Compression Machine, MC500 PR), produced by Gilson Company shown in Figure 2.5. The compressive strength test was performed in accordance with ASTM C 39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens". ACI 363 rigidity requirements were met due to the compression machines stiff load frames. The lower and upper platens are nickel and locking stems secure the upper platen while allowing quick substitution of fixture. The machine was electric-hydraulic variety and had a capacity of 113,398 to 226,796 kg (250,000 to 500,000 pounds). Figure 2.5 demonstrates the compressive testing machine.

Figure 2.5: Compressive testing machine

Curing periods of 28, 90, and 180 days were assigned to the test specimens. Specimens were cast in cylindrical molds with a 100 mm (4 inch) diameter and 200 mm (8 inch) height. Testing equipment used in this experiment are molds, pads and retainers complying with ASTM C 1231, and the compression machine described above. The step by step procedure is listed below:

(1) Testing specimens were cast in the molds described above and left to cure for the specific date.

(2) After the curing period, specimens were covered with pads and retainers.

(3) Specimens were placed on the top of spherical seating block and situated with the center of the specimen aligned with the centroid of the steel bearing block.

(4) The compression loading was applied at a rate of 0.138 to 0.345 MPa/sec (20 to 50 psi/sec)

(5) Loading was continued until failure.

(6) The compressive strength was calculated by dividing the applied compressive loading by the area of the specimen.

2.3.4 Capillary Absorption

Capillary absorption examined the water transportation through capillaries left in concrete after hydration. Excess water proves hazardous to concrete as the excess water escapes and leaves a system of interior pores and thin capillaries. Water primarily transports into concrete through capillary absorption, and when chlorides or oxygen are present, reinforcing bar can corrode (Howes and McDonald 2006).

To measure the capillary absorption of the concrete specimens, the test procedure set forth by ASTM C 1585 “Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes” was used. The apparatus used in this test were a pan, a support device, top-pan balance, timing device, environmental chamber, and a sealing material. The support device was made of materials resistant to corrosion and allowed access of water to the surface of the test specimen. The test specimens are prepared with a diameter of 100 mm (4 inches) and a height of 50 mm (2 inches). These specimens were prepared by hardening in molds constructed specifically for this research.

The test procedure is as follows

(1) The specimens were placed in a dessciator with a temperature of 50 °C ± 2°C (122 ° ± 3 °F) and a relative humidity of 80 ± 3 % for 3 days by use of potassium bromide saturated with 401 grams to 500 grams of water.

(2) After the 3 days in the environmental chamber, the specimens were placed in a sealable container at 23 °C for 15 days.

(3) The specimen's mass was recorded to the nearest 0.01 gram. Four diameters of the specimen were recorded to the nearest 3 mm (0.1 inch). The average of these four diameters is used to calculate the specimen area.

(4) The sides of the specimen were sealed with sealing material and a plastic sheet placed on the surface not exposed to water.

(5) The mass of the sealed specimen was measured to the nearest 0.01 gram.

(6) The support device was placed in the pan. Water was then filled in the pan to approximately 1-3 mm above the support device. This height was maintained throughout testing.

(7) A stopwatch was started and the sealed specimen placed on the support device.

(8) The mass was recorded at intervals of 60 seconds ± 2 seconds, 5 minutes ± 10 seconds, 10 minutes, 20 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 24 hours, 48 hours, 72 hours, 4 days, 5 days, 6 days, 7 days, and 8 days. With every measurement, the surface was wiped of any excess water and the specimen inverted so it did not come into contact with the balance pan.

(9) The calculation for the absorption is as follows: $I = \frac{m_t}{a/d}$ where I equals absorption, m_t, is the change in mass at time t, a is the exposed area of the specimen measured in mm^2, and d is the density of the water in g/mm^3

(10) The plot of absorption I and the $t^{0.5}$ was determined and the first and second slope of the curve calculated. The first slope was denoted as the primary absorption (mm/s^2) and the second slope denoted as the secondary absorption (mm/s^2).

2.3.5 Absorption Test

The absorption test was a measurement of concrete's effective porosity, the mass of water which will fully saturate a specimen. The final product of the absorption test was the volume of permeable pores as a percent of the concrete sample's total volume. This test was performed in regulations with ASTM C 642 "Standard Test for Density, Absorption, and Voids in Hardened Concrete".

The test apparatus used in this test was a balance sensitive to 0.025% mass of the specimen and a container that would be sufficient to immerse the specimen in water. SCC samples were cast in 100 mm (4 inch) diameter by 50 mm (2 inch) height cylinder molds. The volume of the specimen did not exceed 350 cm^3.

The test procedures are as follows;

(1) The original mass of the specimen was recorded as X_1.

(2) The specimen was dried in an oven at a temperature of 100 to 110°C for at least 24 hours and then left to cool to room temperature. The specimen was then weighed and the new mass was recorded as X_2. If the difference between X_1 and X_2 was greater than 0.5%, the specimen was dried for another 24 hours and weighed again. This process was repeated until the two consecutive readings differed by 0.5% or less. The final weight was designated as Oven Dry Mass (A).

(3) The specimen was subsequently immersed in water for 48 hours and then weighed. If the difference between these two readings was greater than 0.5%, the

process was repeated every 24 hours until the difference was less than 0.5%. The final mass was recorded as the saturated weight (B).

(4) The specimen was placed in boiling water for 5 hours and left to cool overnight. The sample was dried, weighed and the mass was recorded as (C).

(5) The specimen was then suspended by a wire in water. This apparent mass was noted as (D).

(6) The calculation for absorption after immersion in percent was as follows:

$$\% = \left[\frac{B - A}{A}\right] X100$$

(7) Absorption after immersion and boiling in percent was calculated by:

$$\% = \left[\frac{C - A}{A}\right] x100$$

(8) The volume of permeable pore space (voids) in percent was calculated by three equations:

$$g_1 = Bulk\ density\ dry = \left[\frac{A}{(C - D)}\right] x\rho$$

$$g_2 = Apparent\ density = \left[\frac{A}{(A - D)}\right] x\rho$$

$$Volume\ of\ permeable\ pore\ space\ (voids)\ \% = \left[\frac{(g_2 - g_1}{g_2}\right] x100$$

2.3.6 Water Penetration Test

The depth of water penetration was a method to measure a concrete's resistance to water pressure applied. The 150 mm x 150 mm (6 inch by 6 inch) cube SCC sample was water cured for a selected curing age of either 28 or 90 days. The testing equipment used in this procedure was the model 55-C0244/AV Concrete water impermeability equipment produced by Controls. This test was performed in accordance with European Committee for Standardization (CEN) EN 12390-8:2000 “Testing hardened concrete- Part 8: Depth of penetration of water under pressure.” The testing apparatus with samples placed is shown in Figure 2.6. Step by step procedures are listed below:

Figure 2.6: Water penetration testing apparatus

(1) Once the specimens are demolded, the surface of the specimens was roughened with a wire brush.

(2) Once the specimens were cured, they were placed in the apparatus and sealed tightly.

(3) A water pressure of 500 ± 50 KPa was applied for exactly 72 hours.

(4) Periodic observation of the surface was performed to make sure that leakage did not occur. If leakage occurred, the test was considered invalid.

(5) After the test, the specimen was wiped dry of excess water.

(6) The specimen was split in half, perpendicular to the surface where the water was applied. When splitting, it was ensured that the test specimen's surface exposed to water was bottom down.

(7) When water penetration can be observed, the water front of the specimen was marked.

(8) The maximum depth was measured under the test area and recorded to the nearest millimeter

(9) The profile of the water penetration was also measured at increments of 5 mm.

2.3.7 Rapid Chloride Penetration Test

The rapid chloride penetration test examined the ability of the concrete to resist chloride ion penetration. This test follows the standards set forth by ASTM C 1202 "Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration". As stated in the capillary absorption test, chloride ions in concrete can be hazardous to the structural integrity of the concrete as it presents possible corrosion of the reinforcement steel.

The testing equipment used in this test was a vacuum desiccator, a vacuum pump, beaker, specimen-cell sealant, and power supply. The SCC samples were cast in 100 mm (4 inches) diameters and 50 mm (2 inches) height molds. A belt sander was used to remove any burrs on the specimen. Figure 2.7 demonstrates the testing apparatus used.

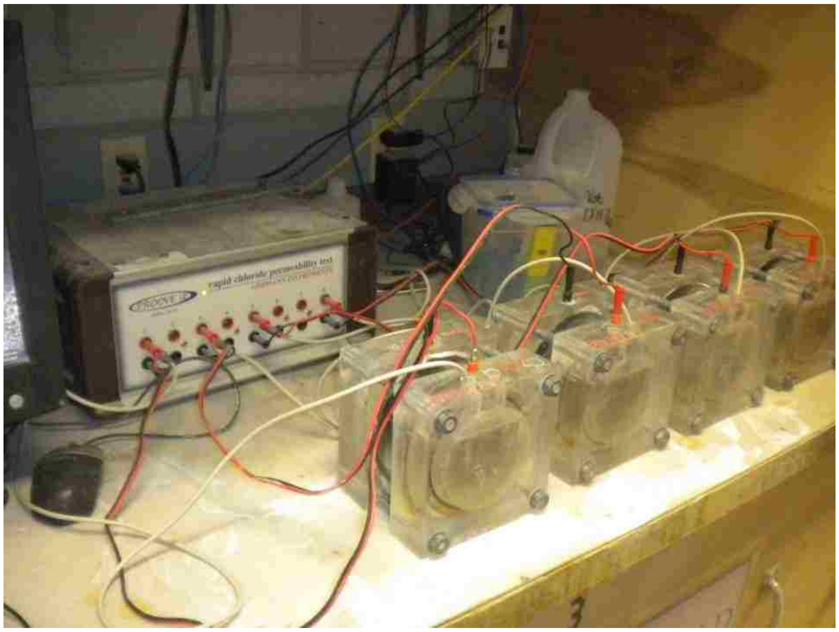

Figure 2.7: Rapid chloride penetration testing apparatus

The test procedure is as follows:

(1) One liter of water was boiled and allowed to cool to room temperature. If using distilled water, this step was omitted.

(2) The specimens were air dried for at least 1 hour and the sides were coated with plastic dip and allowed to cure.

(3) The specimens were placed in the desiccator and the pump was operated for the 3 hours. The pressure of the desiccator was maintained at less than 1 mm Hg (133 Pa).

(4) The de-aerated water was attached to the desiccator. With the pump still running, the stopcock was turned open to allow water to fill the desiccator. Water was filled in the desiccator until the specimens were fully immersed.

(5) The stopcock was turned off and the pump was run for an additional hour.

(6) The pump was turned off and the stopcock was turned to allow air to re-enter the desiccator. The specimens were left in the desiccator for 18 ± 2 hours.

(7) The specimens were removed and any excess water was wiped off. The specimens were then placed in the sealant cells with rubber gaskets to maintain the specimens at a relative humidity of 95 % or higher.

(8) The sides of the testing cell were filled with either 3.0% NaCl (side connected to negative terminal of power supply) or with 0.3 N NaOH solution (side connected to positive terminal of the power supply).

(9) Lead wires were attached to the cell banana posts. The computer program "Proove-It" was used with settings set for 60.0 Volts and the testing time of 6 hours. The initial current reading was recorded. The temperature of the cell should be maintained at 20 to 25 °C (68 to 77°F).

(10) The equipment was set for 6 hours. The equipment calculated the charge passed automatically.

2.3.8 Rapid Migration Test

The rapid migration test examined the ability of the concrete to resist chloride ion penetration similarly to the rapid chloride penetration test, but examined the chloride ingress as a measure of pore structure contribution. This test follows the standards set forth by NT Build 492 "Chloride Migration Coefficient from Non-Steady-State Migration Experiments".

The testing equipment used in this test was a vacuum desiccator, a vacuum pump, beaker, splitting device, ruler, ammeter, and a migration apparatus. The migrations apparatus is displayed in Figure 2.8. The apparatus included a silicone rubber sleeve, clamp, catholyte reservoir, plastic support, cathode, and anode. Reagents include calcium hydroxide, sodium chloride, sodium hydroxide, and silver nitrate. The test specimen was cast in 100 mm (4 inches) diameters and 50 mm (2 inches) height molds. A belt sander was used to remove any burrs on the specimen.

Figure 2.8: Rapid migration testing apparatus

The test procedure is as follows

(1)Specimens were air dried until the surface was completely dry.

(2) The specimens were placed with both sides exposed in the desiccator and the pump was operated for the 3 hours. The pressure of the desiccator was maintained at 1-5 KPa.

(3) A calcium hydroxide solution was attached to the desiccator. With the pump still running, the stopcock was turned open to allow solution to fill the desiccator. Solution was filled in the desiccator until the specimen was fully immersed.

(4) The stopcock was turned off and the pump was run for an additional hour.

(5) The pump was turned off and the stopcock was turned to allow air to re-enter the desiccator. The specimens were left in the desiccator for 18 ± 2 hours.

(6) The specimens were removed and any excess moisture was wiped off.

(7) The catholyte reservoir was filled with about 12 liters of 10% NaCl solution made with 100 grams of NaCl dissolved in 900 grams of water.

(8) The specimen was put in the rubber sleeve and clamped securely.

(9) The specimen was placed on the plastic support in the catholyte support.

(10) The sleeve was filled with the anolyte solution which was a 0.3 M NaOH solution. The anode was then placed in the anolyte solution.

(11) The cathode was connected to the negative pole and the anode to the positive pole of the power supply.

(12) The power supply was turned on to an initial voltage of 30 Volts and the initial current was recorded. Based on the initial current, the voltage and the testing duration were adjusted based on Table 2.15.

(13) The final current and temperature were just recorded before testing termination.

(14) The specimen was dissembled in the reverse process of the assembly process and rinsed with tap water.

(15) The specimen was split in half axially and then misted with a 0.5 N silver nitrate solution.

(16) The solution reacted with the chloride ions of the sample and the surface changed color. This color change was the indication of chloride penetration depth.

(17) Seven depths of the concrete specimen were recorded.

(18) The rapid migration was measured by dividing the penetration depth by the applied voltage and test duration time in hours.

Table 2.15: Rapid migration test voltage and duration

Initial Current (mA)	Applied Voltage (V)	Possible New Initial Current (mA)	Test Duration (hour)
$I_0 < 5$	60	$I_0 < 10$	96
$5 \le I_0 < 10$	60	$10 \le I_0 < 20$	48
$10 \le I_0 < 15$	60	$20 \le I_0 < 30$	24
$15 \le I_0 < 20$	50	$25 \le I_0 < 35$	24
$20 \le I_0 < 30$	40	$25 \le I_0 < 40$	24
$30 \le I_0 < 40$	35	$35 \le I_0 < 50$	24
$40 \le I_0 < 60$	30	$40 \le I_0 < 60$	24
$60 \le I_0 < 90$	25	$50 \le I_0 < 75$	24
$90 \le I_0 < 120$	20	$60 \le I_0 < 80$	24
$120 \le I_0 < 180$	15	$60 \le I_0 < 90$	24
$180 \le I_0 < 360$	10	$60 \le I_0 < 120$	24
$I_0 \ge 360$	10	$I_0 \ge 120$	6

2.3.9 Chloride Diffusion Test

The chloride diffusion test was an assessment of concrete’s resistance to chloride ion penetration through means of diffusion. Diffusion is the migration of chloride ions driven by the concentration gradient between a higher chloride ion concentration area and a lesser concentration area. This test was performed in accordance with ASTM C 1556 "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion." The testing apparatus used in this test were a balance with an accuracy of 0.01 gram, plastic container, and a power grinder to grind off samples, resalable bags, beakers, filter, watch glass, stirrer, and a titration device. Solutions used in this test were a calcium hydroxide solution of 3 grams per liter of distilled water, a sodium chloride solution of 165 grams per liter of distilled water. The grinder and titration device used in this test are shown in Figures 2.9 and 2.10 respectively.

Test specimens used in this experiment are free of any defects. Specimens were cast in 100 mm (4 inch) diameter by 50 mm (2 inch) height molds. Specimens were cured for 28 and 90 days and left to sit for 24 hours in the laboratory at room conditions. The specimens were sealed with a plastic coating on all sides except for the finished surface.

The step by step testing procedures is described below:

(1) After specimen preparation, the initial mass of the specimen was recorded.

(2) The initial chloride content was measured by splitting a specimen in half, and measuring the chloride ion by titration.

(3) The specimen was then placed in the calcium hydroxide bath for 24 hours in a sealed plastic container. This process was repeated until the specimen's mass did not change by 0.1% in a 24 hour period.

(4) Once the test specimen mass did not change by 0.1%, the specimen was removed and rinsed with tap water. The specimen was then placed in the sodium chloride solution and sealed for 35 days.

(5) Multiple test specimens were used and no obstruction between them was allowed. If evaporation was observed, the test was considered invalid. The time the specimen was immersed was recorded to the nearest hour.

(6) Once the specimen was removed, it was rinsed with tap water, dried, and left for 24 hours in room temperature.

(7) Grinding samples were obtained by a drill that grinds off concrete material. Recommended by ASTM C 1557 depths of powder grinding are listed in Table 2.16. Since a w/cm ratio of 0.45 was used, depths are assumed to fall between 0.40 and 0.50. For this research, 3 grams were used as the chloride concentration was found to be high.

(8) Depth measurement was recorded from a slide caliper for five measurements.

(9) The powdered sample was transferred to a container and pulverized so that all the material will pass an 850 µm (No. 20) sieve. The sample having a mass of 3 grams was introduced into a 250 mL beaker. The sample was immersed with 75 mL of water and with no delay 25 mL of dilute (1+1) nitric acid was added slowly. In a case of strong hydrogen sulfide smell, 3 mL of hydrogen peroxide (30% solution) was added. Then, 3 drops of methyl orange indicator was added and stirred.

(10) The beaker was covered with a watch glass and allowed to rest for 1 to 2 minutes. A faint pink or red color should persist. If the solution was instead yellow to yellow-orange, additional dilute nitric acid (1+1) was added.

(11) Nine centimeter filter paper was washed with 25 mL increments of water. The sample solution was filtered and the beaker was rinsed with a small portion of water. The filtrate was transferred to a 250 mL beaker. The filtrate was then cooled to room temperature and the volume measured to ensure the total liquid was less than 175 ml.

(12) Two mL of standard 0.05 N NaCl solution was added to the cooled sample beaker by pipet. The beaker was then placed on a magnetic stirrer and a TFE-fluorocarbon-coated magnetic stirring bar was added into the beaker. The electrodes were submerged into the solution. The delivery tip of the 10 mL buret, filled to the mark with standard 0.05 N silver nitrate solution was placed above the solution.

(13) While titrating, the amount of standard 0.05 N silver nitrate solution required to bring the millivolt meter reading to 60.0 mV of the equivalence point was recorded.

(14) Titration was continued with 0.20 mL increments and the burette reading and corresponding millivolt meter were recorded accordingly.

(15) Titration was carried on until three readings past the approximate equivalence point.

(16) The difference in millivolt readings between successive additions of titrant were calculated and recorded. The differences between consecutive values

were recorded as well. The equivalence point of the titration was found within the maximum Δ mV intervals and the precise equivalence point was interpolated from the data recorded.

(17) A blank determination using 75 mL of water in place of the sample was made. The results obtained were then corrected by subtracting the blank.

(18) Calculation for the chloride concentration at the surface and the apparent chloride diffusion coefficient were as follows:

$$C(x,t) = C_x - (C_s - C_i) \cdot \mathrm{erf}(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}$$

Where:

$C(x,t)$= chloride concentration, measured at depth x and exposure time t, mass (%)

C_s= predicted chloride concentration at the interface between the salt water and which is determined by regression analysis, mass (%).

C_i= initial chloride concentration determined by titration of specimen before submersion into exposure liquid mass (%).

X= depth below the exposed surface layer (to the center of the layer)

D_a= apparent chloride diffusion coefficient, m^2/s

t= the exposure time, s

erf= the error function

(19) MATLAB was used for regression analysis to determine C_s and D_a. Other calculations included the measured chloride contents at all points versus depth below the surface. A best fit curve was plotted.

Figure 2.9: Power grinder for chloride diffusion test

Figure 2.10: Automatic titration device for chloride diffusion

Table 2.16: Grinding depths based on ASTM C 1557

w/cm	0.40	0.50
Depth 1	0-1 mm	0-1 mm
Depth 2	1- 3 mm	1- 3 mm
Depth 3	3-5 mm	3-5 mm
Depth 4	5-7 mm	5-8 mm
Depth 5	7-10 mm	8-12 mm
Depth 6	10-13 mm	12-16 mm
Depth 7	13-16 mm	16-20 mm
Depth 8	16-20 mm	20-25 mm

CHAPTER 3

INFLUENCE OF LIMESTONE POWDER ON FLOW PROPERTIES AND ADMIXUTRE REQUIREMENT OF SELF-CONSOLIDATING CONCRETES

The purpose of this chapter is to present (1) the selected limestone-contained self-consolidating concretes proportions and constituents to include coarse-to-fine aggregate ratio, powder content, and water-to-binder (cement and fly ash) ratio that most effectively demonstrates limestone powder's influence (2) the optimum admixture requirements for each replacement level of limestone powder using a High Range Water Reducing Admixture (HRWRA) and potentially a Viscosity Modifying Admixture (VMA) to achieve target flow properties which include target properties of slump flow of 625 mm ± 25 mm (25 inches ± 1 inch); visual stability index (VSI) of 0 (highly stable concrete) or 1 (stable concrete), and J-ring less than 50 mm (2 inches), and (3) the flow properties for each given replacement and size of limestone powder which include slump flow, VSI, T_{50} flow time, and J-Ring.

3.1 Mixture Proportion Design

The required engineering properties and the mixture economy based on the raw materials presented in chapter 2 influenced selection of mixture proportions and constituents used in this research. A medium slump flow (635 mm) and non-air entrained self-consolidating concrete mixtures were utilized. A high powder type self-consolidating concrete was adopted. Other factors that influence the studied mixture proportion design are discussed in the following sections.

3.1.1 Engineering Properties

3.1.1.1 Fresh Properties

Flow ability, passing ability, filling ability, and stability are the characterizations of self-consolidating concrete's flow characteristics. To accomplish all four of these characterizations, the following considerations in the mixture proportions are considered. These considerations include (1) an optimum coarse-to-fine aggregate ratio (2) suitable water-to-cementitious materials ratio (w/cm) (3) minimum cementitious materials content, and (4) an optimum dosage of combined HRWRA and potentially VMA. The adopted flowability target limits are displayed in Table 3.1.

Table 3.1: Fresh property target limits

Test	Target Limit
Slump flow	635 ± 25.4 mm (25 ± 1 inch)
J-Ring	0 to 50 mm (0 to 2 inch)
VSI	0 to 1 (Highly Stable to Stable)

3.1.1.2 Hardened Properties

Concrete's hardened characteristics were not greatly considered due to the high powder content, a relatively low water-to-cementitious ratio, and the use of Type V Portland cement. The high powder content and low water-to-cementitious material, which are discussed in details in Section 3.1.2, can positively impact concrete's bulk characteristics. Type V Portland cement provides adequate resistance to sulfate attack. Some consideration to the compressive strength was given when considering the mixture proportioning design.

3.1.2 Mixture Design Considerations

To construct a mixture proportion that accounts for the previously discussed requirements of SCC, two considerations are discussed. The first consideration was fine-to-coarse aggregate ratio which was important to achieve SCC workability. The second consideration was water-to-cementitious materials (w/cm) and cement or cementitious materials partial replacement by limestone powder both of which can affect SCC's flow and hardened properties.

3.1.2.1 Coarse-to-Fine Aggregate Ratio Selection

The optimum coarse-to-fine aggregate ratio was chosen based on Shilstone's combined aggregate gradation (1990). Shilstone's original band that demonstrated the optimum workability factor and coarseness factor based on the coarse and fine ratio applied to traditional concrete mixtures. Since SCC requires more workability than traditional concrete, a different optimum coarseness factor and workability factor was required. In a technical bulletin circulated by W.R. Grace & Co.-Conn. (2005), it was stated SCCs should have an optimum coarseness factor below 40 and its workability factor to remain above 40. The coarseness factor was calculated as (Q / Q + I) x 100, or as the percent retained above the 9.5 mm sieve divided by the percent retained above the 2.36 mm sieve multiplied by 100. The workability factor was calculated based on the percent passing 2.36 mm sieve (Shilstone 1990).

To calculate workability and coarseness factors, the combined gradation of both the coarse and fine aggregates was required. The fine aggregate gradation was determined in the laboratory by a sieve analysis. Three fine aggregate samples were tested, and the percent passing each sieve was comparatively similar for research purposes. The coarse aggregate gradation was evaluated once obtained from the source as well. In order to maintain consistent aggregate gradation for selected SCCs mixtures, the coarse aggregates were sieved manually for each size gradation before they were combined to meet the desired gradation in the laboratory. The coarse aggregate gradation was determined by averaging the standard specifications for ASTM # 7 for percent passing 12.7 mm sieve and percent passing the 9.51 mm sieve. From test results, the percent passing the 4.76 mm sieve averaged around 0.22 percent and was considered unnecessary in the coarse aggregate gradation as ASTM # 7 allowed for 0-15% passing. The ASTM # 7 standard coarse aggregate specifications as well as the coarse aggregate gradation used in this study are shown in Table 3.2 and 3.3, respectively.

Table 3.2: Coarse aggregate test gradation

Sieve Size		Percent Passing					Selected Gradation
Sieve No.	mm	Sample 1	Sample 2	Sample 3	Sample 4	ASTM # 7	
1/2 sieve	12.5	94	92	99.1	97.7	90-100%	95%
3/8 sieve	9.5	55	40.6	64.1	48	40-70%	55%
No. 4	4.75	0.5	0.28	2.6	0.22	0-15%	0%
Pan		0	0	0	0		

Table 3.3: Selected coarse aggregate gradation by weight

Sieve No.	Percent Passing	Percent Retained	Percent Utilized
3/4 sieve	100	0	0
1/2 sieve	95	5	5
3/8 sieve	55	45	40
No.4	0	100	55

To determine the ratio of coarse aggregate to fine aggregate using the Shilstone combined aggregate gradation, various ratios of coarse-to-fine were examined. The ratios were 9:1 coarse to fine, 8:2, 7:3 and so on until 1:9 coarse to fine ratio. From these ratios, the combined percent passing and percent retained were determined and the coarseness factor (CF) and workability factor (WF) calculated. A sample calculation for the 9:1 ratio is provided in Table 3.4. From these calculations, Table 3.5 was derived to present the coarse to fine ratio, coarseness factor, and workability factor. Figure 3.1 displays the two factors plotted against the coarse-to-fine ratio.

From Figure 3.1, the ratio that held the coarseness factor below 40 and the workability factor above 40 was determined to be 0.426. For simplicity, this value was rounded up to 0.43. The aggregate volume was finalized as 43% coarse aggregate and 57% fine aggregate. This aggregate proportion was kept constant for all studied mixtures.

Table 3.4: Example Calculation of Shilstone (1990) Workability and Coarseness Factor for 9:1 Coarse-to-Fine Ratio

Sieve Size	Coarse	Fine	Total Coarse	Total Fine	Cumulative Retained	Percent Retained	Percent passing
	5 lb.	5 lb.	9 to 1 ratio	9 to 1 ratio			
1/2 sieve	0.25		0.45		0.45	4.5	95.5
3/8 sieve	2		3.6		4.05	40.5	59.5
No. 4	2.75	0.002	4.95	0.0004	9.00	90	9.99
No. 8		0.5		0.1	9.10	91	8.99
No. 16		1.6		0.320	9.42	94.21	5.79
No. 30		1.074		0.215	9.63	96.35	3.64
No. 50		0.9		0.18	9.82	98.15	1.84
No. 100		0.542		0.108	9.92	99.24	0.75
Pan		0.378		0.076	10	100	0
Workability factor equals percent passing No. 8							
8.995196157							
Coarseness factor equals percent retained of 3/8 in sieve divided by percent retained above No.8							
44.50314521							

Table 3.5: Calculated Workability and Coarseness Factors for Various Coarse-to-Fine Ratios

Coarse-to-fine ratio	WF	CF
0.9	8.99	44.50
0.8	17.99	43.89
0.7	26.98	43.14
0.6	35.98	42.17
0.5	44.97	40.89
0.4	53.97	39.11
0.3	62.97	36.45
0.2	71.96	32.09
0.1	80.96	23.63

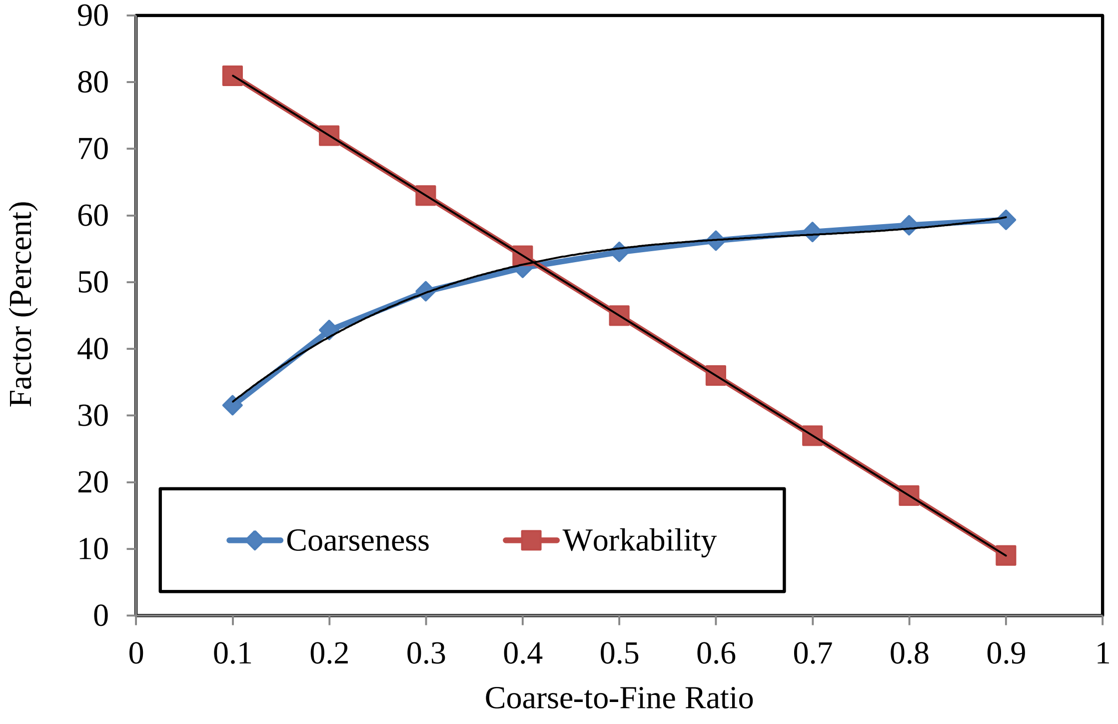

Figure 3.1: Coarseness and workability factor versus various coarse-to-fine ratios

3.1.2.2 Water Content and Powder Content

Another consideration for proportioning the selected SCCs was water-to-cementitious materials ratio and powder content. In regards to the water-to-cementitious materials ratio, the consideration was whether to use a constant water-to-cementitious materials (cement and supplementary cementitious material) ratio or a constant water-to-powder (cement, supplementary cementitious, and limestone powder) ratio.

For the purpose of this study, the upper limit stated by ACI 237 (2007) for a total powder content of 800 lbs/yd^3 was used. This powder content was defined as the cement, supplementary cementitious material, and limestone powder. The cementitious material or binder consisted of cement and supplementary cementitious material such as fly ash or slag. For this study, fly ash was used as supplementary cementitious material and replaced a portion of the Portland cement at a dosage rate of 20% by weight (8:2 ratio) for all studied SCCs. The next task was to examine whether limestone powder should replace a portion of the cement or cementitious materials.

All these considerations were taken into account, and mixture proportions for each scenario were created. The first two selected scenarios used a constant water-to-cementitious materials ratio of 0.40 which from the prior study was found to prevent formation of autogeneous shrinkage (Rodden 2005). The first scenario used limestone powder to substitute a portion of cement only. The mixture proportions for 0, 5, 10, 15, 20, 25, and 30% partial replacement by weight of cement with limestone powder are shown in Table 3.6. The water-to-cementitious materials ratio, water-to-powder ratio, paste percent, mortar percent, and coarse aggregate percent of concrete volume are also displayed in Table 3.7. The second scenario considered limestone powder to replace a portion of cementitious materials (cement and fly ash) at the same rate as discussed previously. The mixture proportions and constituents used in this study are shown in Table 3.8, whereas their water-to-cementitious materials, water-to-powder ratio, paste percent, mortar percent, and coarse aggregate percent of concrete volume are documented in Table 3.9.

The last two selected scenarios examined a constant water-to-powder ratio for mixtures for which limestone powder replaced a portion of cementitious materials (cement and fly ash). The mixture proportions using a constant water-to-powder ratio and limestone powder replacing a portion of cement are shown in Table 3.10. The water-to-cementitious materials ratio, water–to-powder, paste percent, mortar percent and coarse aggregate percent are presented in Table 3.11. Mixture proportions for SCCs utilizing constant water-to-powder mixtures and limestone powder replacing a portion of cementitious materials are shown in Table 3.12 along with the SCC's respective mixture characteristics in Table 3.13.

Table 3.6: Mixture proportions for constant water-to-cementitious materials and limestone powder replacement of cement (materials by weight kg/m^3)

MIX ID	Cement	Fly Ash	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate
L/C 0, W/CM .40	395.51	79.10	0.00	189.85	756.04	1005.46
L/C 5%, W/CM 0.40	375.74	79.10	19.78	181.94	764.25	1016.37
L/C 10%, W/CM 0.40	355.96	79.10	39.55	174.03	772.45	1027.28
L/C 15%, W/CM 0.40	336.19	79.10	59.33	166.12	780.65	1038.18
L/C 20%, W/CM 0.40	316.41	79.10	79.10	158.21	788.85	1049.09
L/C 25%, W/CM 0.40	296.64	79.10	98.88	150.30	797.06	1060.00
L/C 30%, W/CM 0.40	276.86	79.10	118.65	142.38	805.26	1070.91

Table 3.7: Constant water-to-cementitious materials and limestone powder replacement of cement

MIX ID	W/C	W/CM	W/CM+P	% Paste	% Mortar	% Coarse Aggregate
L/C 0, W/CM .40	0.48	0.40	0.40	36.45	72.67	27.33
L/C 5% W/CM 0.40	0.48	0.40	0.38	35.03	72.38	27.62
L/C 10%, W/CM 0.40	0.49	0.40	0.37	33.61	72.08	27.92
L/C 15% W/CM 0.40	0.49	0.40	0.35	32.19	71.78	28.20
L/C 20% W/CM 0.40	0.50	0.40	0.33	30.77	71.48	28.50
L/C 25% W/CM 0.40	0.51	0.40	0.32	29.35	71.19	28.80
L/C 30%, W/CM 0.40	0.51	0.40	0.30	27.90	70.89	29.10

Table 3.8: Mixture Proportions for constant water-to-cementitious materials and limestone powder replacement of cementitous materials (materials by weight kg/m3)

MIX ID	Cement	Fly Ash	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate
L/C 0, W/CM .40	395.51	79.10	0.00	189.85	756.04	1005.46
L/CM 5%, W/CM 0.40	375.73	75.16	23.73	180.36	766.42	1019.25
L/CM 10%, W/CM 0.40	355.95	71.21	47.46	170.86	776.79	439.76
L/CM 15%, W/CM 0.40	336.18	67.25	71.19	161.37	787.15	1046.83
L/CM 20%, W/CM 0.40	316.40	63.30	94.92	151.88	797.52	1060.62
L/CM 25%, W/CM 0.40	296.63	59.34	118.66	142.39	807.89	1074.41
L/CM 30%, W/CM 0.40	276.85	55.38	142.39	132.89	818.26	1088.20

Table 3.9: Constant water-to-cementitious materials and limestone powder replacement of cementitous materials

MIX ID	W/C	W/CM	W/CM+P	% Paste	% Mortar	% Coarse Aggregate
L/CM 5%, W/CM 0.40	0.48	0.40	0.38	34.70	72.29	27.70
L/CM 10%, W/CM 0.40	0.48	0.40	0.36	32.90	71.90	28.08
L/CM 15%, W/CM 0.40	0.48	0.40	0.34	31.20	71.50	28.45
L/CM 20%, W/CM 0.40	0.48	0.40	0.32	29.40	71.17	28.82
L/CM 25%, W/CM 0.40	0.48	0.40	0.30	27.70	70.90	29.20
L/CM 30%, W/CM 0.40	0.48	0.40	0.28	25.90	70.40	29.57

Table 3.10: Mixture Proportions for constant water-to-powder and limestone powder replacement of cement (materials by weight kg/m3)

MIX ID	Cement	Fly Ash	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate
L/C 0, W/CM .40	395.51	79.10	0.00	189.85	756.04	1005.46
L/CM 5%, W/CM 0.40	375.74	79.10	19.78	189.85	754.83	1003.84
L/CM 10%, W/CM 0.40	355.96	79.10	39.55	189.85	753.62	1002.23
L/CM 15%, W/CM 0.40	336.19	79.10	59.33	189.85	752.40	1000.61
L/CM 20%, W/CM 0.40	316.41	79.10	79.10	189.85	751.19	999.00
L/CM 25%, W/CM 0.40	296.64	79.10	98.88	189.85	749.97	997.38
L/CM 30%, W/CM 0.40	276.86	79.10	118.65	189.85	748.76	995.77

Table 3.11: Constant water-to-powder and limestone powder replacement of cement

MIX ID	W/C	W/CM	W/CM+P	% Paste	% Mortar	% Coarse Aggregate
L/C 5% W/CM + P 0.40	0.51	0.42	0.40	35.80	72.72	27.28
L/C 10%, W/CM+P 0.40	0.53	0.44	0.40	35.19	72.76	27.24
L/C 15% W/CM+P 0.40	0.56	0.46	0.40	34.56	72.81	27.19
L/C 20% W/CM+P 0.40	0.60	0.48	0.40	33.90	72.84	27.15
L/C 25% W/CM+P 0.40	0.64	0.51	0.40	33.31	72.89	27.11
L/C 30%, W/CM +P 0.40	0.69	0.53	0.40	32.68	72.93	27.06

Table 3.12: Mixture Proportions for constant water-to-powder and limestone powder replacement of cementitious materials (materials by weight kg/m^3)

MIX ID	Cement	Fly Ash	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate
L/C 0, W/CM .40	395.51	79.10	0.00	189.85	756.04	1005.46
L/CM 5%, W/CM 0.40	375.73	75.16	23.73	189.85	755.11	1004.22
L/CM 10%, W/CM 0.40	355.95	71.21	47.46	189.85	754.19	1002.99
L/CM 15%, W/CM 0.40	336.18	67.25	71.19	189.85	753.26	1001.74
L/CM 20%, W/CM 0.40	316.40	63.30	94.92	189.85	752.32	1000.51
L/CM 25%, W/CM 0.40	296.63	59.34	118.66	189.85	751.39	999.27
L/CM 30%, W/CM 0.40	276.85	55.38	142.39	189.85	750.46	998.04

Table 3.13: Constant water-to-powder and limestone powder replacement of cementitious materials

MIX ID	W/C	W/CM	W/CM+P	% Paste	% Mortar	% Coarse Aggregate
L/C 5% W/CM + P 0.40	0.51	0.42	0.40	35.60	72.70	27.29
LC 10%, W/CM+P 0.40	0.53	0.44	0.40	34.85	72.74	27.26
LC 15% W/CM+P 0.40	0.56	0.47	0.40	34.05	72.77	27.22
L/C 20% W/CM+P 0.40	0.60	0.50	0.40	33.25	72.80	27.19
L/C 25% W/CM+P 0.40	0.64	0.53	0.40	32.46	72.80	27.15
L/C 30%, W/CM +P 0.40	0.69	0.57	0.40	31.67	72.88	27.12

The American Concrete Institutes mixture proportioning requirements for self-consolidating concrete are as follows: paste volume of 34-40%, mortar volume of 68-72%, and coarse aggregate volume of 28-32% (ACI 2007). From Tables 3.7, 3.9, 3.11, and 3.13, it was observed that a constant water-to-powder ratio provided slightly below required coarse aggregate volume. As can be seen in Table 3.13, the use of uniform water-to-powder ratio resulted in an increase in water-to-cementitious materials ratio of the SCCs. This in turn could effectively reduce concrete strength as excess water reduces calcium silicate hydrate bonds (MAST 2014). As such, it was decided to use a constant water-to-cementitious materials ratio for all selected SCCs used in this study.

The next consideration for this study was whether the limestone powder would replace cement only, or the total cementitious materials consisting of cement and fly ash. From Tables 3.7 and 3.9, it can be seen that using limestone as a partial replacement of both cementitious materials created the lowest water-to-cement ratio which was desired to produce better concrete bulk properties. As such, for the purpose of this investigation, a constant water-to-cementitious materials ratio and partial replacement of cementitious materials by weight with limestone powder were adopted.

To ensure that the water-to-cementitious materials ratio of 0.40 could provide acceptable flowability for higher replacement levels, a trial batch of 30% by weight replacement of cementitious materials by limestone powder was used. The resulting freshly-mixed SCC was too dry for HRWRA to generate the target flow properties. As an alternative, it was decided to increase the water-to-cementitious materials ratio to 0.45, which could still provide adequate resistance from autogeneous shrinkage. A subsequent trial batch produced a fresh matrix that met the required fluidity with the use of HRWRA. The mixture proportions using water-to-cementitious materials ratio of 0.45 is shown in Table 3.14 along with the required HRWRA admixture dosage used for each replacement level of cementitious materials by limestone powder. The water-to-cement ratio, water-to-cementitious materials ratio, water-to-powder ratio, paste percentage, mortar percentage, and coarse aggregate percentage by volume are shown in Table 3.15.

Table 3.14: Mixture proportions for water-to-cementitious materials ratio of 0.45 and limestone partial replacement of cementitious materials (materials by weight kg/m^3)

Mix ID	Cement	Fly Ash	Limestone Powder	Water	Coarse Aggregate	Fine Aggregate	HRWRA
L/CM 0[1], W/CM .45[2]	395.5	79.1	0.0	213.6	727.8	965.5	0.87
L/CM 5%, W/CM 0.45	375.7	75.2	23.7	202.9	739.6	981.1	1.03
L/CM 10%, W/CM 0.45	356.0	71.2	47.5	192.2	751.4	996.7	1.22
L/CM 15%, W/CM 0.45	336.2	67.3	71.2	181.5	763.1	1012.3	1.44
L/CM 20%, W/CM 0.45	316.4	63.3	94.9	170.9	774.9	1028.0	1.55
L/CM 25%, W/CM 0.45	296.6	59.3	118.7	160.2	786.7	1043.6	1.58
L/CM 30%, W/CM 0.45	276.9	55.4	142.4	149.5	798.5	1059.2	1.87

[1]- denotes limestone powder replacing portion of cementitious material and percent replacement

[2]-denotes constant water to cementitious material ratio of 0.45

Table 3.15: Water-to-cementitious materials ratio of 0.45 and limestone powder partial replacement of cementitious materials

MIX ID	W/C[1]	W/CM[2]	W/CM+P[3]	% Paste[4]	% Mortar	% Coarse Aggregate
L/CM 0, W/CM .45	0.54	0.45	0.45	38.83	73.69	26.31
L/CM 5%, W/CM 0.45	0.54	0.45	0.43	37.84	73.27	26.73
L/CM 10%, W/CM 0.45	0.54	0.45	0.41	36.85	72.84	27.16
L/CM 15%, W/CM 0.45	0.54	0.45	0.38	35.86	72.42	27.58
L/CM 20%, W/CM 0.45	0.54	0.45	0.36	34.87	71.99	28.01
L/CM 25%, W/CM 0.45	0.54	0.45	0.34	33.87	71.57	28.43
L/CM 30%, W/CM 0.45	0.54	0.45	0.32	32.88	71.14	28.86

[1]- denotes water to cement ratio

[2]- denotes water to cementitious ratio which includes cement and fly ash

[3]- denotes water to cementitious and powder ratio; includes cement, fly ash, and limestone powder

[4]- percentage of paste of total volume; includes water, cement, fly ash, and limestone powder

3.2 Mixing Procedure

All SCCs were batched in an electric counter-current pan mixer with a rotating rate of 14.5 rpm and a capacity of 0.028 m^3 (1 ft^3). A uniform volume of 0.0127 m^3 (0.45 ft^3) was used to ensure uniform batching for all selected SCCS. The mixing sequence consisted of adding the coarse aggregate first with one third of the total water and blending for two minutes. Afterward, the fine aggregate were added with another one third of the water for another two minutes before the cement, supplementary cementitous material, limestone powder, and the remaining water (except 20 grams to wash chemical admixture) were added to blend for three minutes. Lastly, chemical admixtures such as HRWRA and/or VMA were added and washed out with the remaining 20 grams of water. The mixing continued for three minutes, allowed two minutes to rest, and then restarted for an additional two minutes.

Upon batching, flow property tests of slump flow, T_{50} flow time, visual stability index (VSI), and J-Ring were conducted to ensure target flow ability, passing ability, and segregation resistance were met. Their tests were performed immediately, usually within two minutes after mixing, to guarantee there was no discrepancy with time.

Concrete compressive strength and transport properties tests were examined after selected curing ages were reached. Compressive strength specimens were casted in cylindrical molds of 102 mm (4 inches) diameter and 204 mm (8 inches) height. The selected transport properties tests were water penetration, capillary absorption, absorption, rapid chloride penetration, rapid migration, and chloride diffusion. All transportation tests, except for water penetration test, used 102 mm (4 inches) diameter and 51 mm (2 inches) height cylindrical molds. Water penetration samples were casted in 152.4 mm (6 inches) cubes. After casting, all samples were cured in air tight molds for 24 hours. Upon demolding, the samples were placed in a moist curing room at room temperature for 28, 90, and 180 days before testing took place. A summary of the test methods and standards used are presented in chapter 2.

3.3 Admixture Dosage

To obtain the optimum dosage of admixture required for adequate SCC, trial batches were mixed and tested for slump flow, T_{50}, visual stability index (VSI), and J-Ring. Selected SCC mixtures included the control (cement and fly ash), a series of SCCs containing 5 to 30% partial replacement of cementitious materials by limestone powder with approximately average particle size of 8 microns designated as L8 series, and a series of SCCs containing 10, 15 and 20% by weight with limestone powder which had an average particle size of 3 microns designated as L3 series.

A combination of HRWRA and VMA were initially tested to achieve desired fresh properties. An initial assumption of admixture dosage was added to trial batches, the fresh properties were tested, and the dosage was adjusted based on observation. This process was repeated until all mixtures obtain a slump flow of 635 mm ± 25.4 mm (25 ±1 inch), a VSI of 0 to 1 (highly stable to stable), and a J-Ring of 50 mm (2 inches) or less. Table 3.16 demonstrates the selected HRWRA dosage (kg/m^3), VMA dosage (kg/m^3), slump flow (mm), VSI, T_{50} flow time, and J-Ring (mm) results for the control SCC, L8 limestone powder series and L3 limestone powder series.

As seen in Table 3.16, the HRWRA dosage increased with increasing partial replacement of cementitious materials with limestone powder while VMA was not required for studied SCC batching. As limestone powder content increased in studied

SCCs, the water content reduced in order to maintain a uniform water-to-cementitious materials ratio which in turn created a higher demand of HRWRA to achieve fluidity. VMA was unnecessary as the high powder content used in SCC mixture proportions provided acceptable viscosity. It can be seen that the smaller sized limestone powder series L3 required slightly higher HRWRA amount at similar partial replacement levels. Detwiler (1995) found narrower particle size distributions result in higher water demand while wide particle size distribution shall decrease the water demand due to a wider particle size distribution filling the gap between cement clinker particles

Table 3.16: Chemical Admixtures Dosage and Flow properties of Studied SCCs

	HRWRA dosage (kg/m$^{3)}$	VMA dosage (kg/m$^{3)}$	Slump flow (mm)	VSI	T_{50} (seconds)	J-Ring (mm)
Control	0.87	0.00	622.30	1.00	1.06	25.00
L8-5	1.03	0.00	635.00	1.00	1.16	12.50
L8-10	1.22	0.00	622.30	1.00	1.47	6.25
L8-15	1.44	0.00	660.40	1.00	1.66	37.50
L8-20	1.55	0.00	660.40	1.00	1.79	25.00
L8-25	1.58	0.00	647.70	1.00	2.02	37.50
L8-30	1.87	0.00	647.70	1.00	2.33	31.25
L3-10	1.34	0.00	622.30	1.00	1.32	25.00
L3-15	1.54	0.00	660.40	1.00	0.78	25.00
L3-20	1.76	0.00	635.00	1.00	1.47	25.00
*L8- designates limestone powder with average particle size of 8 microns						
*L3- designates limestone powder with average particle size of 3 microns						

3.4 Particle Size Distribution

The particle size distribution of studied SCC mixtures was determined to analyze L8 limestone powder's effect on studied SCC's physical characteristics. Figure 3.2 displays the particle size distribution of the powder (cement, fly ash, and limestone powder) and was focused on particle size less than 10 microns to examine limestone powder's effect on finer size distribution.

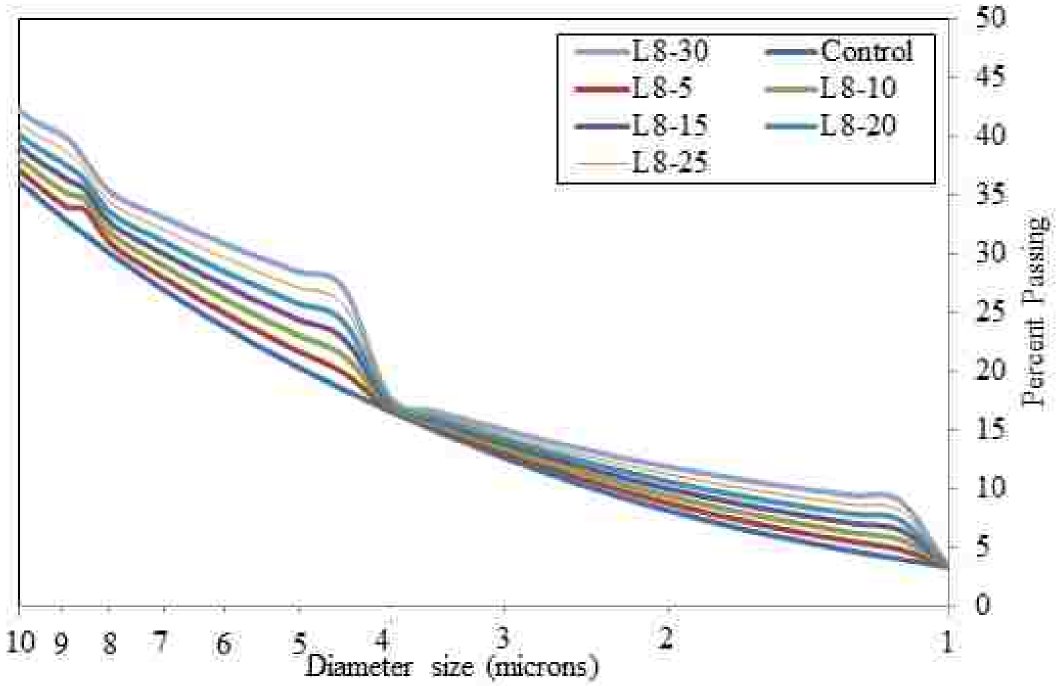

Figure 3.2: Particle size distribution of the total powder content of the studied SCCs containing L8 limestone powder

From Figure 3.2, it was apparent that increasing L8 limestone powder content created a finer particle size distribution especially for distribution of particles in diameter of 10 microns or less. This indicated that L8 limestone powder was finer than the cement and fly ash, and created a finer gradation compared to the control SCC (cement and fly ash). The decrease in fineness of the particle size distribution at diameter size of 4 microns was due to a more detailed particle size analysis provided for cement and fly ash. L8 limestone powder's particle size analysis provided by the manufacturer did not have the same number of gradation sizes as cement and fly ash did.

The powder particle size distribution which incorporated L3 limestone powder as a partial replacement of cementitious materials was also examined in order to verify the impact of smaller sized limestone powder on SCC powder size distribution. Figure 3.3 demonstrates the powder particle size distribution of the L3 limestone powder series compared to control SCC and L8 limestone powder contained SCCs.

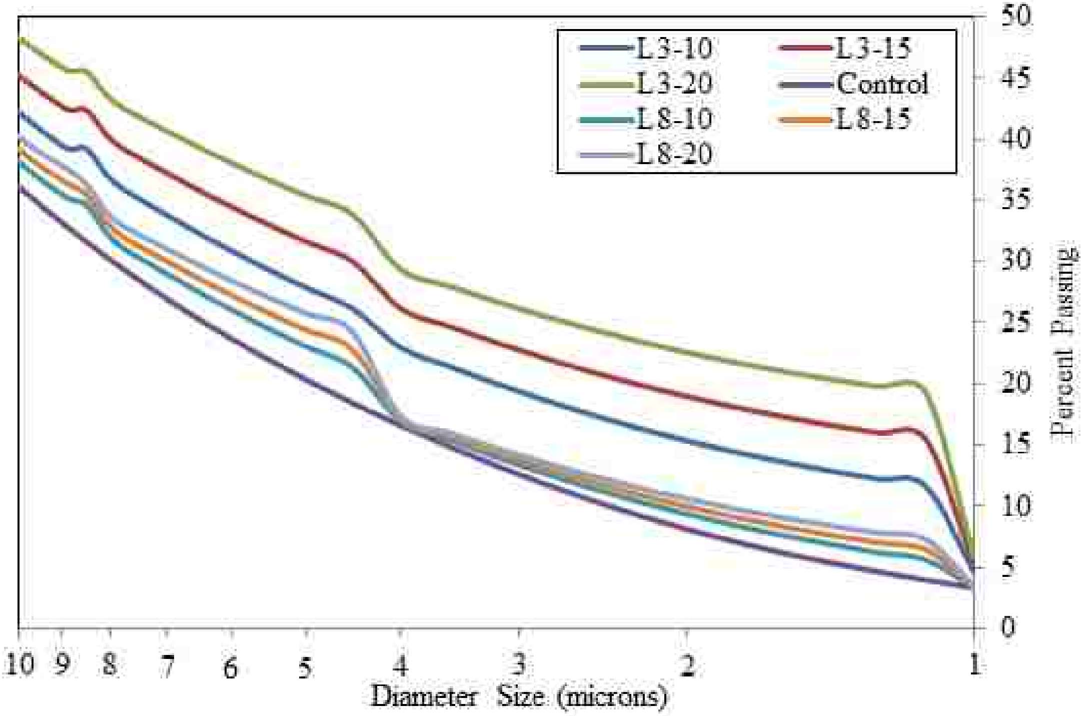

Figure 3.3: Particle size distribution of the total powder content of the studied SCCs using L8 and L3 limestone powder

As shown from Figure 3.3, the fineness of the particle size distribution curve was greatly improved with increasing L3 limestone powder content as compared with the control and L8 limestone powder. This was expected as L3 limestone powder had a much smaller particle mean size than that of L8 limestone powder. The same decrease at diameter size of 4 microns was observed but was not as apparent due to L3 limestone powder's much smaller size gradation.

3.5 X-Ray Diffraction Analysis

Limestone powder, as mentioned from previous studies, has the ability to react with the C_3A phase of cement to produce either a mono-carboaluminate or hemi-carboaluminate hydrate (De Weerdt et. al. 2010). De Weerdt et. al. (2010) found in X-ray diffraction analysis of limestone powder contained pastes that calcium monocarbonate and calcium hemicarbonate hydrate replaced the calcium monosulphate hydrate. X-ray diffraction was implemented to analyze whether the carboaluminate hydrate was present in pastes containing either of the two limestone powders with average sizes of 8 and 3 microns. A control paste which contained cement and fly ash was also analyzed. The paste samples were cured for 90 days. The results of the X-ray diffraction are shown below in Figures 3.4 through 3.6.

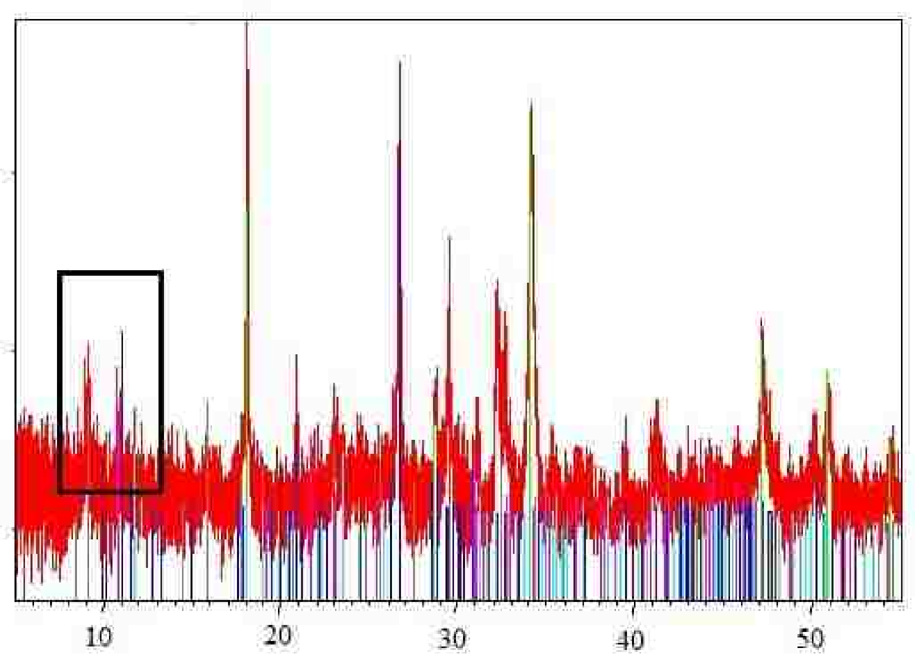

Figure 3.4: Control (cement and fly ash) paste X-ray diffraction

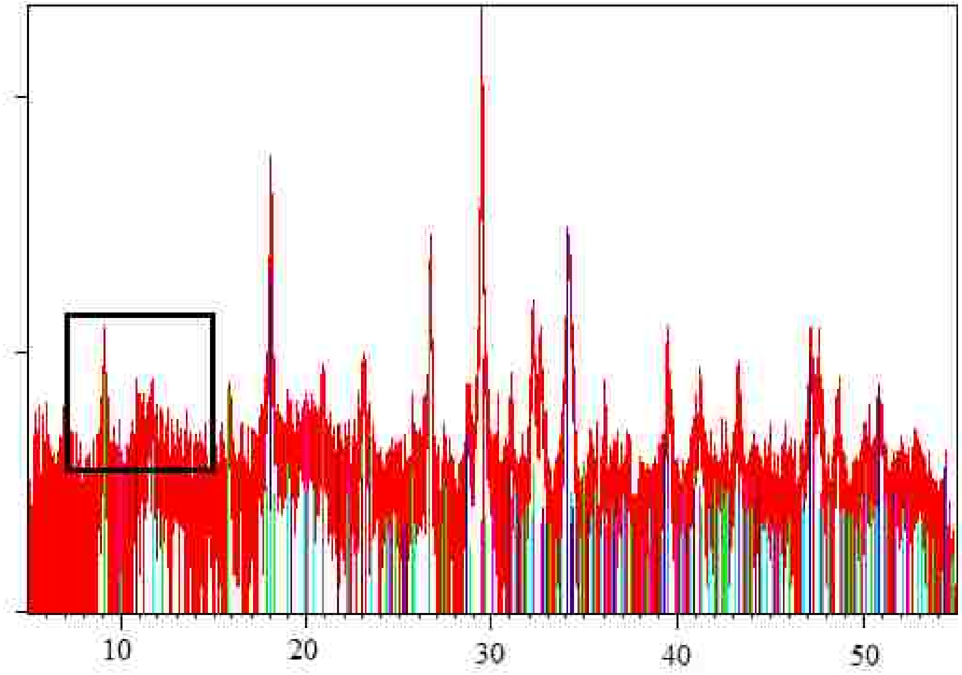

Figure 3.5: L8-10 (L8 limestone powder replacing 10% of cementitious materials) paste X-ray diffraction

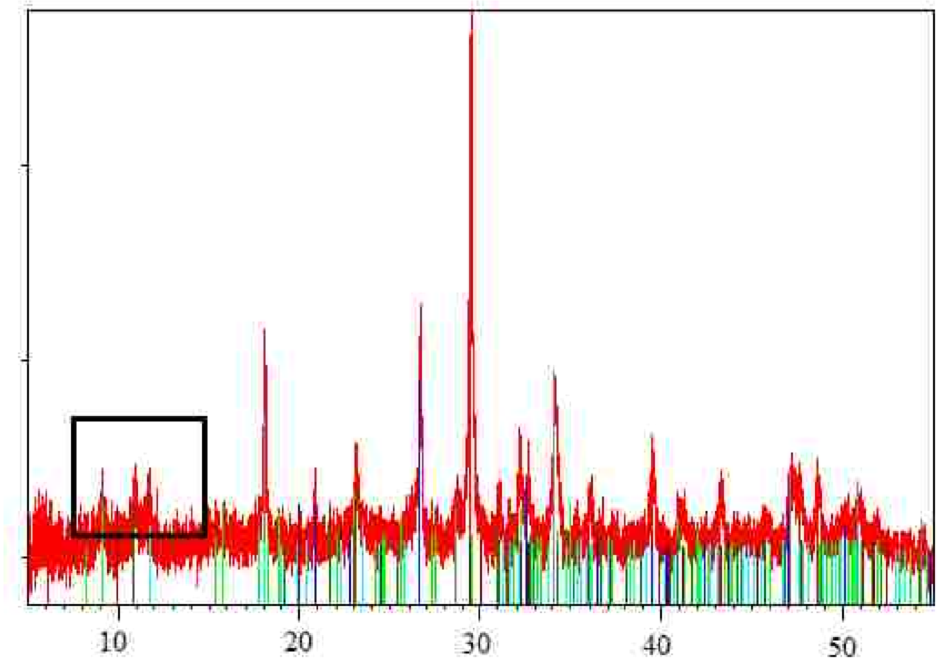

Figure 3.6: L3-10 (L3 limestone powder replacing 10% cementitious materials) paste X-ray diffraction

Examining the X-ray diffraction results, it was apparent the three pastes had similar crystalline phases. When observing the area of the graphs highlighted in black, the crystalline phases appeared to differ between the control paste and the two limestone powder contained pastes. The two limestone powder contained pastes appeared to have two peaks in place where the control paste had its second straight peak. The program X'Pert HighScore Plus demonstrated the two crystalline phases calcium aluminum carbonate hydrate and calcium aluminum oxide carbonate hydroxide hydrate were present in the highlighted region of both L3 and L8 limestone powder contained paste X-ray diffractions. This finding conformed to the results of prior X-ray diffraction studies (De Weerdt et. al. 2010).

3.6 Conclusions

Based on the findings of the tests conducted for this chapter, the following conclusions can be made:

(a) The selected optimum ratio of coarse-to-fine aggregate to ensure required flowability for the self-consolidating concretes was 43 to 57. This ratio was determined by using Shilstone's combined gradation (1990) and recommendations provided by Grace Construction (2005).

(b) In lieu of water-to-powder ratio, a constant water-to-cementitious materials ratio was selected to ensure optimum strength properties. This approach resulted in reduction of concrete fluidity which was compensated by inclusion of additional chemical admixtures. It was also decided to have limestone powder replacing a portion of cementitious materials, instead of cement alone, to maintain a uniform water-to-cement and water-to-cementitious materials ratio. The water-to-cementitious ratio of 0.45 was selected as it provided enough fluidity to meet target flow properties.

(c) The inclusion of limestone powder at all levels of partial replacement for cementitious materials did not require the use of a viscosity modifying admixture as the high powder content of the studied SCCs provided adequate viscosity to prevent segregation.

(d) For the medium sized limestone powder, designated as L8, increasing limestone powder replacing a portion of cementitious materials resulted in increasing HRWRA dosage as a result of decreasing water content to maintain a uniform water-to-cementitious materials ratio. The smaller sized limestone powder referred to as L3 displayed similar results but required slightly larger dosages of HRWRA due to its small particle size distribution. All studied SCCs achieved the target flow properties.

(e) The particle size distribution was improved with increasing content of limestone powder. Limestone powder with an average size of 3 microns greatly improved the particle size distribution with further partial replacement of cementitious materials as compared to when limestone powder with average size of 8 microns partially replaced the cementitious materials.

(f) X-ray diffraction was implemented to determine the presence of either mono-carboaluminate or hemi-carboaluminate in pastes containing either L8 or L3 limestone powder. The results demonstrated the carboaluminate hyrdates were present yet not in a control paste (cement and fly ash).

CHAPTER 4

INFLUENCE OF LIMESTONE POWDER AS A PARTIAL REPLACEMENT OF CEMENTITIOUS MATERIALS ON COMPRESSIVE STRENGTH AND TRANSPORT PROPERTIES OF SELF-CONSOLIDATING CONCRETES

The purpose of this chapter is to evaluate the influence of limestone powder on the transport properties of self-consolidating concrete. The transport properties examined were absorption, capillary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion. Compressive strength of the studied SCCs was also evaluated. For this portion of the study, a medium gradation of limestone powder denoted as L8 was selected to substitute a portion of the cementitious materials (Portland cement and fly ash) at levels of 5, 10, 15, 20, 25, and 30% by weight. In this chapter, various aspects of the individual tests are discussed; the results are presented; and an interpretation and explanation of results are offered.

4.1 Compressive Strength

Compressive strength is the required stress to cause fracture in a specimen. ASTM C 39, was used to evaluate the compressive strength of the studied self-consolidating concretes. The compressive strength of concrete is highly dependent on the utilized water-to-cement ratio, which is defined as the mass of water in the mix divided by the mass of cement in the mix (WHD Microanalysis Consultants Ltd 2005). Where a suitable water-to-cement ratio is used, in theory, the cement can form cement hydration products by reacting with water. However, with higher w/c ratios, the excess water that occupies space can form into either pores filled with water or air which negatively affects concrete’s strength (WHD Microanalysis Consultants Ltd 2005). Concrete’s strength comes from three main components, which include the mortar phase, the aggregates, and the interfacial transition zone. Larger aggregates tend to produce a weaker interfacial transition zone which can cause additional micro-cracks (Nemati 2013). Coarse aggregates, however, can provide greater crack arresting mechanisms than the paste matrix or fine aggregates (Naus et. al. 1970).

Limestone powder can improve concrete's early strength by acting as nucleation sites for CH and C-S-H reaction products. This accelerates the hydration of the clinker minerals, especially C_3S (Pera et. al. 1999; Bonavetti 1998). Limestone powder particles can also fill voids between cement grains to produce an improved particle packing as well as a dispersion of the cement clinker (Ellerbrock et. al. 1990). It is also possible limestone powder can react with cement's C_3A phase to create a mono-carboaluminate hydrate which can slightly increase the hydration products volume, and in turn, increase the compressive strength (Matschei et. al. 2007; Lothenbach et. al. 2008; Hiaro et. al. 2007).

The pozzolanic chemical reaction of fly ash with the calcium hydroxide provided by cement hydration contributes to the development of the strength (FHWA 2011). The reaction is demonstrated below.

$$\mathrm{C_3S + H \rightarrow CaOH + CSH}$$

$$\mathrm{S + CaOH \rightarrow CSH}$$

The first line is the reaction of cement particles with water to form calcium hydroxide and a CSH hydrate. The second line demonstrates the reaction of the silica from fly ash with the calcium hydroxide products to produce additional CSH products. The continued development of CSH compounds contributes to an ongoing strength gain of fly ash contained concretes (FHWA 2011). Alsadey (2012) discussed the role of superplasticizer in increasing the compressive strength by providing additional water in concrete mixing which can accelerate cement hydration due to cement particle deflocculation and also yield a denser concrete.

4.1.1 Compressive Strength of Studied L8 Limestone Powder Contained SCCs at 28-, 90-, and 180-day Curing Ages

The average results for the 28-, 90-, and 180-day curing compressive strength for studied L8 limestone powder contained SCCs are shown in Table 4.1 and Figure 4.1. The strength improvement, expressed in percentage, from the control SCC for each L8 limestone powder contained SCC at 28-day, 90-day, 180-day is also displayed. Lastly, the strength improvements from 28 to 90 days, from 28 to 180 days, and from 90 to 180 days are presented in Table 4.1. Individual sample compressive strengths are presented in Appendix B, Table B4.1.

Table 4.1: 28-, 90-, and 180-day average compressive strength of studied L8 limestone powder contained SCCs

Mix ID	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day CS (MPa)	55.89	57.29	60.12	59.23	59.91	60.74	59.80
% gain from control		2.49	7.56	5.96	7.19	8.67	6.99
90-day CS (MPa)	70.91	73.97	74.32	73.33	74.96	75.81	76.08
% gain from control		4.32	4.82	3.42	5.71	6.91	7.29
180-day CS (MPa)	83.53	85.31	87.16	87.68	86.86	89.91	90.19
% gain from control		2.13	4.35	4.98	4.00	7.64	7.98
% gain from 28 to 90	26.87	29.13	23.60	23.82	25.11	24.81	27.22
% gain from 28 to 180	49.44	48.92	44.99	48.05	44.99	48.03	50.82
% gain from 90 to 180	15.11	13.29	14.73	16.37	13.71	15.68	15.65

The overall trend at 28-day curing was a negligible increase in compressive strength with each 5% by weight incremental increase in the amount of limestone powder replacing the same percentage level of Portland cement and fly ash. Mixture L8-5 had only a 2% increase in compressive strength from that of the control SCC. From this point on, additional replacement of cementitious materials with limestone powder had a marginal change in compressive strength, ranging between 6 and 8%, when compared to that of the control SCC. This was mainly due to a constant water-to-cementitious materials ratio used for the studied SCCs which allowed for its sizeable substitution by limestone powder without drastically altering the paste quality.

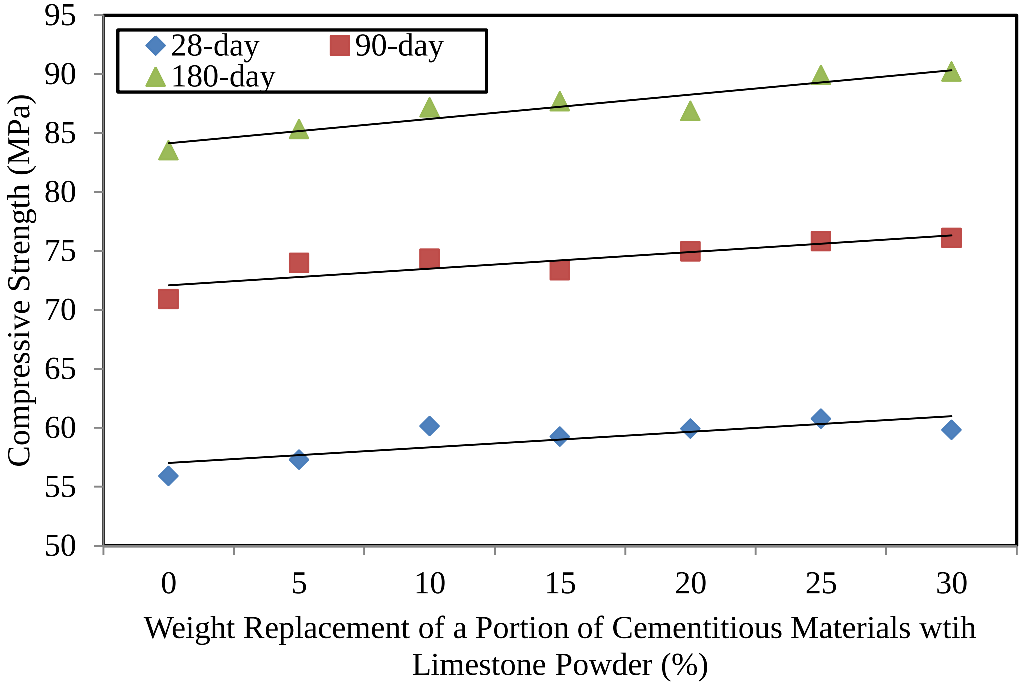

Figure 4.1: 28-, 90-, 180-day compressive strength results as a function of limestone powder replacing a portion of cementitious materials

The marginal improvement in compressive strength at 28-day curing age can be attributed to the limestone powder's filler effect which can improve packing density and compressive strength. The particle size analysis of L8 limestone powder, fly ash, and Portland cement discussed in Chapter 3 demonstrated the inclusion of L8 limestone powder produced a finer powder matrix. As shown in Chapter 3, increasing limestone powder content required a slightly higher coarse aggregate volume. The slightly higher aggregate volume may in turn have slightly increased the compressive strength due to better crack arresting. Lastly, the role of superplasticizer on compressive strength cannot be ignored. As noted in Table 3.17, the increase in limestone content required higher amounts of high range water reducer to obtain uniform flow properties. The slightly higher dosage of HRWRA may have resulted in a more dense concrete which slightly improved the compressive strength.

It can be surmised as with 28-day curing, that the 90-day curing compressive strength marginally improved with additional partial replacement of cementitious materials with limestone powder. The studied L8 limestone powder contained SCCs appeared to generally have a 4 to 7% gains in compressive strength. Lower partial replacement levels with limestone powder such as Mixtures L8-5, L8-10, and L8-15 demonstrated comparatively 4%. Mixtures L8-20, L8-25, and L8-30 displayed a marginally larger strength improvement with an average gain in compressive strength of 7%.

The marginal improvement in compressive strength between the control SCC and L8 limestone powder contained SCCS can be attributed to similar factors affecting 28-day cured samples. Constant water-to-cementitious materials ratio provided sufficient water for the cement and fly ash to react, but did not produce excess water to negatively affect the pore structure among the studied SCCs. The finer size of L8 limestone powder provided improved particle packing and may have marginally increased the compressive strength. Slightly higher volume of coarse aggregate with increasing limestone powder content could have also provided better crack arrestment to increase compressive strength. The role of superplasticizer may have also led to a denser pore structure and in turn marginally higher compressive strength of L8 limestone powder contained SCCs.

The compressive strength of studied SCCs at 180-day curing displayed a similar strength improvement as compared to the control SCC with limestone powder replacing a portion of the cementitious materials as seen in the 28- and 90-day curing results. Mixture L8-5 only demonstrated an increase of strength of approximately 2%. Increasing limestone powder partial replacement of cementitious materials provided strength improvements ranging between 4 and 8% for all other studied L8 limestone powder contained mixtures. The marginal strength gain can be attributed to the filler effect provided by the limestone powder, increase in coarse and fine aggregate, or an increase in HRWRA content as discussed in 28- and 90-day curing compressive strength results.

All SCCs demonstrated similar strength gains of approximately 25% strength increase between 28- and 90-day curing. Likewise, increasing compressive strength was evident between 90- and 180-day curing, however in a less extent, with an average strength gain of 17%. The higher strength gain from 28- to 90-day curing as opposed from 90- to 180-day curing signified the fly ash was mainly reactive between 28 and 90 days of continuous curing. After 90 days, it was apparent some pozzolanic reaction was still present, yet not as significant prior to 90 days. The strength gain between all curing ages was due to fly ash's pozzolanic reaction which produced additional CSH compounds to create a denser pore structure and in turn increase compressive strength.

4.2 Absorption

Absorption of the studied self-consolidating concretes was evaluated in accordance with ASTM C 642 "Standard Test Method for Density, Absorption, and Voids in Hardened Concrete." The absorption was divided into three separate tests; absorption after immersion, absorption after immersion and boiling, and volume of air voids. The results of these tests are discussed in the following sub sections.

4.2.1 Absorption After Immersion (AAI)

The process of absorption assumes that larger capillary spaces in a paste are filled with water first. The finer gel pores are filled much slower with water due to their lower permeability. The aggregate's coarse pores may be filled with water only after a relatively excessive amount of saturation occurs in the paste around the aggregate. Water from the aggregate can be removed by the paste's much finer pore structure if the degree of saturation is low. The air voids after long exposure to water may become filled with water (Verbeck 1978).

Sellevold (2005) used an absorption process of immersing specimens in water for one week to measure the amount of water taken up due to water suction. It may be assumed that the absorption after immersion can be a function of the capillary suction occurring in the concrete. Capillary absorption is where the pores fill with water due to capillary suction (Benn et. al. 2012).

Limestone powder replacing a portion of the cementitious materials can affect the absorption due to either physical or chemical effects. Limestone powder can produce a filler effect in which limestone powder's small particles fill the voids between cement particles. The filler effect may enhance the packing density, decrease the essential void structure, and lessen the entrapped water in the system. Limestone powder's chemical effects incorporate supplied ions into the phase solution, thus transforming the kinetic of hydration and the morphology of hydration products (Daimon and Sakai 1998). Fly ash can react with cement by binding calcium hydroxide with free silica through pozzolanic reactions, thus producing a non-soluble CSH structure which decreases capillary structures and reduce water infiltration (O'Flahtery and Mangat 1999).

4.2.1.1 Absorption After Immersion of Studied L8 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The average absorption after immersion results for the investigated SCCs are given in Table 4.2, whereas their individual results are documented in the Appendix B, Table B4.2. Table 4.2 also presents percent difference between absorption after immersion of L8 limestone powder contained SCCs and that of the control SCC. In Figure 4.2, the absorption after immersion results of 28 and 90 days curing are also presented as a function of replacement percentage of cementitious materials with L8 limestone powder

Table 4.2: 28- and 90-day average absorption after immersion (AAI) of L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day AAI (%)	5.98	5.69	5.03	2.93	2.51	1.50	1.39
% reduction from control		4.90	15.95	51.03	58.04	74.93	76.75
90-day AAI (%)	4.66	4.72	3.49	2.53	2.18	1.29	1.16
% reduction from control		-1.21	25.19	45.69	53.29	72.26	75.20
% reduction from 28 to 90-day	22.06	17.05	30.62	13.57	13.22	13.75	16.88

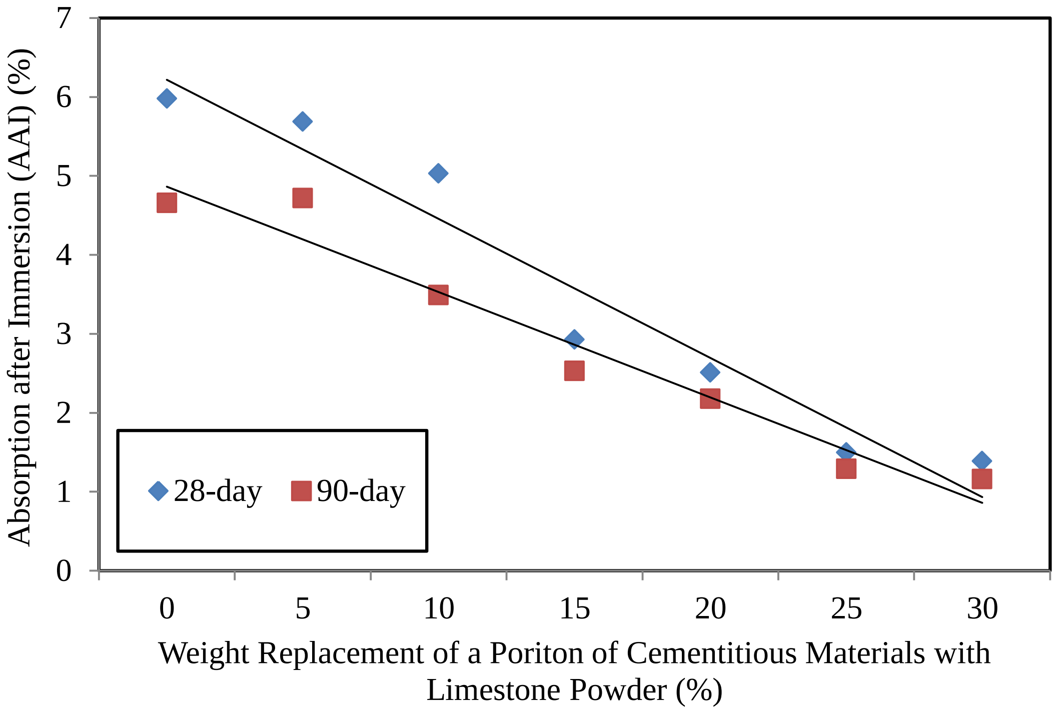

Figure 4.2: 28- and 90-day absorption after immersion results as a function of limestone powder replacing a portion of cementitious materials

Overall, the absorption after immersion results displayed a significant improvement with limestone powder replacing a portion of the cementitious materials. There was not a significant reduction in absorption after immersion from the control SCC to Mixture L8-5 with approximately a 5% decrease. Mixture L8-10 demonstrated more improvement when compared to that of the control SCC with a reduction of almost 16%. Mixture L8-15 decreased a significant 51% in absorption after immersion. With increasing limestone powder partial replacement of cementitious materials, the absorption after immersion continued to reduce to about 77% for Mixture L8-30 when compared to that obtained for the control SCC. Improvement with increasing partial replacement of cementitious materials can be due to either limestone powder's physical and/or chemical effects. At larger replacement levels of cementitious materials (ie., 15 to 30%), the finer limestone powder particles filled voids between cement grains much more efficiently than smaller replacement levels (i.e., 5 to 10%). This was demonstrated by the particle size distribution graph discussed in Figure 3.2. The chemical effect can be attributed to limestone powder modifying hydration products which can better fill up the capillary voids.

At 90-day curing, the absorption after immersion continued to decrease with increasing L8 limestone powder replacing a portion of the cementitious materials. The improvement between the control concrete and Mixture L8-5 was marginal with a slight increase of 1% in absorption after immersion. The improvement between control SCC and Mixture L8-10 was roughly 25% and the trend at a faster rate continued with an increasing level of limestone powder. At 30% partial replacement of cementitious materials with limestone powder, the reduction in absorption after immersion as compared to that of the control SCC was approximately 75%, a similar trend to the one observed with 28-day curing results. At 90-day curing, voids in microstructure of the studied SCC can also be filled by limestone powder’s small particles which improve the absorption after immersion. Non-soluble CSH structures produced by fly ash can be present at 90-day curing and improve the pore structure and, in turn, the absorption after immersion.

The reduction in absorption after immersion between 28 and 90 days curing was apparent for control SCC which was about 22%. Mixtures L8-5 and L8-10 had a decrease in absorption after immersion between 28 and 90 days of 18% and 30%, respectively. On the average, the reduction in absorption after immersion for the remaining limestone powder contained self-consolidating concrete between 28 and 90 days curing was approximately 14%. A better reduction in absorption after immersion of control SCC can be attributed to its larger content of cementitious materials as compared to limestone powder contained concretes. Fly ash released more aluminates (22.22%) at later ages in which limestone powder can react with, producing a less permeable pore structure. Fly ash, when reactive, produced calcium silicate hydrates that also can reduce concrete's capillary voids. Cement can also provide additional improvement to concrete pore structure from continued hydration.

4.2.2 Absorption After Immersion And Boiling (AAIB)

The absorption after immersion and boiling test was a continuation of the absorption after immersion test. Once testing from absorption after immersion was concluded, the same specimens were placed in boiling water. Sellovold (2005) implemented a pressure tank of 50 MPa to fill the air voids to determine the total volume of air voids in the concrete. It was assumed that the boiling water produced the same effect. The difference between immersion and immersion/ boiling was that immersion solely considered voids filled by capillary suction, while immersion/boiling considered the air voids in the concrete.

Water-to-powder ratios may affect the total porosity and likewise absorption after immersion and boiling. De Schutter (2007) found at a constant water-to-cement ratio, an increasing cement-to-powder ratio resulted in an increase in the total porosity of the concrete. Therefore, reduced water-to-powder ratio may reduce concrete's total porosity. Superplasticizers may also reduce the porosity due to the decrease in mixing water of the system and dispersion of fine particles (Macias and Goni 1999; Khatib and Mangat 1999).

4.2.2.1 Absorption After Immersion and Boiling of Studied L8 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

Table 4.3 presents the average absorption after immersion and boiling results for the investigated L8 limestone powder contained and control SCCs. The individual results for the studied SCCS are documented in the Appendix B, Table B4.3. The percent difference between the control SCC and L8 limestone powder contained SCCs is also displayed in Table 4.3. The absorption after immersion and boiling results of 28 and 90 days curing are also presented in Table 4.3 and in Figure 4.3 as a function of replacement percentage of cementitious materials with L8 limestone powder.

Table 4.3: 28- and 90-day average absorption after immersion and boiling of L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day AAIB (%)	6.59	6.12	5.96	4.09	3.74	2.44	2.59
% reduction from control		7.16	9.60	37.93	43.24	63.05	60.78
90-day AAIB (%)	5.17	4.99	4.88	3.44	2.50	2.40	2.11
% reduction from control		3.54	5.61	33.57	51.72	53.69	59.28
% reduction from 28 to 90 day	21.53	18.48	18.07	16.02	33.25	1.65	18.53

The results for 28-day curing of the studied SCCs demonstrated an overall reduction in the water absorbed after immersion and boiling with increasing limestone powder percentage replacing a portion of cementitious materials. However, the decrease was not as significant from the control SCC to Mixture L8-10 with only a 10% decrease observed. As seen in absorption after immersion results, the absorption after immersion and boiling displayed significant reduction of nearly 30% for Mixture L8-15. Increasing cementitious materials partial replacement by limestone powder continued to reduce with a 60% reduction from the control SCC observed for Mixture L8-30.

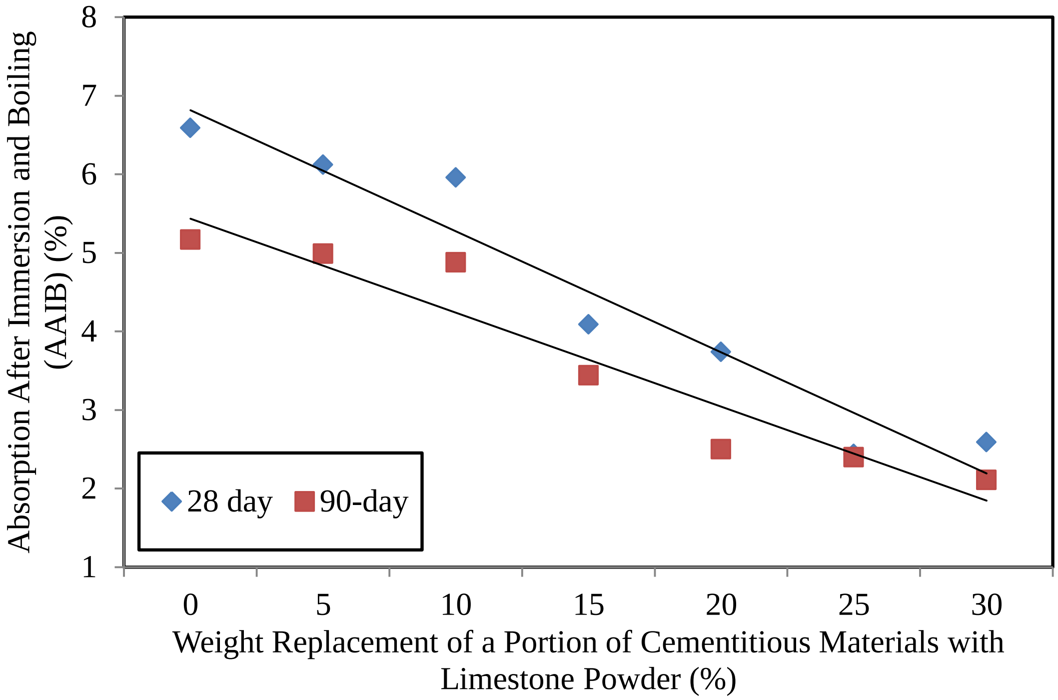

Figure 4.3: 28- and 90-day absorption after immersion and boiling results as a function of limestone powder replacing a portion of the cementitious materials

The reduction in absorption after immersion and boiling can be attributed to the similar factors that affected the results for absorption after immersion. The physical effect of limestone powder allowed for smaller particles to decrease voids between cement grains, thus producing a denser structure. Likewise, the modification to hydration products produced by limestone powder can reduce the voids in the system. Water-to-powder ratios of the studied SCCs decreased with increasing limestone powder content due to maintaining a constant water-to-cement ratio. The decreasing water-to-powder ratio reduced the SCC's porosity which, in turn, reduced absorption after immersion and boiling. Lastly, the increasing HRWRA dosage with increasing limestone powder content reduced concrete absorption after immersion and boiling due to less mixing water trapped in the system and well-dispersed powder particles.

Absorption after immersion and boiling results at 90-day curing presented an overall reduction between the control SCC and L8 limestone powder contained SCCs. As in the 28-day curing, the absorption after immersion and boiling at 90-day curing did not alter significantly between control SCC and Mixtures L8-5 and L8-10 with only approximately a 5% decrease. For Mixture L8-15, the reduction in absorption after immersion and boiling was far more significant with almost 34% reduction. The absorption after immersion and boiling between Mixtures L8-20, L8-25, and L8-30 was relatively similar and demonstrated a significant reduction from the control SCC.

The reduction in absorption at 90-day curing can be attributed to limestone powder's filler effect and fly ash's formation of a non-soluble hydrate product to fill air voids. Decreasing water-to-powder ratios and increasing HRWRA dosages of the studied SCCs also reduced the absorption after immersion and boiling similar to 28-day curing results.

The difference in absorption after immersion and boiling between 28- and 90-day curing was similar for control SCC and Mixtures L8-5, L8-10, and L8-15 with an average decrease of 18%. There was significant reduction for 20% by weight partial replacement of cementitious materials of almost 33% difference between 28 and 90 days. Mixture L8-25 demonstrated little variation between the two ages while the L8-30 exhibited similar reduction of 18% in curing age as SCCs containing little (i.e., 5 to 15%) or no limestone powder. The difference in results observed in 28 and 90-day absorption after immersion and boiling was related to fly ash's reactivity. Fly ash reactivity generally does not occur until later curing ages, and when present, produces additional hydrates which can fill up voids efficiently. Therefore, later curing ages should demonstrate a lower absorption after immersion and boiling.

4.2.3 Volume of Voids (VOV)

The volume of voids test followed the absorption after immersion and boiling, and considered the samples suspended weight to calculate the total available volume of voids percent by volume. It can be affected by limestone powder's physical and chemical contributions, fly ash reactivity, water-to-powder ratios, and the amount of HRWRA used as seen in absorption after immersion and boiling results.

4.2.3.1 Volume of Voids of Studied L8 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The average volume of voids for the control SCC and L8 limestone powder contained SCCs are presented in Table 4.4 along with the percent difference between the results of limestone powder contained mixtures and control SCC. Also displayed is the percent difference between 28- and 90-day curing results. Figure 4.4 presents average volume of voids as a function of limestone powder replacing a portion of the cementitious materials for 28- and 90-day cured test samples. The results of volume of voids for each test individual sample volume of voids are shown in the Appendix B, Table B4.4.

Table 4.4: 28- and 90-day average volume of voids (percent) of L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day VOV	15.16	14.13	13.84	9.60	8.80	6.12	5.96
% reduction from control		6.80	8.74	36.70	41.99	59.64	60.69
90-day VOV	12.86	12.56	11.40	7.12	6.59	6.23	5.47
% reduction from control		2.34	11.40	44.63	48.75	51.55	57.44
% reduction from 28- to 90-day	15.18	11.12	17.65	25.81	25.07	-1.84	8.18

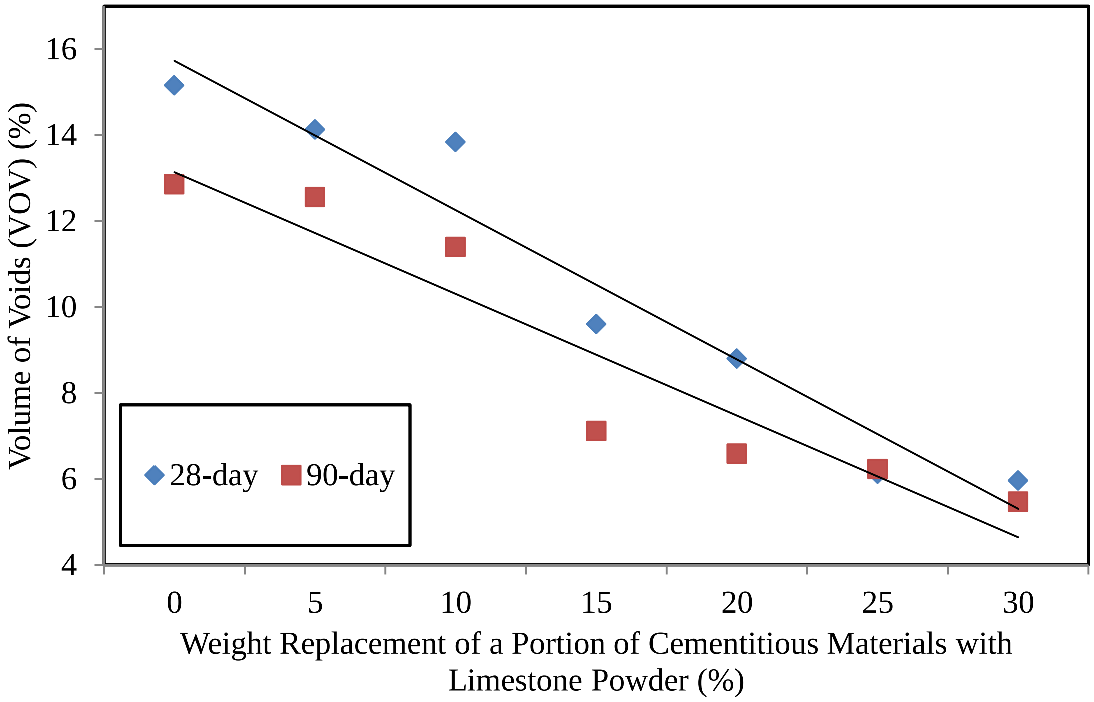

Figure 4.4: 28- and 90-day absorption after immersion and boiling results as a function of limestone powder replacing a portion of cementitious materials

The volume of voids for the 28-day cured samples decreased with increasing limestone powder content. The differences between control SCC and L8 limestone powder contained SCCs were similar to the results obtained for absorption after immersion and boiling due to similarity in testing mechanisms. Mixtures L8-5 and L8-10 displayed similar reductions of the volume of voids of nearly 10% when compared to the results obtained for the control SCC. With 30% partial replacement of the cementitious materials, limestone powder contained SCCs provided approximately a 60% decrease in volume of voids. As in absorption after immersion and boiling, the volume of pores was reduced by limestone powder's small size and modification to hydration products. Decreasing water-to-powder ratios and increasing HRWRA dosages with increasing limestone powder content also improved the volume of voids for the studied SCCs.

Similar to the results obtained for 28-day cured samples, the volume of voids for the 90-day cured SCC test specimens decreased with increasing limestone powder content. Mixture L8-5 only presented a marginal decrease of 2% compared to that of control SCC whereas Mixture L8-10 produced a larger reduction in volume of voids of approximately 12%. Also, observed in 28-day curing results, Mixture L8-30 had reduction in total volume of voids of approximately 57% when compared to that of control concrete. An explanation for this trend is similar to those presented for the 28-day curing results. Limestone powder's small size provided a better filler effect and produced additional hydrates in the presence of fly ash. The decreasing water-to-powder ratio with increasing limestone powder content of the studied SCCs also reduced the volume of voids. Lastly, higher amounts of superplasticizer potentially provided a smaller void volume due to improved dispersion of fine particles during batching of concrete.

The control SCC and Mixtures L8-5 and L8-10 demonstrated similar reductions between 28- and 90- day curing with an average reduction of 15% observed. Mixtures

L8-15 and L8-20 displayed slightly higher reductions while Mixtures L8-25 and L8-30 exhibited minimal reduction between the two ages. A possible explanation for this trend is the available content of fly ash and limestone powder in each mixture. Fly ash and limestone powder have the potential to react and form a non-soluble hydration product. However, if the limestone powder or fly ash in the mixture was limited, the formation of the hydration product can be limited as well. The control SCC and Mixtures L8-5 and L8-10 may not have contributed sufficient limestone powder to optimize the volume of hydration products. Mixtures L8-25 and L8-30 may have had excessive partial replacement of cementitious materials and the amount of available fly ash was insufficient to optimize the hydration products volume. Based on the trend provided, 15 and 20% replacement of cementitious materials with limestone powder appeared to optimize hydration reactivity between fly ash and limestone powder.

4.3 Capillary Absorption

The capillary primary absorption, also referred to as sorptivity, was measured in accordance with ASTM C 1585. Capillary pores are formed when mixing water that is required for cement hydration exits out concrete creating a network of pores. These capillary pores interact with water resulting in capillary absorption and is the main mechanism of water transportation in concrete (Hycrete, Inc. 2011). The water transportation is highly dependent on capillary porosity, connectivity, pore structure tortuosity, constriction, and disconnection. All of these parameters are greatly impacted by the water-to-binder ratio and continued cement hydration (Ramezanianpour et. al. 2009).

The difference between capillary absorption testing and absorption after immersion testing is the latter uses full-immerged specimens whereas the former uses partially immerged samples (one side of the sample). Capillary absorption testing also incorporates concrete specimen's exposed surface facing downwards onto water's surface. This allows for only upward capillary suction of water to be considered and eliminates gravitational effects of water seepage.

As stated in section 4.2.1, limestone powder can contribute either physically or chemically to improve capillary absorption. Physically, the small size of the limestone powder can improve the particle packing and lead to less permeable concrete. Limestone powder can contribute chemically, especially in the presence of fly ash, by hydration products called mono-carboaluminates (De Weerdt 2010). The tricalcium silicate, C_3S, can potentially interact with limestone powder's calcium carbonate to accelerate C_3S hydration and alter the Calcium/Silicate ratio of CSH hydration products (Pera et. al 1999).

Irassar (2009) found cement pastes with certain water-to-cement ratios had capillary pore structures that became disconnected at distinct hydration degrees. It was also found to obtain discontinuity in capillary pore structures with increasing limestone powder content, the water-to-binder (cement and limestone powder) had to be decreased. Ramezanianpour et. al. (2009) discovered decreasing water-to-binder (water-to-clinker and limestone powder) ratios decreased sorptivity and also found there was minimal difference in sorptivity between concretes containing 0 and 5% limestone powder.

4.3.1 Capillary Absorption of Studied L8 Limestone Powder Contained SCCs at 28- and 180-day Curing Ages

The average primary capillary absorption results obtained for 28- and 180-day curing, as well as the percent difference between limestone powder contained mixtures and the control SCC are offered in Table 4.5. Individual sample results are presented in the Appendix B, Table B4.5. The comparison between the two curing ages is demonstrated in Table 4.5. 28- and 180-day curing primary capillary absorption results as a function of limestone powder replacing a portion of cementitious materials are shown in Figure 4.5.

Table 4.5: 28- and 180-day average primary capillary absorption of L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day CA	6.73	7.55	5.60	4.04	3.31	2.95	4.00
% reduction from control		-12.27	16.78	39.98	50.73	56.18	40.57
180-day CA	2.39	2.75	2.03	1.69	1.34	1.09	0.76
% reduction from control		-14.90	15.18	29.39	44.01	54.46	68.11
% reduction from 28- to 180-day	64.41	63.58	63.73	58.13	59.56	63.01	80.90

The overall trend was a decreasing capillary absorption coefficient with increasing limestone powder content replacing a portion of the cementitious materials. There was a slight increase with 5% partial replacement of approximately 12% but the trend decreased after with each increasing limestone powder replacement interval. At 20 and 25% partial replacement, there was significant reduction in capillary absorption ranging between 50 and 55%. Possible explanations of the overall decreasing coefficient can be attributed to limestone powder improving the capillary pore structure through physical and chemical contributions. Discussed in Chapter 3, increasing limestone powder content improved the particle size distribution of the studied SCCs. The presence of a carboaluminate hydrate, a product of limestone powder with cement's aluminate phase, was found in limestone powder contained SCCs through means of X-ray diffraction analysis provided in Chapter 3. Also possible was the decreasing water-to-powder ratio with increasing limestone powder content decreased the capillary primary absorption and is supported from prior studies (Ramezanianpour et. al 2009).

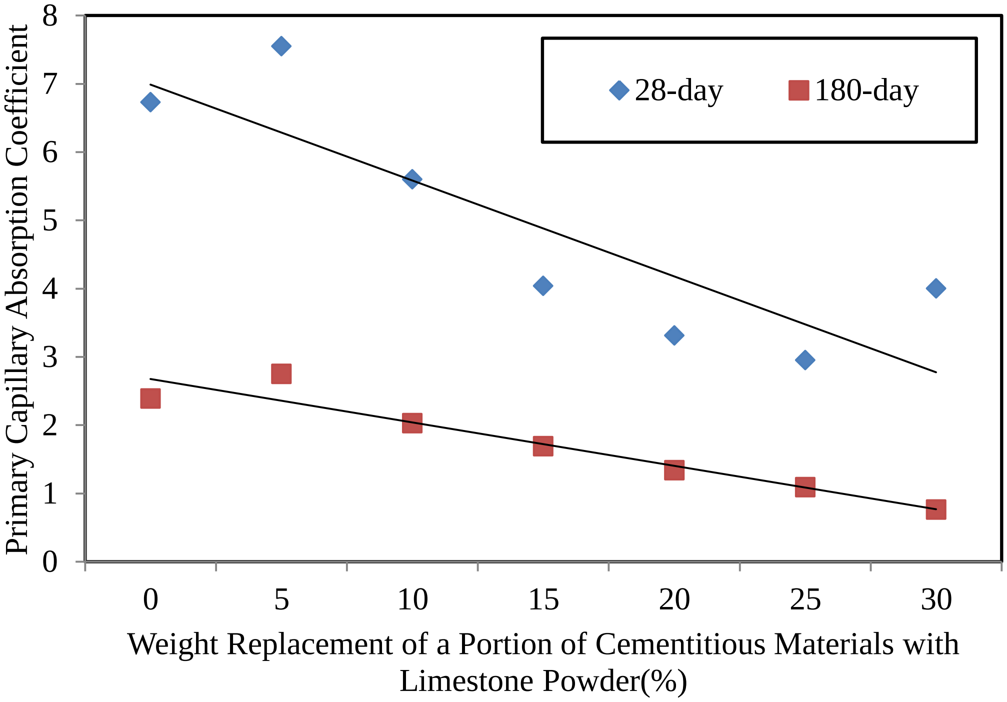

Figure 4.5: 28- and 180-day capillary primary absorption results as a function of limestone powder replacing a portion of the cementitious materials

Capillary absorption results for 180-day curing displayed a similar trend to that of 28-day curing with generally decreasing capillary absorption with increasing limestone powder content. As seen in 28-day curing, Mixture L8-5 demonstrated an increase from the control SCC of nearly 15%. From 5% limestone powder partial replacement, the capillary absorption decreased with increasing limestone powder content. Mixture L8-30 displayed a reduction from the control SCC of 68%. The 180-day capillary absorption may decrease with increasing limestone powder due to similar reasons observed in 28-day results. The filler effect and hydrate provided by limestone powder inclusion may have reduced the capillary void structure. Also possible at the later curing age was the reducing water-to-powder ratio effectively decreased the capillary void structure which decreased the capillary primary absorption.

The reduction in the capillary absorption reduced within in the range of 60% for all studied SCCS with the exclusion of Mixture L8-30 between 28- and 180-day curing. This can be attributed additional hydration products provided by fly ash's latent reactivity which improved the capillary pore structure of the studied SCCs. Continued cement hydration also contributed to effectively filling the capillary voids and reduced the capillary absorption.

4.4 Water Penetration

The European Committee for Standardization (CEN) EN 12390-8 was implemented to evaluate 150 mm^3 SCC specimen's water penetration depth. The water penetration of SCC cube was measured by examining the amount of water penetrated into sample through splitting concrete specimens and observing the depth of discoloration produced by water (Hearn et. al 2006). It is noted that water penetration tests are complicated by non-uniform moisture distribution and initial moisture content of specimens. Concrete's microstructural characteristics also change with the introduction of water which modifies the matrix's pore size distribution (Hearn et. al. 2006).

Ramazenianpour et. al. (2009) found concrete water penetration depths increased with increasing water-to-binder (cement and limestone powder) ratios. It was however found that concretes containing 10% limestone powder produced lower water penetration depths as compared to concretes containing either no limestone powder or greater than 10% content. It was proposed this reduction and after increase with limestone powder was a result of limestone powder's dilution effect, filler effect, and heterogeneous nucleation. Heterogeneous nucleation can lead to a more disoriented crystallization of CH structures due to limestone powder acting as nucleation sites which accelerates cement hydration (Irassar 2009).

4.4.1 Water Penetration of Studied L8 Limestone Powder SCCs at 28- and 90-day Curing Ages

The average water penetration results of the studied SCCs are shown in Table 4.6 while individual sample results are presented in the Appendix B, Table B4.6. The percent difference between the limestone powder contained mixtures and the control SCC and the percent difference between the results of the two curing ages are likewise presented in Table 4.6. The 28- and 90-day water penetrated results are plotted in Table 4.6 as a function of the percent limestone powder replacing a portion of the cementitious materials.

Table 4.6: 28- and 90-day average water penetration depths of studied L8 limestone powder SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day WP (mm)	12.63	9.40	8.77	8.42	8.23	8.77	9.04
% reduction from control		25.57	30.53	33.35	34.83	30.53	28.43
90-day WP (mm)	9.94	7.10	6.73	6.34	6.00	5.48	5.87
% reduction from control		28.62	32.28	36.20	39.61	44.89	40.97
% reduction from 28 to 90-day	21.28	24.50	23.26	24.65	27.06	37.55	35.07

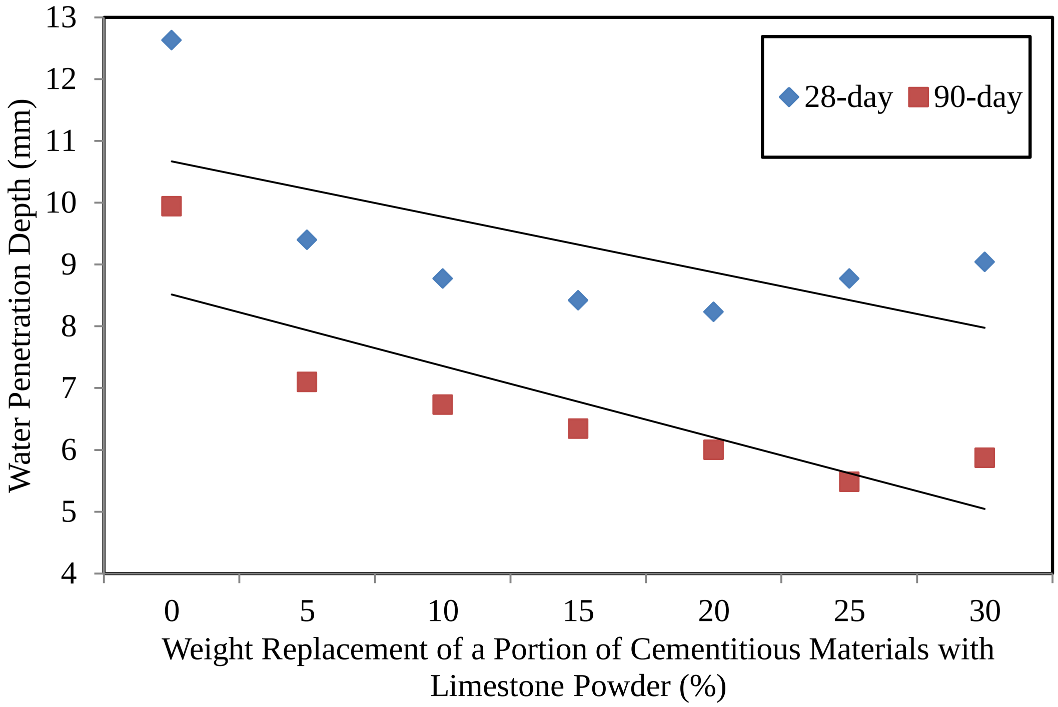

Figure 4.6: 28- and 90-day water penetration results as a function of limestone powder replacing a portion of cementitious materials

There was a significant reduction of water penetration depth of nearly 20 % between the control SCC and Mixture L8-5. Beyond 5% partial replacement of cementitious materials, the improvement from the control SCC with each 5% increment of limestone powder by weight was between 28 and 34%. A possible explanation on this trend was similar to that found from prior studies (Irassar 2009) where limestone powder had a dilution effect, filler effect, and heterogeneous nucleation effect. The inclusion of limestone powder may have improved the water penetration depth due to a disorientation of the CH structures, but additional partial replacement of cementitious materials had little effect on the water penetration depth.

As can be seen in the 28-day curing, there was significant reduction of approximately 29% from 90-day cured control SCC to Mixture L8-5. Afterwards, the improvement with limestone powder content (i.e., 10 to 30%) was between 32% and 45%. This can be attributed to similar explanation for the 28-day curing results, where the inclusion of limestone powder modified the CH structures to where water penetration depth was improved. However, additional limestone powder content did not modify the CH structure to where the water penetration would be greatly improved.

Between the two concrete curing ages, there was reduction in the water penetration depth for all studied SCC mixtures. The reduction between curing ages appeared to increase with increasing limestone powder replacing cementitious materials (25 to 30%). The lower water penetration depth at later curing ages may be a result of the formation of additional hydrates provided by continued cement hydration and fly ash's latent pozzolanic reactivity. Both of these phenomena contribute to creating a denser pore structure which resists penetration of water more efficiently.

4.5 Rapid Chloride Penetration (RCPT)

The Rapid Chloride Penetration Test (RCPT) was originally developed as a quick assessment of concrete's permeability to chloride ions. RCPT measures chloride ingress as a migration process, where the transport of ions in electrolytes is due to the action of an electrical field where positive ions will travel to the negative electrode and negative ions vice versa (Cement Concrete and Aggregates Australia 2009).

According to Shi (2003), the Rapid Chloride Penetration test is an assessment of concrete's electro-conductivity, which is affected by both the concrete's pore structure and the chemistry of the pore solution. The pore structure refers to not only the total volume of pores but also the pore size, distribution, and continuity. The initial porosity according to Hearn et. al. (2006) is affected by aggregate porosity, water/air filled voids after consolidation and final set, and the water/air filled voids after partial hydration of cement. During the life-cycle of concrete, continued hydration, drying and wetting, and concrete deterioration process are all factors that continually modify the pore structure (Hearn et. al. 2006).

Class F fly ash is a gradually reacting pozzolan that improves the pore structure and permeability due to cement's calcium hydroxide which are released by the calcium silicate compounds (C_2S and C_3S) reacting with fly ash. This reaction can lead to formation of additional calcium-silicate hydrates. These calcium-silicate hydrates can decrease concrete capillary pore space (Erodgan 2006). It is possible though the pozzolan reaction may take several weeks before its starts reacting significantly (DeWeerdt 2010).

Limestone powder may potentially accelerate the hydration of cement, particularly the C_3S phase, by functioning as a nucleation surface for portlandite and CSH precipitation (Ramachandran 1988; Pera et. al. 1999). The powder may also react chemically with the aluminate phase of cement to produce hydration products (Kakali et. al. 2000). Small inclusions of limestone powder may replace the monosulphaluminate hydrate with a mono-or hemi-carboaluminate hydrate and more ettringite. This hydration product alteration may marginally increase the volume of hydration products (Matschei et. al. 2007). The increase in volume of hydration products can lead to decreased permeability through improvement in concrete pore structure. However, this reduction is restrained by the small amount of aluminate present in cement (De Weerdt 2010).

The reaction between fly ash and limestone powder is expected to enhance hydration product as fly ash is an aluminate rich pozzolan and as it reacts, it introduces additional aluminates to the system. De Weerdt and Justnes (2008) found in a preliminary study of fly-ash-limestone-calcium hydroxide-alkaline solution, there was a well-defined interaction between fly ash and limestone powder. Also, it was confirmed there was a calcium carboaluminate hydrate present in the hydration products.

The chemistry of the pore solution does not significantly affect the transport or chloride ions; however it significantly affects concrete's electro-conductivity. The concentration of conductive ions in the pore solution can be greatly impacted by many variables such as cement composition, aggregate, mixing proportions, supplementary cementitious material, and chemical admixtures (Shi 2003).

Cement components release substantial amounts of aqueous ions when mixed with water. These aqueous ions include Na^+, K^+, OH^- , Ca^{+2}, and SO_4^{-2}. Ca^{+2} and SO_4^{-2} reduce to almost insignificant amounts after setting and hydration, thus producing a pore solution consisting mostly of alkali hydroxides (Shi 2003). Cement will release most of its hydroxides to the pore solution, which means high alkali content cement will have a similar pore structure but higher pore solution electro-conductivity than compared to that of low alkali content cement (Shi 2003).

The use of supplementary cementitious material may decrease concrete pore solution conductivity. Shi et. al. (1998) examined the effect of fly ash on specific electrical conductivity at certain ages. The results indicated fly ash's effect will vary from source, replacement levels, and age. One source of fly ash increased the electrical conductivity at all times, while another was constant at 28-day curing then decreased, and another decreased at 28-day curing and further decreased till 90-day curing. Therefore, the impact of fly ash on the pore solution chemistry varied from source. Limestone powder does not contribute to the alkalinity of the pore solution.

The coarse and fine aggregate quantity may also impact the pore solution conductivity due to a dilution effect. Roy et. al. (1987) studied the porosity, water permeability, and RCPT results of pastes and mortars. The porosity of the mortars was found to be higher than the porosity of the paste. The water permeability for the mortars was also found to be greater than the pastes. However, the results of the RCPT test demonstrated the pastes had charges too high to be measured, but the mortars had lower, measurable charge values. Two possible explanations of the increased porosity and decreased RCPT results of mortar was addition of sand increased porosity but diluted the concentration of conductive ions in the pore solution. Also, the alkalis may potentially be adsorbed on the surface of the acidic sand and produces less mobility for the alkali than in the bulk pore solution (Roy et. al. 1987).

4.5.1 Rapid Chloride Penetration of Studied L8 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The RCPT results for the 28- and 90-day cured control and L8 limestone powder contained self-consolidating concretes are presented in Table 4.7. Results are presented as the charge passed through the studied SCC specimens and are measured in coulombs. Lower charges passed indicate higher resistance to chloride ingress. The percent difference between RCPT results obtained for L8 limestone powder contained SCCs and the control concrete are displayed in Table 4.7. The percent difference between the 90-day RCPT results and those of 28-day curing are also shown in Table 4.7. The individual sample results are presented in the Appendix B, Table B4.7. Figure 4.7 demonstrates the

RCPT values of the studied SCCs as a function of limestone powder replacing a portion of the cementitious materials.

Table 4.7: 28- and 90-day average RCPT results of L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day RCPT (coulombs)	5651	4656.3	4407	3939.3	3538	3309.5	2906.2
% reduction from control		17.60	22.01	30.29	37.39	41.44	48.57
90-day RCPT (coulombs)	1507.3	1359.2	1310	1239.6	1003.8	990.50	1008.33
% reduction from control		9.82	13.09	17.76	33.40	34.29	33.10
% reduction from 28 to 90 day	73.33	70.81	70.27	68.53	71.63	70.07	65.30

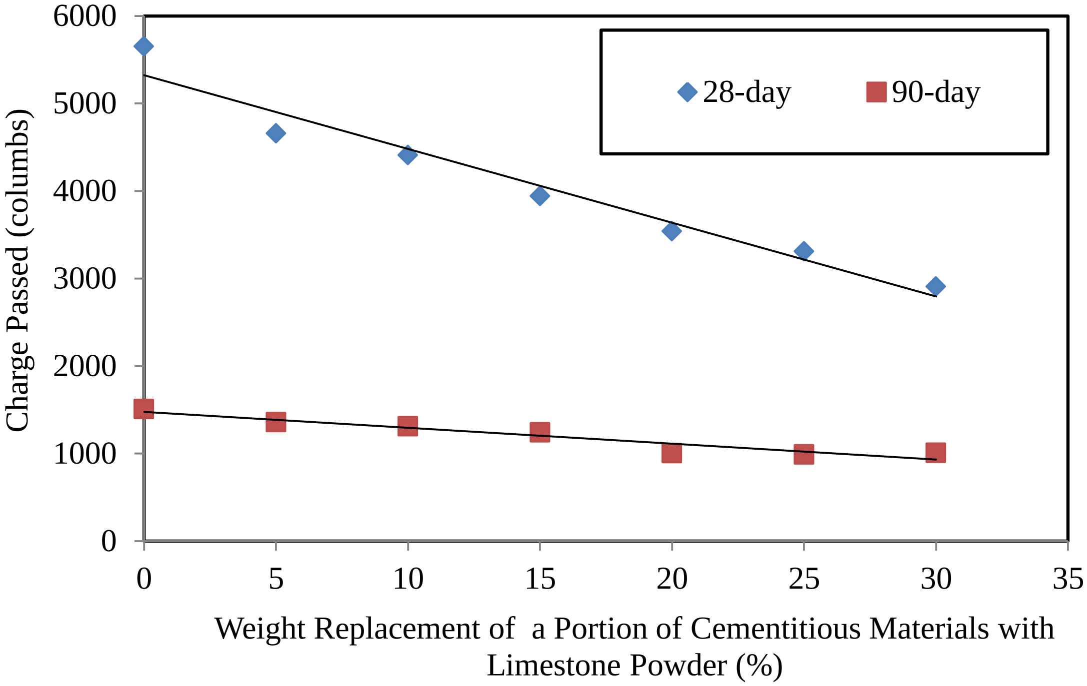

Figure 4.7: 28- and 90-day RCPT results as a function of limestone powder replacing a portion of cementitious materials

Table 4.7 displays that the overall measured charge passed decreased with the inclusion of L8 limestone powder. The control SCC decreased almost 18% with limestone powder replacing 5% by weight of cementitous materials. The charge passed continued to decrease by an average of nearly 5% with each incremental increase in limestone powder replacing cementitious materials.

One possible explanation to the trend found is that the limestone powder had a dilution effect of cement. Cement was the main contributor of alkalis to concrete pore solution. Fly ash may or may not have a dilution effect based on its pozzolanic activity and its sodium potassium content (Shi 2003). When the alkalinity of the pore solution was possibly reduced with additional replacement of cementitious materials, the charge passed may reduce as well.

Another potential contribution to the reduction in charge passed was additional volume of fine and coarse aggregate with each increasing replacement level. Control SCC had roughly 34.8% fine aggregate content and a 26.3% coarse aggregate content as shown in Table 3.15 in Chapter 3. This aggregate volume increased with each portion of cementitious materials substituted by limestone powder replacement level up to 30%, where the fine and coarse aggregate volumes were 37% and 27.9%, respectively. Though this is not a significant increase, as mentioned previously, Roy et. al.(1987) found RCPT results decreased with inclusion of fine aggregates due to a dilution effect and adsorption of alkali ions onto the sand.

Lastly, the significant reduction in charge passed between the control concrete and Mixture L8-5 may be attributed to either acceleration in hydration due to additional nucleation sites provided by the limestone powder or the filler effect provided by limestone powder. It was possible that at 5% replacement level, the acceleration process or filer effect was sufficient enough to provide such a large reduction, for which after, additional levels may only provide a dilution effect on the pore solution's alkalinity. This was observed in water penetration results presented in Section 4.4.

The contribution of the pore structure could not be ignored and was potentially present in the RCPT results with increasing limestone powder levels. However, results and discussion in the Rapid Migration results and Chloride Diffusion results discussed in Section 4.6 and 4.7, respectively, appear to contradict the theory that the pore structure has been modified at 28-day curing.

The overall trend of the 90-day curing RCPT results indicated a decrease in charge passed with additional limestone powder replacing a portion of cementitious materials. The trend supported 28-day results with partial replacement of cementitious materials. It can be seen that the reduction from control SCC to Mixture L8-5 was not as significant as it was in the 28-day curing results. From the control SCC to Mixture L8-5, there was a 10% decrease and then only 3-4% reduction in charge passed up to 15% L8 limestone powder replacing the cementitious materials. The charge passed for 90-day cured Mixtures L8-20, L8-25, and L8-30 had a similar decrease of approximately 33% as compared to the control SCC.

The results supported the theory that limestone powder partially replaced the cement content, thus producing fewer alkalis that normally increase pore solution conductivity. Limestone powder's filling ability contributed to the reduction in the charge passed with increasing limestone powder content. Also possible was the continued dilution of cement with limestone powder. The similar RCPT values produced for Mixtures L8-20, L8-25, and L8-30 maybe a result of insufficient fly ash which could possibly further reduce the charge passed.

All studied SCC mixtures decreased in passed charge between 28- and 90-day curing. The reduction may be attributed to the increased reactivity of fly ash and change in pore structure as additional calcium silicate hydrate occupied capillary pores. Moreover, the reaction between limestone powder and fly ash supplied more hydrates due to additional aluminates in the system. In this study Portland cement incorporated had only 4.25% Al_2O_3 whereas the fly ash had Al_2O_3 content of 22.22%. The pozzolanic reactivity of the fly ash also had the potential to reduce the pore solution conductivity. As suggested by Shi et. al. (1998), increased pozzolanic activities of fly ash with curing age reduced electro-conductivity of the pore solution.

4.6 Rapid Migration (RMT)

Like RCPT, the rapid migration test measures the ingress of chloride ions into concrete through means of an electrical field moving positive ions to the negative electrode and vice versa. Unlike RCPT, the rapid migration has been found not to be affected by the pore solution conductivity (Stanish 2000).

According to Fagerlund (2005), there are three alternatives of how limestone powder may affect concrete's chloride permeability. The first is that the limestone powder can be completely inert. The diffusion coefficient should be unaffected by the limestone powder as no new hydration products are formed and no change to the existing hydration products takes place. This indicates that the chloride permeability is also unaffected.

The second alternative is that the limestone powder does not modify the pore structure but does affect the concrete's chloride binding capacity. In this scenario, limestone powder has no influence on the reaction of C_3S and C_2S which are the main cement components developing the concrete's pore structure. The limestone powder, however, does react with the component C_3A and to some degree C_4AF which determine the concrete's chloride binding capacity (Bonavetti, et. al. 2001). The diffusion coefficient should be unchanged as the pore structure was not modified as well as the concrete's chloride permeability (Fagerlund 2005).

The third alternative is that the limestone powder may react with the components C_3A, and to some extent C_4AF, therefore changing the chloride binding capacity and modifying pore structure. The permeability of the concrete will be either increased or decreased depending on the changes to the pore structure.

As discussed previously, the pore structure can be affected by both limestone powder and fly ash individually and combined. Limestone powder individually may accelerate the hydration of C_3S and potentially react with the aluminate phase to form an additional hydrate. This is limited in ordinary Portland cement due to its small amount of Al_2O_3. Fly ash creates a pozzolanic reaction that may produce additional calcium silicate hydrates to block the capillary voids. When combined, the two can further reduce the permeability due to the additional aluminates provided by fly ash for limestone powder to react with to form a carboaluminate hydration product (DeWeerdt and Justnes 2008).

Audenaert et. al. (2007) concluded that the rapid migration coefficient of self-compacting concrete containing a finer graded limestone powder was smaller, yet the differences were found to be insignificant. The use of fly ash contributed much more significantly which may be attributed to a denser pore structure.

The inclusion of coarse aggregate can also affect the migration coefficient. Shah (2000) and Delagrave et. al. (1997) found that coarse aggregate's dilution effect and tortuosity; due to reduction of cement content and sparse cement particles, respectively; reduce concrete permeability. The aggregate's interfacial transition zone and percoloration effect, which is the slow passage of liquid through filtering material, both increase concrete permeability. Yang and Cho (2003) found that concrete with low coarse aggregate volume were mostly affected by the coarse aggregate's dilution effect.

4.6.1 Rapid Migration of Studied L8 Limestone Powder SCCs at 28- and 90-day Curing Ages

The chloride ion rapid migration coefficient for 28- and 90-day cured SCCs, the percent difference between chloride ion rapid migration coefficients of L8 limestone powder contained SCCs and the control SCC, and the percent difference between 28- and 90-day curing chloride ion rapid migration coefficient results are presented in Table 4.8. Table B4.8 of the Appendix B contains individual sample results. The chloride ion rapid migration coefficient results as a function of limestone powder replacing a portion of the cementitious materials is demonstrated in Figure 4.8.

The chloride ion rapid migration coefficient at 28-day curing did not reduce significantly from control SCC to Mixture L8-25 with only a 4% reduction between the two SCC mixtures. It was a larger reduction (about 13%) with 30% of limestone powder replacing cementitious materials. This reduction was more of a function of testing than concrete's performance. The rapid migration coefficient used the applied voltage for calculation. The applied voltage was determined by observing the initial current, and based on the range of that current, selecting the appropriate voltage. The current measured in mA between L8-25 and L8-30 did not differ significantly as shown in Table 4.9. However, the cutoff range for voltage selection is at 60 mA. Therefore the different voltage was used, produced a much lower value for Mixture L8-30.

Table 4.8: 28- and 90-day average RMT results of the studied L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day RMT ($x10^{-12}$)	14.36	14.27	14.03	13.99	13.94	13.78	12.52
% reduction from control		0.60	2.32	2.58	2.90	4.02	12.84
90-day RMT ($x10^{-12}$)	6.18	6.17	5.81	4.34	4.79	5.17	5.08
% reduction from control		0.15	6.07	29.77	22.46	16.31	17.74
% reduction from 28 to 90 day	56.95	56.76	58.61	68.97	65.63	62.46	59.37

From the results obtained in Table 4.8, the chloride ion rapid migration coefficient decreased marginally as compared to the 28-day curing RCPT results. As RCPT is a function of both pore solution and pore structure, while as RMT is mostly affected by pore structure, it can be inferred that the pore structure did not alter meaningfully as the pore solution did in RCPT 28-day curing results.

The marginal differences between control SCC and L8 limestone powder contained SCCs can be attributed to the same explanation of Audenaert et. al. (2007) in which the limestone powder provided finer grading to the powder matrix. It was also possible that the aggregate provided a dilution effect as described above which decreased permeability marginally as coarse aggregate volume increased with each additional partial replacement of cementitious materials by limestone powder. The limestone powder can have affected the pore structure, however, due to insufficient amount of aluminate present in Portland cement and slow reactivity of the fly ash during the first 28 days curing, there was an insufficient amount of carboaluminate compounds present to modify the pore structure.

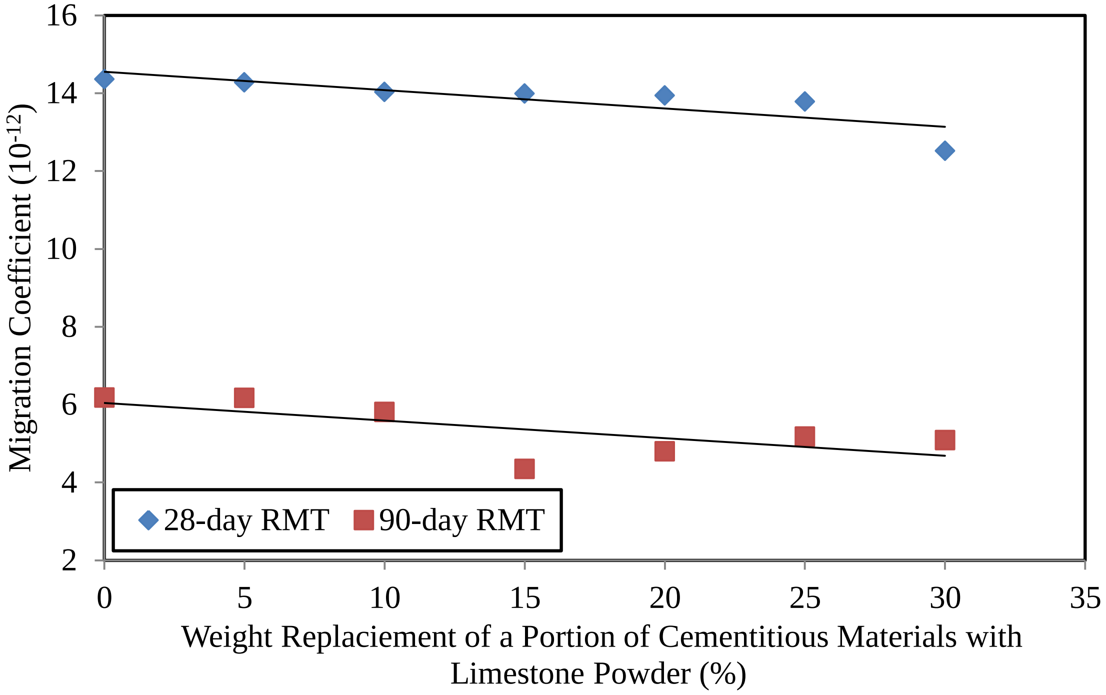

Figure 4.8: 28- and 90-day RMT results as a function of limestone powder replacing portion of cementitious materials

The 90-day curing chloride ion rapid migration results observed a greater difference between the control SCC and L8 limestone powder contained SCCs. The decrease from control SCC to Mixture L8-5 was insignificant with less than 1% decrease. Mixture L8-10 had a more apparent reduction of 6%. Mixture L8-15 provided the greatest reduction of almost 30%, yet the reduction decreased with additional cementitious materials partial replacement. The limestone powder at 90-day curing reduced the rapid migration coefficient and modified the pore structure. A possible explanation of the improved chloride ion rapid migration coefficient can be a denser pore structure resulting in decreased permeability. The denser pore structure may result from the combined hydration products of fly ash and limestone powder. At 28-day curing, there was an insufficient amount of aluminates for the limestone powder to react with thereby limiting the extent of its influence on modifying the pore structure. As fly ash became reactive with increasing curing age, it released additional aluminates into the system, with which the limestone powder can react with to form carbo-aluminates. The presence of the carbo-aluminate was confirmed in Chapter 3's X-ray diffraction analysis. Fly ash, itself, improved the pore structure by providing additional calcium-silicate hydration products into the system.

Table 4.9: L8 limestone powder initial currents at 28-day curing

	Sample 1	Sample 2	Sample 3	Average
Control	81.8	88.8		85.3
L8-5	73.5	78.2	77.5	75.85
L8-10	76.6	72.7	76.6	74.65
L8-15	67.7	68.9	60.9	68.3
L8-20	66.4	74.3	60.9	70.35
L8-25	63.6	66.1	68.3	64.85
L8-30	54.2	56.2	51.5	55.2

The reduction in rapid migration coefficients peaked at Mixtures L8-15, suggesting the optimum replacement of cementitious materials by limestone powder in reducing chloride ion rapid migration coefficient for the selected self-consolidating concretes. At Mixture L8-5, there may be insufficient amount of limestone powder to produce carbo-aluminates, yet as the limestone powder increased more calcium carbonate was added to the system to create the hydration product. Once 20% of cementitious materials content was replaced by limestone powder, the fly ash volume reduced to where the effect between fly ash and limestone powder became less effective. The decrease in fly ash content resulted in further reduction of CSH formation which adversely affected the pore structure of the metrics. This trend was further corroborated with additional replacement of cementitious material by limestone at the level of 25 and 30%.

Reducing chloride ion rapid migration coefficients between control SCC and L8 limestone powder contained SCCs can also be a physical phenomenon. The limestone powder is capable of filling the voids which can provide a denser structure. As demonstrated in Chapter 3 Section 3.4, the particle size distribution was enhanced with limestone powder addition. This enhancement can improve the pore structure and reduce the migration coefficient of limestone powder contained SCCs.

Between 28- and 90-day curing, the chloride ion rapid migration coefficient decreased significantly due to additional CSH through reactivity of fly ash with increasing curing age. The additional calcium silicate structure reduced the capillary pore space; improved pore structure; and resulted in reduced chloride ion rapid migration coefficient. Moreover, fly ash provided additional aluminates to the limestone powder to form carboaluminate hydrates which improved the pore structure and reduced concrete permeability.

4.7 Chloride Diffusion

Diffusion is the transfer of mass of unbound ions or molecules in the pore solution producing a net flow from regions of greater concentration to lower concentration regions of the diffusing material (Cement Concretes and Aggregates Australia 2009). In a non-steady state diffusion process, the free chloride ions in the pore solution's gradient is the active driving force. Concrete's chloride binding capacity is the ability of hydrating cement to bind chlorides from the pore solution. This is important for the longevity of the concrete as only free chlorides can initiate rebar corrosion (Sumranwanich and Tangtermisiriku 2002).

Fagerlund's (2005) three alternative apply to concrete's chloride diffusivity as well as chloride's permeability. Alternative one where the limestone powder is inert will result in no change of the chloride binding capacity and therefore no change in the diffusion coefficient (Fagerlund 2005).

In Fagerlund's second alternative, the limestone powder may react with cement's C_3A and to some limitation C_4AF but does not react with C_3S and C_2S which are the main components in determining the pore structure. This reaction may decrease the chloride binding capacity due to an exhaustion of C_3A to produce the carboaluminate hydrate. The decrease in chloride binding capacity can result in a higher diffusion coefficient due to more free chlorides to transfer (Fagerlund 2005).

Alternative three also considers limestone powder as reactive with C_3A which can produce a modification in the pore structure as well as the chloride binding capacity. As in alternative two, the chloride binding capacity can decrease and the diffusion coefficient can increase (Fagerlund 2005).

Fly ash contributes to higher resistance to chloride penetration and chloride diffusion due to a denser pore structure (Thomas and Matthews 2004; Papadakis 2000). At early ages prior to fly ash reactivity, the chloride diffusion coefficient can increase. When fly ash's pozzolanic reaction occurs, the chloride diffusion coefficient should decrease. The surface concentration should also increase with decreasing diffusion coefficient due to the higher chloride resistance. Jensen and Pratt (1989) found the reaction products of fly ash are calcium silicate hydrates which can decrease capillary pores and calcium aluminates hydrates which can increase the chloride binding capacity. Haque and Kayyali (1995) also reported that the addition of fly ash increased the chloride binding, yet the use of a superplasticizer appeared to decrease it.

Inclusion of aggregates can also have an effect on the chloride diffusion coefficient. Several studies have found that the inclusion of aggregates increases the diffusion coefficient due to an interface effect. Delagrave et. al. (1997) found the interface zone has 10 times higher diffusivity of chloride than bulk pastes (combination of cement and water). Halamickvoa et. al. (1995) discovered the chloride transportation coefficients increased with the addition of sand at a constant hydration.

4.7.1 Chloride Diffusion of Studied L8 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The chloride diffusion of the studied SCCs is represented as a chloride diffusion coefficient. The 28- and 90-day curing results are shown in Table 4.10. The results of individual samples are presented in the Table B4.10 of the Appendix B. The chloride diffusion coefficient of the studied SCCs was also plotted against the percent limestone powder replacing a portion of the cementitious materials and the results are shown in Figure 4.9.

Table 4.10: 28- and 90-day average chloride diffusion coefficients of studied L8 limestone powder contained SCCs

Mix No.	Control	L8-5	L8-10	L8-15	L8-20	L8-25	L8-30
28-day CD ($x10^{-12}$)	7.25	7.30	7.54	7.99	8.04	7.95	9.89
% increase from control		0.66	3.98	10.28	10.93	9.71	-
90-day CD ($x10^{-12}$)	3.47	3.35	3.10	3.52	3.37	3.37	3.33
% reduction from control		3.28	10.49	-1.48	2.94	2.95	3.93
% reduction from 28 to 90 day	51.03	54.03	58.81	55.97	58.14	57.68	66.31

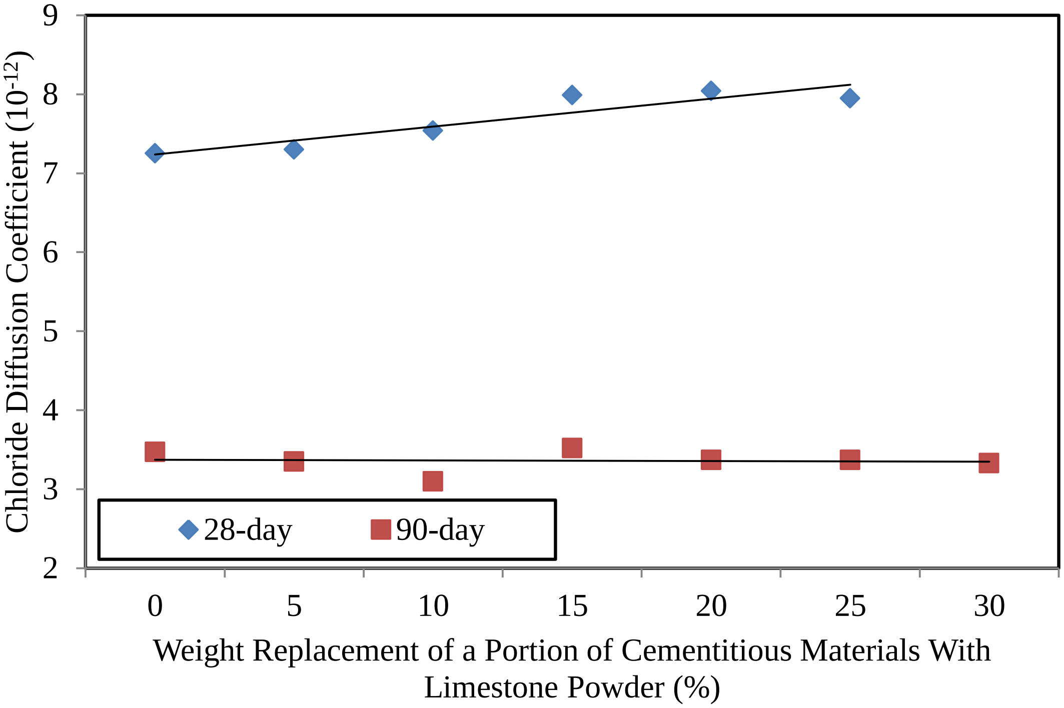

Figure 4.9: 28- and 90-day chloride diffusion coefficient results as a function of limestone powder replacing a portion of cementitious materials

As shown in the 28-day curing results, there was an overall increase in chloride diuffsion coefficient with the inclusion of limestone powder. Mixture L8-5 had a similar chloride diffusion coefficient comparable to that of control SCC. With 10% and higher inclusion of limestone powder replacing the cementitious materials, the chloride diffusion coefficient was marginally larger. One possible explanation was that the limestone powder was reactive at 28 days and consumed the C_3A compound which caused reduction in concrete's chloride binding capacity. The reduction of chloride binding capacity increased mobility of the free chloride ions, resulting in an increased chloride diffusion coefficient. The inclusion of aggregates may have also provided more interface effect, which increased the chloride diffusion coefficient.

The 90-day curing results of the studied SCCs indicate a minor reduction of the chloride diffusion coefficient which remained independent of limestone powder substituting for cementitious materials. When compared to the 28-day curing results, the limestone powder exhibited positive influence on chloride diffusion at 90-day curing. A possible explanation is that aluminates not present in the 28-day concrete were released from the fly ash at 90-day curing. These aluminates were available to react with limestone powder's calcium carbonate to produce carboaluminates compounds which were responsible for a denser pore structure. The positive influence on chloride diffusion seen in 90-day cured SCC samples can also be attributed to the additional formation of calcium aluminates (due to reaction of calcium hydroxide and aluminum oxide in fly ash) which can result in increased binding capacity and reduction of chloride diffusion. The interface effect of the aggregates may have been present at 90-day curing as well, and were compensated by the fly ash contribution.

When comparing the 28-day and 90-day curing chloride diffusion coefficients, it was apparent there was a reduction between the two curing ages. The studied SCC samples displayed a reduction in the diffusion coefficient averaging 50 and 70% between the two curing ages. The increased pozzolanic reactivity provided by fly ash with increased curing age resulted in the formation of additional calcium aluminates compounds (responsible to improve the chloride binding capacity) and formation of more calcium silicates compounds (responsible for improvement of the pore structure).

4.8 Conclusions

From the results presented in this chapter, the following conclusions can be made.

(a) The compressive strength marginally increased between 2% and 8% compared to the control SCC at all concrete curing ages for studied L8 limestone powder contained SCCs. This can be a result of limestone powder's contribution to particle packing, slightly higher coarse aggregate volume with a higher limestone powder content, and higher amount of superplasticizer used. Strength gain between 28 to 90 days curing averaged 25% for all studied SCCs and continued to improve from 90 to 180 days with an average gain of 17%. The higher strength gain at 90 days was a result fly ash's latent reactivity which supplied additional hydrates to the pore structure.

(b) The absorption after immersion, absorption after immersion/boiling, and volume of pores decreased with increasing limestone powder content at both curing ages. The incremental reduction in volume of voids between 10 and 30% replacement of cementitious materials by weight with limestone powder as compared to the control SCC was on the whole 30, 5, 10, and 3% for both curing ages. Possible explanations for this reduction are limestone powder's improvement to particle packing, formation of non-soluble hydration products, decreasing water-to-powder ratios, and increasing HRWRA dosage.

(c) The capillary absorption slightly increased with 5% replacement of cementitious materials by limestone powder, and then generally decreased with increases in limestone powder content for both 28 and 180-day curing. Up to limestone powder replacing 10% of cementitious materials, the capillary absorption results decrased on an average of 16% for both curing ages compared to the control SCC results. For 28-day cured samples, the reduction in capillary absorption decreased by 40% for 15% replacement of cementitious materials and was relatively unchanged with increase limestone powder content (i.e., 20 to 30%). The 180-day cured capillary absorption results decreased by 30, 44, 55, and 68% compared to the control SCC for 15 to 30% replacement of cementitious materials by weight with limestone powder. The improved particle packing and the formation of the carboaluminate hydrate both provided by limestone powder improved capillary absorption.

(d) Water penetration depth levels displayed a large reduction from control SCC to 5% replacement cementitious materials of 25% at 28 days curing and 29% at 90 days curing. Increasing limestone powder produced minimal improvement in the water penetration depths. The heterogeneous nucleation provided by limestone powder might have been sufficient enough at 5% replacement of cementitious materials, where increase limestone powder content did not greatly reduce water penetration depth. Increasing curing age produced a decrease in the water penetration depth by an average of 27% and was a result of fly ash reactivity supplying additional hydrates to the void system to reduce water penetration.

(e) Limestone powder decreased the rapid chloride penetration results of the studied SCCs. For 28-day cured samples, the decrease in charge passed compared to the control SCC was almost 18% for 5% limestone powder replacing cementitious materials. The charge passed continued to decrease by an average of 5% between each 5% incremental replacement of cementitious materials. The 90-day cured SCCs demonstrated an average decrease of 5% up to 15% limestone powder replacing the cementitious materials. Mixtures L8-20, L8-25, and L8-30 demonstrated similar reductions from the control SCC of approximately 33%. Dilution of the pore solution's alkalinity by means of limestone powder replacing cement was one possible explanation of the charge passed reduction. Another explanation for decreasing RCPT results was minor improvement to the pore structure provided by limestone powder. The reduction between 28 and 90 days averaged 70% for all studied SCCs and was largely impacted by the reactivity of fly ash which supplied hydrates to reduce concrete permeability and in turn the charge passed.

(f) Rapid migration coefficients displayed a marginal decrease with increasing limestone powder at 28-day curing of only 4% to that obtained for the control SCC between limestone powder replacing 5 and 25% of cementitious materials. For 30% replacement of cementitious materials, the reduction in rapid migration coefficient compared to the control SCC was 12%. At 90-day curing, the reduction in rapid migration coefficient was more noticeable and reached an optimum reduction at 15% partial replacement with a 30% decrease compared to the control SCC. The 90-day rapid migration coefficient reduction of the limestone powder contained SCCS can be a result of fly ash's latent reactivity. Fly ash provided aluminates for the limestone powder to react with and it was possible that 15% partial replacement provided the optimum balance between fly ash and limestone powder to form hydration products.

(g) At 28-day curing, the chloride diffusion coefficient marginally increased between 3 and 10% with increasing limestone powder replacing a portion of cementitious materials. At 90-day curing, the opposite trend was observed for L8 limestone powder contained SCCs with decreasing chloride diffusion coefficients between 3 and 10% compared to the control SCC. The chloride diffusion coefficient decreased by an average of 55% for all studied SCCs between 28 and 90 days curing. The binding capacity may have been reduced at early curing ages due to limestone powder consuming cement's C_3A and aggregate interface effects. It may have been counteracted at later ages due to additional aluminates present in the fly ash for which limestone powder could have reacted with.

CHAPTER 5

INFLUENCE OF LIMESTONE POWDER SIZE ON TRANSPORT PROPERTIES OF SELF-CONSOLIDATING CONCRETE

The aim of this chapter is to present the results pertaining to strength and transport properties of self-consolidating concretes containing limestone powder with an average particle size of 3 microns. The limestone powder was used to partially replace a portion of the cementitious materials at levels of 10, 15, and 20% by weight. Compressive strength and transport properties including absorption, water penetration, rapid chloride penetration, and rapid migration were evaluated for SCCs cured for 28 and 90 days. From the results obtained in this chapter, the effect of limestone powder size on mechanical and transport properties of the studied self-consolidating concretes was also evaluated.

5.1 Compressive Strength of L3 Limestone Powder Contained SCCs

As mentioned previously in Section 4.1, concrete compressive strength can be affected by many factors. Lower water-to-cement ratios can increase compressive strength due to less entrapped water after mixing and decreased air voids in the hardened concrete. Coarse aggregates can improve concrete compressive strength due to better crack arresting mechanisms. Limestone powder can enhance compressive strength due to better particle packing and accelerated cement hydration. Fly ash provides late-strength gain due to pozzolanic reactions which supply additional CSH hydrates. Lastly, superplasticizer can increase compressive strength by providing additional water in concrete mixing which can accelerate cement hydration due to cement particle deflocculation and also produce a denser concrete (Alsadey 2012).

Zhu and Gibbs (2005) found when comparing three different limestone powder sizes, the finest limestone powder produced higher strength gain compared to coarser limestone powder contained SCC mixtures. It was hypothesized the smaller particle size resulted in improved particle packing and chemical reactivity of the limestone powder with Portland cement which both contributed to a higher compressive strength. Thongsanitgarn et. al. (2011) also observed concrete compressive strength increased with the fineness of limestone powder. Sato and Beaudoin (2011) found nano-limestone powder accelerated early age reactions in systems containing cement and Class F fly ash. De Weerdt et. al. (2011) found intensive grinding of fly ash appeared to make fly ash more reactive. Also, the addition of fine limestone powder with fly ash resulted in higher strength gain. This was attributed to a synergetic reaction between fly ash and limestone powder.

5.1.1 Compressive Strength of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The average compressive strengths at 28- and 90-day curing and the percent increase between the two curing ages of L3 and L8 limestone powder contained SCCs are shown in Table 5.1. Individual L3 limestone powder contained SCCs compressive strengths are presented in the Appendix B, Table B5.1. Also, displayed in Table 5.1 is the percent increase in compressive strength of L3 limestone powder contained SCCs compared to that of L8 limestone powder contained SCCs. In Figure 5.1, average 28- and 90-day compressive strengths of L3 and L8 limestone powder contained SCCs are plotted against percentage of limestone powder substituting a portion of the cementitious materials.

Table 5.1: 28- and 90-day average compressive strength of L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 CS (MPa)	60.1	61.7	64.2
28-day L8 CS (MPa)	60.11	59.23	59.91
% gain of L3 from L8 at 28-day curing	-0.10	4.21	7.12
90-day L3 CS (MPa)	77.6	76.2	83.7
90-day L8 CS (MPa)	74.32	73.33	74.96
% gain of L3 from L8 at 90-day curing	4.41	3.90	11.61
% gain from L3 28 to 90-day curing	29.13	23.45	30.35
% gain from L8 28 to 90-day curing	23.63	23.86	25.11

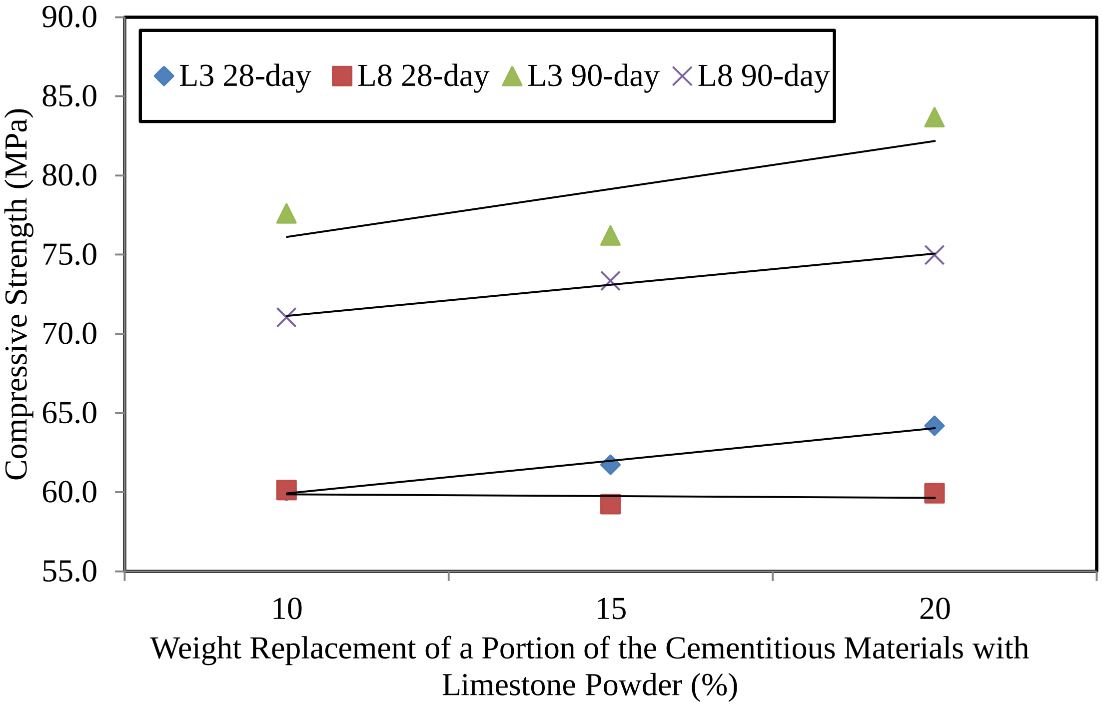

Figure 5.1: 28- and 90-day compressive strength results as a function of limestone powder replacing a portion of cementitious materials

Increasing limestone powder content from 10 to 15 to 20% by weight, the compressive strength of SCCs containing limestone powder with an average 3 micron in size increased by 2.5% and 4%, respectively. In contrast when limestone powder with an average size of 8 microns was used, the 28-day curing compressive strengths remained unchanged for the same increase in limestone powder content. There was a minor improvement in compressive strength with increasing L3 limestone powder content replacing a portion of cementitious materials as compared to that of L8 limestone powder contained SCC's. When limestone powder replaced 10% by weight of cementitious materials, there was little difference between L3 and L8 limestone powder contained SCC's compressive strength. When examining 15 and 20% limestone powder percent replacing a portion of the cementitious materials, the strength increase was approximately 4% and 7%, respectively for L3 limestone powder as compared to that of L8 limestone powder contained SCCs.

The strength increase at 28-day curing for SCCs containing L3 limestone powder as compared to L8 limestone powder contained SCCs can be attributed to three factors. First, as discussed in Section 4.1, higher dosages of superplasticizer may increase the compressive strength. From the results obtained in Chapter 3, L3 limestone powder contained SCCs required additional HRWRA to achieve target flow properties. L3 limestone powder's finer size can also fill the gaps between coarser cement particles more effectively than L8 limestone powder can. This can lead to a less porous concrete which in turn can enhance compressive strength. Lastly, as observed by Sato and Beaudoin (2011), finer limestone powder may accelerate early age hydration reactions which can improve early age concrete strength.

Self-consolidating concretes containing limestone powder with average size of 3 microns at 90-day curing had similar compressive strengths for 10 and 15% replacement by weight of cementitious materials. When 20% by weight of the cementitious materials was replaced with L3 limestone powder, the compressive strength increased almost 9% as compared to Mixtures L3-10 and L3-15. When examining the difference in strength between the two limestone powders, L3 limestone powder contained SCCs had strength gains between 4% and 12% when compared to that of SCCs containing L8 limestone powder. The higher strength gain of L3 limestone powder contained SCCs at 90-day curing can be a result of better particle packing due to L3 limestone powder's smaller size. The particle size distribution of L3 limestone powder shown in Chapter 3 demonstrated that L3 limestone improved particle packing. It was also possible that L3 limestone powder provided a more synergetic reaction with fly ash as discussed by prior study (DeWeerdt 2011).

The strength gain between 28 and 90 days curing for L3 limestone powder contained self-consolidating concretes averaged between 23 and 30%. When compared to the strength gain (23 to 25%) observed for SCCs containing limestone powder with average size of 8 microns, it was apparent that L3 limestone powder contained SCCs had marginally higher strength gain between the two curing ages. As stated previously, smaller sized limestone powders may produce earlier reactions with cement and fly ash which in turn can increase compressive strength.

5.2 Absorption of L3 Limestone Powder Contained SCCs

The following section discusses absorption results of L3 limestone powder contained SCCs. Absorption testing includes; absorption after immersion, absorption after immersion and boiling, and the volume of air voids. All three properties were indicators of concrete void structure.

5.2.1 Absorption After Immersion (AAI) of L3 Limestone Powder Contained SCCs

As discussed in Section 4.2.1, limestone powder can decrease the amount of water absorbed in concrete by decreasing the void system by means of filling gaps between coarse cement particles. It can also contribute to a reduction in water absorption by chemical reactivity with cement in the presence of either silica fume or fly ash to produce a non-soluble CSH structure (O'Flahtery and Mangat 1999).

5.2.1.1 Absorption After Immersion of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The average 28- and 90-day L3 and L8 limestone powder contained SCCs absorption after immersion results are shown in Table 5.2. The percent reduction from 28- to 90-day curing of L3 limestone powder contained SCCs is also presented in Table 5.2. Individual results of L3 limestone powder contained SCCs absorption after immersion are presented in the Appendix B, Table B5.2. L3 and L8 limestone powder contained SCCs' absorption after immersion results at 28- and 90-day curing are also displayed in Figure 5.2 as a function of limestone powder replacing a portion of cementitious materials.

Table 5.2: 28- and 90-day average absorption after immersion of L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 AAI (%)	2.59	1.60	1.35
28-day L8 AAI (%)	5.03	2.93	2.51
% reduction of L3 from L8 at 28-day	48.5	45.39	46.21
90-day L3 AAI (%)	2.64	1.87	1.57
90-day L8 AAI (%)	3.49	2.53	2.18
% reduction of L3 from L8 at 90-day	24.36	26.08	27.98
% reduction from L3 28 to 90-day	-1.94	-16.8	-16.29
% reduction from L8 28 to 90-day	30.62	13.57	13.22

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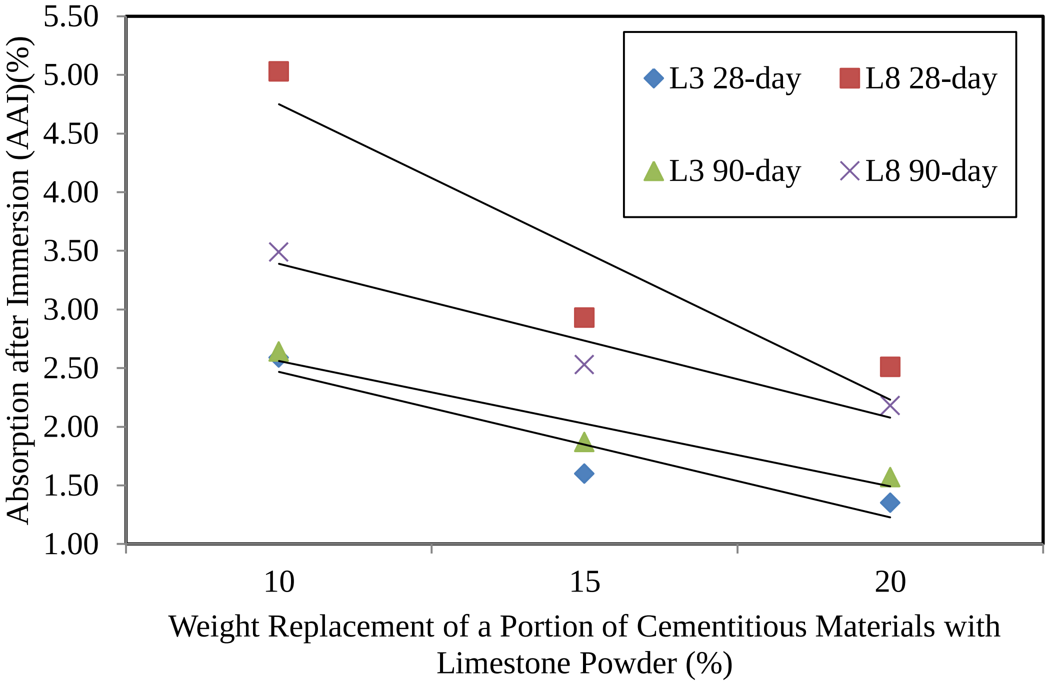

Figure 5.2: 28- and 90-day absorption after immersion results as a function of limestone powder replacing a portion of cementitious materials

For 28-day cured SCCs, the percent reduction in absorption after immersion results from 10 to 15 to 20% replacement by weight of cementitious materials with L3 limestone powder was 38% and 16%, respectively. The L3 limestone powder contained SCCs had lower water absorbed after immersion when compared to that of L8 limestone powder contained SCCs (nearly by an average of 46%). This indicated that L3 limestone powder's smaller particles were filling air voids more efficiently than L8 limestone powder. The readily reactivity of the finer size limestone powder with cement and fly ash to produce the non-soluble calcium silicate hydrate also allowed for its lower absorption after immersion as compared to that of the larger size limestone powder contained (L8) SCCs

The absorption after immersion results at 90-day curing with L3 limestone powder replacing 10% and 15% by weight of the cementitious materials decreased 29% between the two partial replacement of cementitious materials levels. When examining the percent difference between Mixtures L3-15 and L3-20, the reduction was 16%. L3 limestone powder contained SCCs absorption after immersion results remained approximately 26% lower compared to that of their 90-day cured L8 limestone powder counterparts. The reduction between the two limestone powder contained SCCs again were attributed to L3 limestone powder's small size providing a better particle packing as compared to L8 limestone powder. The improved chemical reactivity between limestone powder and fly ash, due to L3 limestone powder's smaller size, also contributed to the improved pore structure and in turn absorption after immersion of SCCs containing smaller limestone powder particle sizes.

When examining the difference between the two curing ages of L3 limestone powder contained SCCs, there appeared to be similar results between 28 and 90 days absorption after immersion. Discrepancy between the values may be a result of testing precision. It can, however, be surmised that the water after absorption did not appear to significantly alter between curing ages. It was possible that L3 limestone powder's size filled voids efficiently from particle packing at early ages to where fly ash's chemical contribution was insignificant at later ages. The reduction between the two curing ages for SCCs containing L8 limestone powder was more apparent with an average reduction in absorption after immersion of 18%. The larger size of L8 limestone powder may have allowed later fly ash reactions to contribute to decreasing the void system.

5.2.2 Absorption After Immersion and Boiling (AAIB) of L3 Limestone Powder Contained SCCs

The absorption after immersion and boiling test was performed after the absorption after immersion testing, and required concrete samples to be boiled for five hours after immersion has taken place. As stated in section 4.2.2, it was surmised that the test analyzed total pore volume water uptake in addition to capillary suction uptake. Limestone powder can provide a filler effect and additional hydrates, both of which can produce a denser pore structure. Other factors that influence absorption after immersion and boiling results are water-to-powder (cement, fly ash, and limestone powder) ratios and the use of superplasticizer. As stated in section 4.2.2, decreasing water-to-powder ratio and a higher amount of superplasticzer can decrease the pore volume due to less entrapped water and deflocculation of cement particle, respectively.

5.2.2.1 Absorption after Immersion and Boiling of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

Table 5.3 demonstrates the 28- and 90-day average absorption after immersion and boiling results for L3 and L8 limestone powder contained SCCs at 10, 15 and 20% replacing a portion of cementitious materials. The percent reduction between 28- and 90-day curing of L3 limestone powder contained SCCs is presented in Table 5.3. The Appendix B, Table B5.3 offers individual L3 limestone powder contained SCCs absorption after immersion and boiling results. Figure 5.3 demonstrates L3 and L8 limestone powder contained SCCs absorption after immersion and boiling results as a function of limestone powder replacing a portion of cementitious materials.

Table 5.3: 28- and 90-day average absorption after immersion and boiling results (percent) of the studied L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 AAIB	4.13	3.00	2.45
28-day L8 AAIB	5.96	4.09	3.74
% reduction of L3 from L8 at 28-day	30.70	26.65	34.49
90-day L3 AAIB	4.12	3.00	2.85
90-day L8 AAIB	4.88	3.44	2.50
% reduction of L3 from L8 at 90-day	15.57	12.70	-14.00
% reduction from L3 28 to 90-day	0.2	0	-16.32
% reduction from L8 28 to 90-day	18.07	16.02	33.25

When L3 limestone powder content was increased from 10 to 15 to 20%, the decrease in absorption after immersion and boiling results was 27% and 18%, respectively, for 28-day cured SCCs. Similar to 28-day absorption after immersion results, the absorption after immersion and boiling results of L3 limestone powder contained SCCs were less than L8 limestone powder contained SCCs by an average of

30% for all studied partial replacement of cementitious materials levels. The lower water absorbed after boiling of L3 limestone powder contained SCCs could have been a result of L3 limestone powder providing better particle packing due to its smaller size. The role of superplasticizer could have affected the total porosity of the system as it dispersed fine particles more efficiently. L3 limestone powder contained SCCs required higher dosages of HRWRA (superplaticizer) to meet target flow properties. The required higher dosage in turn may have produced better porosity and less water absorption in L3 limestone powder contained SCCs.

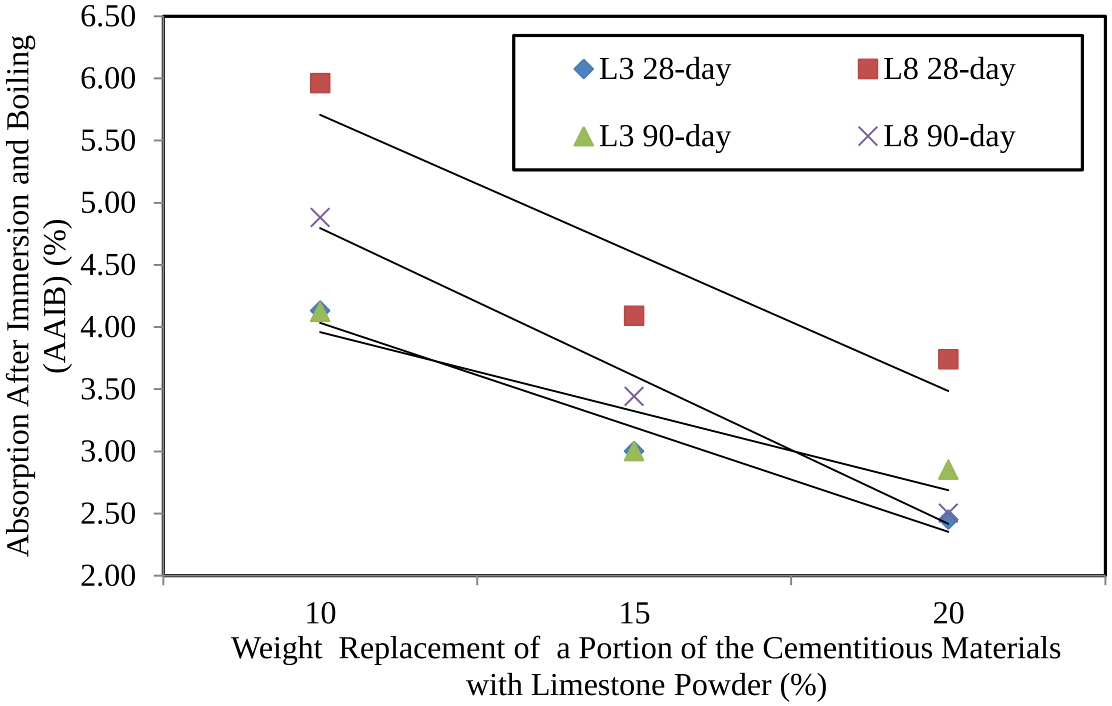

Figure 5.3: 28- and 90-day absorption after immersion and boiling results as a function of limestone powder replacing a portion of cementitious materials

With increasing L3 limestone powder content for 90-day cured SCCs, the absorption after immersion and boiling results decreased approximately 27% from 10 to

15% replacement by weight of cementitious materials. The absorption after immersion and boiling results remained relatively similar for L3 limestone powder replacing 15 and 20% of the cementitious materials. At 90-day curing, SCCs containing limestone powder with average size of 3 microns had lower absorption after immersion and boiling than L8 limestone powder contained SCCs with the exception of 20% replacing a portion of the cementitious materials which had comparable results. The percent difference between L3 and L8 limestone powder for limestone powder replacing 10 and 15% of cementitious materials was approximately 15% and 12%, respectively. Comparable absorption after immersion and boiling for Mixtures L3-20 and L8-20 could be a result of the pore space at later curing ages (i.e., 90 days) and larger limestone powder content (i.e., 20%) being sufficiently filled which produced similar absorption results.

The reduction in absorption after immersion and boiling between 28 and 90 days for SCCs containing L3 limestone was for the most part non-existent. Increase in absorption after immersion and boiling for 20% L3 limestone powder replacing the cementitious materials may have been a result of testing precision. SCCs containing L8 limestone powder had an average decrease between curing ages of 22%. The minimal strength gain may be a result of L3 limestone powder providing a sufficient filler effect and formation of hydrates to where fly ash's later contribution to fill the voids was insignificant.

5.2.3 Volume of Voids (VOV) of L3 Limestone Powder Contained SCCs

The volume of air voids demonstrated the percentage of the studied SCC's volume that is occupied by air voids. It was derived in the same mannerism as absorption after immersion and boiling results but considered SCC sample's suspended weight to determine the percent volume of air voids. The air void volumes of the studied SCC are impacted by fly ash reactivity, limestone powder physical and chemical contribution, water-to-powder ratios, and the use of superplasticizer.

5.2.3.1 Volume of Voids of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The volume of air voids (percent) of the studied L3 limestone powder contained SCCs and the comparison between the L3 and L8 limestone powder contained SCCs at both 28- and 90-day curing is shown in Table 5.4. Individual sample results are presented in the Appendix B, Table B5.4. The percent difference between 28- and 90-day curing of the studied L3 limestone powder contained SCCs is also offered in Table 5.4. Lastly, Figure 5.4 presents the volume of voids of L3 and L8 limestone powder contained SCCs as a function of limestone powder replacing a portion of the cementitious materials.

Table 5.4: 28- and 90-day average volume of voids of the studied L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 VOV (%)	9.63	7.10	5.87
28-day L8 VOV (%)	13.84	9.60	8.80
% reduction of L3 from L8 at 28-day	30.41	26.04	33.29
90-day L3 VOV (%)	9.64	6.98	6.83
90-day L8 VOV (%)	11.40	7.12	6.59
% reduction of L3 from L8 at 90-day	15.43	1.96	-3.65
% reduction from L3 28 to 90-day	-0.1	1.69	-16.35
% reduction from L8 28 to 90-day	17.65	25.82	25.07

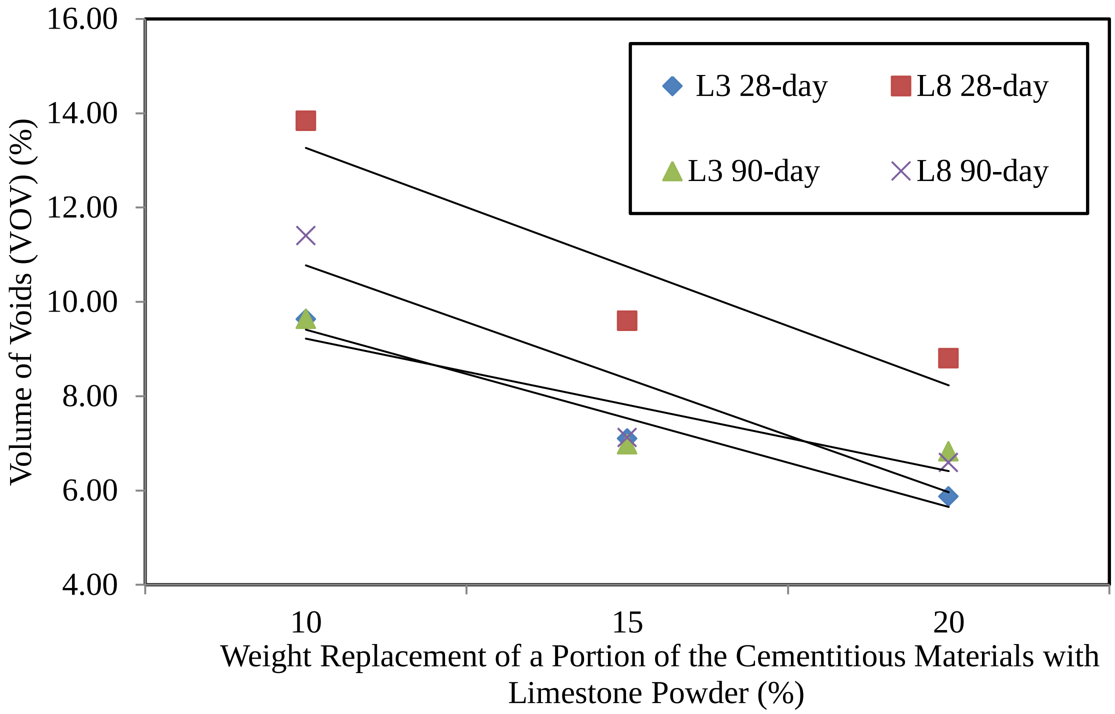

Figure 5.4: 28- and 90-day volume of voids results as a function of limestone powder replacing a portion of cementitious materials

Increasing L3 limestone powder content with 5% by weight incremental replacement of the cementitious materials produced a decrease in the volume of air voids for 28-day cured SCCs. From Mixtures L3-10 to L3-15 to L3-20, there was an observed reduction in the volume of air voids of 28% and 16%, respectively. The volume of air voids for L3 limestone powder contained SCCs decreased on average of 30% as compared with that of L8 limestone powder contained SCCs. This was expected as the L3 limestone powder contained SCCs absorption after immersion/ immersion and boiling both results decreased when compared their equivalent L8 limestone powder contained SCCs. L3 limestone powder's small size contributed physically to reduce pore size which in turn reduced the volume of air voids. Also possible was L3 limestone powder reacted with cement and fly ash more readily due its smaller size which provided additional hydrates to occupy voids. Lastly, additional amounts of HRWRA in L3 limestone powder contained SCCs as compared to their L8 limestone powder counterparts may have further reduced the volume of voids due to better dispersion of cement particles.

The volume of air voids at 90-day curing decreased approximately 32% between 10% and 15% replacement by weight of cementitious materials with L3 limestone powder. When examining 15% and 20% by weight replacement of cementitious materials, the volume of air void remained relatively similar. L3 limestone powder replacing 10% by weight of cementitious materials 90-day volume of voids results were 6% lower than L8 limestone powder at identical replacement levels of cementitious materials. Increasing L3 limestone powder content (i.e., 20%) produced volume of voids that were comparable to results of L8 limestone powder contained SCCs. It appeared that at later curing ages and larger replacement levels of cementitious materials, L3 limestone powder contained SCCs had similar pore structure to that of slightly coarser limestone powder. It was possible that at larger limestone powder content replacing cementitious materials and later curing ages, the void structure was sufficiently occupied regardless of limestone powder size.

Similar to absorption after immersion and boiling results, the reduction in volume of voids between the curing ages of 28 and 90 days was minimal. An increase observed for Mixture L3-20 may have been a result of testing precision. The reduction between 28 and 90 days curing in volume of voids for SCCs containing L8 limestone powder ranged between 17 and 25%. Fly ash’s latent reactivity and contribution to reducing the volume of voids were significant for L8 limestone powder but were not for L3 limestone powder content. This was likely due to L3 limestone powder providing sufficient filling of voids at earlier ages as compared to that of L8 limestone powder which required later curing age to minimize pore volume.

5.3 Water Penetration of L3 Limestone Powder Contained SCCs

As discussed in Section 4.4, the water penetration test measured the depth of water penetration into concrete’s surface. The water penetration depth can be affected by limestone powder’s filler effect, dilution effect, and heterogeneous nucleation which can distort crystalline CH structures. Fly ash contributes to reduced water penetration by means of calcium silicate hydrate structures which can reduce pore structures and in turn water penetration into the structure.

5.3.1 Water Penetration of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

The depth of water penetration (mm) of the studied L3 limestone powder contained SCCs as well as the comparison between L3 and L8 limestone powder contained SCCs at concrete curing age of 28 and 90 days is shown in Table 5.5. The percent difference between L3 limestone powder contained SCCs’ water penetration depth between the two curing ages is also presented in Table 5.5. Individual water penetration depths of L3 limestone powder contained SCCs are given in the Appendix B, Table B5.5. The water penetration depths of L3 and L8 limestone powder contained SCCS at 28- and 90-day curing are given in Figure 5.5 as a function of limestone powder replacing a portion of the cementitious materials.

With increasing L3 limestone powder replacing a portion of cementitious materials, the 28-day average water penetration depth marginally decreased an average 2% for each 5% incremental replacement level of cementitious materials. The water penetration depth of L3 limestone powder contained SCCs decreased at 28-day curing as compared to that of equivalent L8 limestone powder contained SCCs water penetration depth. The percent reduction for Mixtures L3-10, L3-15, and L3-20 remained between 5% and 8% when compared to their equivalent L8 limestone powder contained SCCs. L3 limestone powder provided lower water penetration depths as compared to L8 limestone powder contained SCCs due to its smaller size providing a better filler effect.

Table 5.5: 28- and 90-day average water penetration depths of the studied L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 WP (mm)	8.08	7.95	7.65
28-day L8 WP (mm)	8.77	8.42	8.23
% reduction of L3 from L8 at 28-day	7.92	5.54	7.00
90-day L3 WP (mm)	6.19	5.915	5.825
90-day L8 WP (mm)	6.73	6.34	6.00
% reduction of L3 from L8 at 90-day	8.06	6.70	2.91
% reduction from L3 28 to 90-day	23.38	25.59	23.85
% reduction from L8 28 to 90-day	23.26	24.65	27.06

The average 90-day water penetration depths of the L3 limestone powder contained SCCs produced marginal differences between 10, 15, and 20% replacement of cementitious materials with an average decrease of 3% between each increment. A decrease in average 90-day water penetration depths of 8% was observed between L3 limestone powder and L8 limestone powder at 10 and 15 % replacing the cementitious materials. At limestone powder replacement of 20% of cementitious materials, L3 and L8 limestone powder had similar water penetration depths. L3 and L8 limestone powder may have formed similar amounts of non-soluble hydrates at higher partial replacement levels at later curing ages. Also, the reducing fly ash content at larger limestone powder percent replacing which limited CSH hydrates resulted in similar water penetration depths between the two limestone powders.

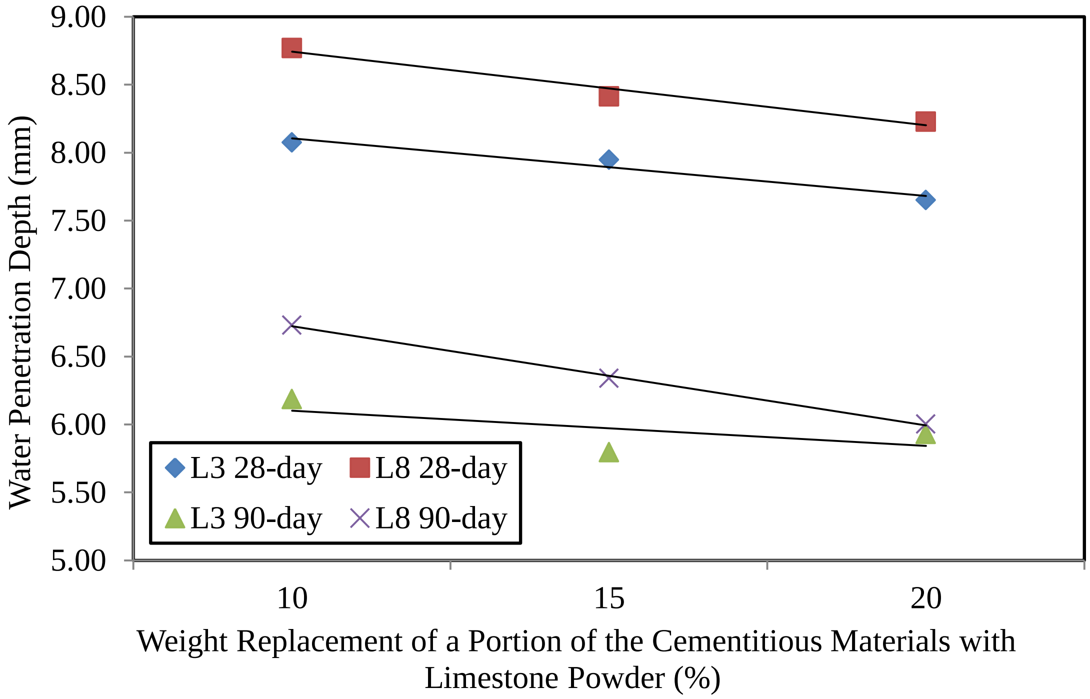

Figure 5.5: 28- and 90-day water penetration results as a function of limestone powder replacing a portion of cementitious materials

The difference between 28- and 90-day water penetration depths for SCCs containing L3 limestone powder (24%) were comparable to their equivalent L8 limestone powder contained SCCs reduction between curing ages (25%). The contribution of fly ash's latent reactivity to decreasing the water penetration appeared to be unaffected by limestone powder size.

5.4 Rapid Chloride Penetration of L3 Limestone Powder Contained SCCs

As discussed in section 4.6, the rapid chloride penetration indicates concrete's electro-conductivity which is affected by concrete's pore structure but primarily by the pore solution chemistry as RCPT measures all ions, not exclusively chloride ions, passed through the sample. Large amounts of cement can increase the alkalinity of the pore solution which in turns increases the electro-conductivity and the measured chloride penetration. Both fly ash and limestone powder can reduce concrete electro-conductivity by means of dilution and improved pore structure. Fly ash improves concrete pore structure at later curing ages due to pozzolanic reactions which provide additional calcium silicate hydrates products to enhance the pore structure. Limestone powder provides reduced alkalinity of the pore solution by means of partial replacement of cement and modified pore structure through smaller particle size and possible formation of additional hydration products. Also possible is a synergetic reaction between fly ash and limestone powder which will further reduce the pore structure (De Weerdt 2010) which in turn may decrease concrete permeability.

5.4.1 Rapid Chloride Penetration of L3 Limestone Powder Contained SCCs at 28- and 90-day Curing Ages

Table 5.6 presents the average 28- and 90-day RCPT results of the L3 limestone powder contained SCCs, percent difference between L3 and L8 limestone powder contained SCCs RCPT results at both curing ages, and percent difference between L3 limestone powder contained SCC RCPT results between 28- and 90-day curing. RCPT individual results are presented in the Appendix B, Table B5.6. The average RCPT results presented as coulombs of both L3 and L8 limestone powder contained SCCs are shown in Figure 5.6 as a function of limestone powder replacing a portion of the cementitious materials.

Table 5.6: 28- and 90-day average RCPT results of the studied L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 RCPT (coulombs)	3805	3715	3432
28-day L8 RCPT (coulombs)	4407	3939.33	3538
% reduction of L3 from L8 at 28-day	13.66	5.69	3.01
90-day L3 RCPT (coulombs)	936.7	1001.3	1000.7
90-day L8 RCPT (coulombs)	1310	1239.66	1003.83
% reduction of L3 from L8 at 90-day	28.50	19.23	0.32
% reduction from L3 28 to 90-day	75.38	73.05	70.84
% reduction from L8 28 to 90-day	70.27	68.53	71.63

Increasing L3 limestone powder content from 10 to 15 to 20% replacement by weight of the cementitious materials produced a decrease in the 28-day RCPT results of 3 and 7%, respectively. It was observed that L3 limestone powder replacing a portion of cementitious materials at lower levels (i.e., 10%) reduced the rapid chloride penetration as compared with RCPT results obtained for L8 limestone powder contained SCCs at 28-day curing. At 10% limestone powder replacing a portion of the cementitious materials, the percent reduction between L3 and L8 limestone powder contained SCCs was approximately 14%. At increasing limestone powder replacing a portion of cementitious materials, the percent difference between the two limestone powders was marginal with only 6% and 3% reduction observed for 15% and 20% replacement levels of cementitious materials.

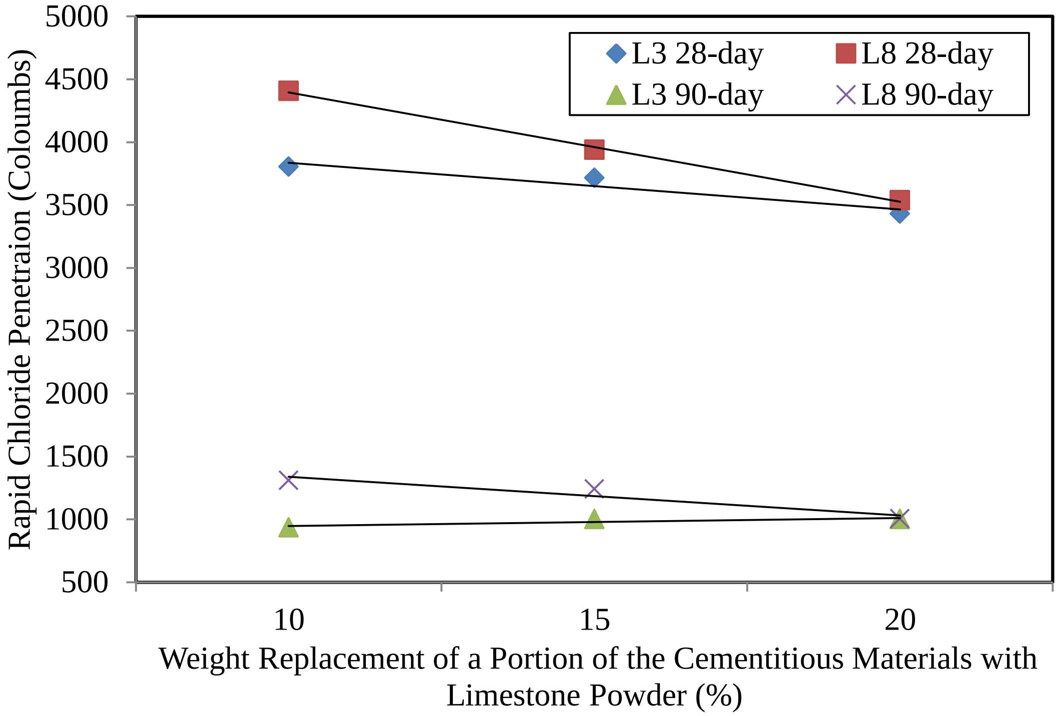

Figure 5.6: 28- and 90-day rapid chloride penetration results as a function of limestone powder replacing a portion of cementitious materials

L3 limestone powder may have a more synergetic reaction with fly ash than compared to L8 limestone powder due to its smaller size. However, increasing L3 limestone powder content did not produce increasing RCPT reduction between the two limestone powder contained SCCs. This may be a result of reduced fly ash content with increasing limestone powder content which limited additional CSH and carboaluminate hydrates.

The average 90-day RCPT results demonstrated an increase of approximately 6% from 10 to 15% replacement by weight of the cementitious materials with L8 and L3 limestone powder. Increasing limestone powder with an average size of 3 microns content from 15 to 20% replacement of cementitious materials produced minimal variation. When comparing the L3 and L8 limestone powder contained SCCs at 90-day curing, L3 limestone produced lower RCPT results for limestone powder replacing 10 and 15% of cementitious materials by 28 and 19%, respectively. At limestone powder replacing 20% of cementitious materials, the two limestone powder sizes produced a similar charge passed.

L3 limestone powder may have accelerated synergetic reaction with fly ash at lower partial replacement when there was sufficient fly ash to react with. Additional limestone powder replacing a portion of the cementitious materials (i.e., 20%) reduced the fly ash content to where L3 and L8 limestone produced similar effects on both concrete pore structure and pore solution. The decrease in the charge between 28 and 90 days curing ranged between 70 and 75% regardless of the limestone powder size. This demonstrated the contribution of fly ash to reducing the pore structure and pore solution conductivity was unaffected by limestone powder size.

5.5 Rapid Migration of L3 Limestone Powder Contained SCCs

The rapid migration coefficient is another method to measure chloride ingress, yet is not affected by pore solution conductivity as rapid chloride penetration is. It is primarily a measurement of concrete's pore structure to resist chloride ion migration. A lower rapid migration coefficient indicates a higher resistance to chloride ingress. As discussed in Section 4.7, Fagerlund (2005) discussed three possible effects limestone powder can have on concrete permeability. The first explanation is the limestone powder is inert and does not modify concrete permeability or pore structure. Secondly, it is possible the limestone powder reacts with C_3A but does not react with C_3S or C_2S which should still not modify concrete permeability or pore structure. Lastly, the limestone powder may react with all three cement components C_3S, C_2S, and C_3A which can modify the pore structure and in turn concrete permeability. This in turn can either increase or decrease the permeability based on how the pore structure was modified.

De Weerdt and Justness (2008) found that limestone powder in the presence of fly ash would further reduce concrete permeability due to additional aluminates provided by fly ash which will more readily react with limestone powder to produce additional hydrates. These additional hydrates can improve the pore structure and in turn reduce the rapid migration coefficient.

5.5.1 Rapid Migration of L3 Limestone Powder Contained SCCS at 28- and 90-day Curing Ages

The chloride ion rapid migration coefficients of the studied L3 limestone powder contained SCCs at curing age of 28 and 90 days as well as the age comparison is shown in Table 5.7. Also presented is a comparison between L8 and L3 limestone powder contained SCCs 28- and 90-day rapid migration results. Individual RMT results are given in the Appendix B, Table B5.7. The RMT results of L3 and L8 limestone powder contained SCCs are presented in Figure 5.7 as a function of limestone powder replacing a portion of the cementitious materials.

The 28-day chloride ion rapid migration increased an average 5.5% with increasing L3 limestone powder content from 10 to 15 to 20% replacement of cementitious materials by weight. L3 limestone powder contained SCCs demonstrated improvement in rapid migration coefficient at all limestone powder replacing cementitious materials levels as compared with their equivalent L8 limestone powder contained SCCs. For L3 limestone powder replacing 10% of cementitious materials, the improvement from L8 limestone powder contained SCCs was notable but became marginal with increasing L3 limestone powder content. This trend was similar to that observed in the rapid chloride penetration results in which lower L3 limestone powder replacing cementitious materials (i.e., 10%) produced improvement, while at higher replacing levels (i.e., 20%) produced results similar to equivalent L8 limestone powder SCCs.

Table 5.7: 28- and 90-day average RMT results of the studied L3 limestone powder contained SCCs

Replacement of a portion of cementitious materials with limestone powder	10%	15%	20%
28-day L3 RMT (10^{-12})	12.00	12.79	13.37
28-day L8 RMT (10^{-12})	14.03	13.99	13.94
% reduction of L3 from L8 at 28-day	14.43	8.56	4.13
90-day L3 RMT (10^{-12})	3.83	4.19	4.98
90-day L8 RMT (10^{-12})	5.81	4.34	4.79
% reduction of L3 from L8 at 90-day	34.04	3.56	-3.81
% reduction from L3 28 to 90-day	68.10	67.27	62.78
% reduction from L8 28 to 90-day	58.61	68.97	65.63

It appeared that L3 limestone powder was more reactive with both cement and fly ash at earlier ages than L8 limestone powder, likely due to L3's smaller particle size. This early reactivity could have increased carboaluminate hydrate volumes which improved concrete permeability. At higher partial replacement of cementitious materials with L3 limestone powder, the improvement in permeability became marginal likely due to insufficient fly ash content for the limestone powder to react with.

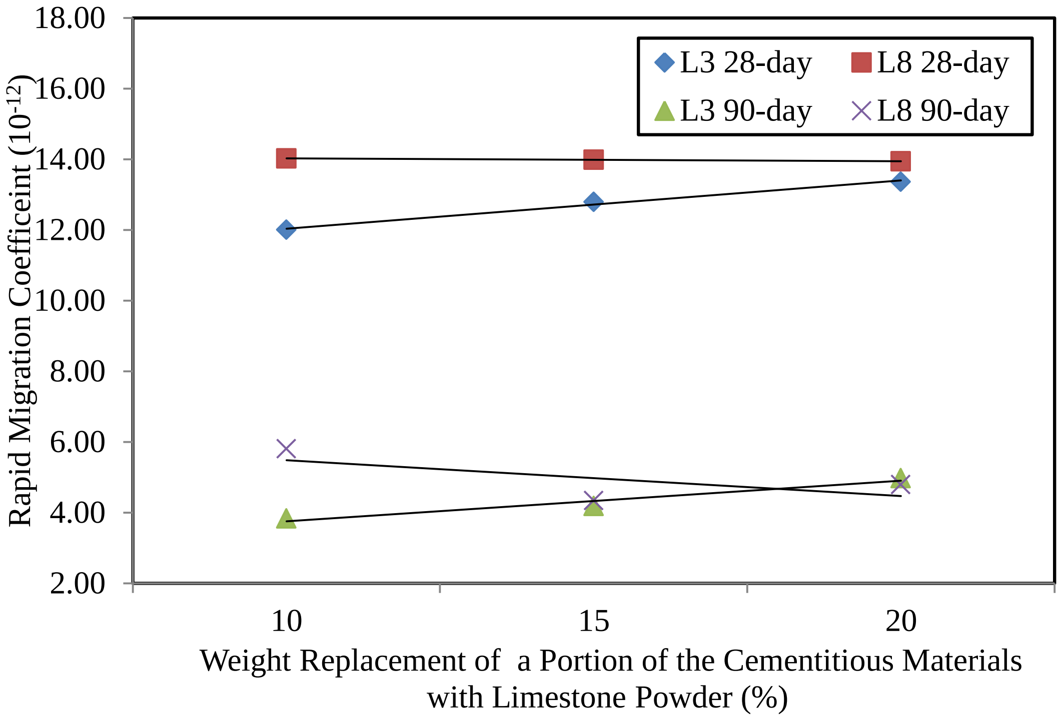

Figure 5.7: 28- and 90-day RMT results as a function of limestone powder replacing a portion of cementitious materials

When observing the average 90-day cured SCCS, the chloride ion migration increased 9 and 18% from 10 to 15 to 20%, respectively, by weight of L3 limestone powder replacing the cementitious materials. The 90-day curing RMT results displayed a 34% reduction of migration coefficient at L3 limestone powder replacing 10% of cementitious materials when compared to that of Mixture L8-10. With higher limestone powder content (15-20%), improvement in the rapid migration coefficient between the two limestone powders became increasingly marginal. Mixture L3-15 had a 3% reduction and Mixture L3-20 had an increase in rapid migration coefficient of approximately 3% when compared to that of their L8 limestone powder contained SCC counterparts.

It appeared at later curing ages that L3 limestone powder was more reactive than L8 limestone powder at lower levels of limestone powder replacing a portion of cementitious materials (i.e, 10%). With increasing incremental content of either L3 or L8 limestone powder content, the rapid migration coefficient became similar which indicated comparable effects of the two limestone powders on concrete permeability. Similar permeability of the L3 and L8 limestone powder contained SCCs can be attributed to the reducing fly ash content. As discussed in section 4.7.2, it can be surmised that at a certain limestone powder percent replacing cementitious materials, the fly ash content will be insufficient to provide the required aluminates to produce optimal hydration products. There appeared to be an optimum ratio between fly ash and limestone powder needed to produce largest amount of hydrates to occupy pore space and reduce rapid migration coefficients.

Between 28 and 90 days curing, the rapid migration coefficient decreased for Mixtures L3-10 and L8-10 by 68 and 58%, respectively. For 15% and 20% replacement of cementitious materials with either limestone powder, the reductions between curing ages were similar. It appeared at lower content replacing a portion of the cementitious materials, L3 limestone powder provided more improvement in the rapid migration coefficient due to an earlier reaction with fly ash to provide additional aluminates which improved the pore structure.

L8 limestone powder contained SCCs at 90 day curing age appeared to have optimum migration coefficient at 15 % partial replacement of cementitious materials.

Optimum migration coefficient for L3 limestone powder contained SCCs occurred at 10 % replacing cementitious materials. The lower optimum L3 limestone powder content may have been attributed to the smaller size of L3 limestone powder readily reacting with fly ash.

5.6 Conclusion

Based on the results presented in this chapter, the following conclusions can be made:

(a) At 28-day curing, 3 microns limestone powder replacing 15 and 20% of cementitious materials produced a 4 and 7% increase in compressive strength compared to their L8 limestone powder counterparts. The compressive strength increased between 3 and 12% for 90-day cured L3 limestone powder contained SCCs when related to SCCs containing limestone powder with average size of 8 microns. Earlier strength improvement can be attributed to the additional use of superplasticizer for L3 limestone powder contained SCCs compared to that of L8 limestone powder contained SCCs. The finer size of L3 limestone powder also provided better particle packing density and additional nucleation sites which further accelerate cement hydration. Later strength improvement may arise from L3 limestone powder readily reacting with fly ash to produce additional non-soluble hydration products.

(b) L3 limestone powder contained SCCs demonstrated lower water absorption and volume of air voids at 28 days of curing as compared with L8 limestone powder contained SCCs. The volume of voids for 28-day curing decreased between 26 and 33% for SCCs containing L3 limestone powder compared to L8 limestone powder. At later curing ages and larger limestone powder percent replacing a portion of cementitious materials, the two limestone powders appeared to have similar absorption and volume of air voids. This may be a result of either limestone powder sufficiently reduce the pore structure regardless of size. L3 limestone powder did not produce a change in absorption results between curing ages whereas L8 limestone powder had an average decrease between 18 and 22% for the three absorption tests. It was apparent fly ash's reactivity contribution to improving the pore structure was insignificant for L3 limestone powder contained SCCs likely due to L3 limestone powder's smaller size providing sufficient filler effect and early age chemical reactions.

(c) Water penetration depth of L3 limestone powder contained SCCs was reduced approximately 6% at 28 days as compared to equivalent L8 limestone powder contained SCCs. It was observed that at 90 days and 20% replacement of cementitious materials, L3 limestone powder demonstrated similar water penetration depths to that of L8 limestone powder at the same level. L3 limestone powder's smaller size better filled the voids to reduce water penetration at both curing ages. The reduction in water penetration depth between curing ages of the two studied limestone powder contained SCCs was similar. The contribution of fly ash to improve the pore structure and reduce water penetration was relatively unaffected by limestone powder size.

(d) The 28-day RCPT results of the studied SCCs decreased approximately 14% with incorporation of L3 limestone powder at 10 % replacement of a portion of cementitious materials with respect to its L8 limestone powder counterpart. With increasing L3 limestone powder substituting a portion of cementitious materials, the rapid chloride penetration was similar to L8 limestone powder contained SCCs at identical replacement level. SCCs containing 10 and 15% L3 limestone powder replacing a portion of cementitious materials had a 28 and 19% reduction, respectively, in 90-day RCPT results compared to Mixtures L8-10 and L8-15. When examining the 20% replacement of cementitious materials, the two limestone powder produced a similar charge passed. This trend can be attributed to L3 limestone more readily reacting with cement and fly ash due to its smaller size. The fly ash content reduction with higher limestone powder content (i.e., 20%) limited the synergetic reaction between limestone powder and fly ash which limited modification to the pore structure and improved RCPT results.

(e) The rapid migration coefficient decreased by 15% at 28-day curing and by 34% at 90-day curing for L3 limestone powder percent replacing 10% of cementitious materials compared to that the equivalent L8 limestone powder contained SCC. With increasing L3 limestone powder content, the rapid migration coefficient became similar to that of L8 limestone powder contained SCCs at both curing ages. This can be attributed to L3 limestone accelerating reactions with fly ash and cement at lower replacement levels than L8 limestone powder which more effectively improved the pore structure and decreased the rapid migration coefficient. Both limestone powders had an optimum percent replacing cementitious materials where the balance between fly ash and limestone powder produced the largest volume of hydration products to reduce permeability. L3 limestone powder had its optimum rapid migration coefficient at 10 % replacing cementitious materials, while L8 limestone powder had its optimum rapid migration coefficient at 15 % replacing cementitious materials.

CHAPTER 6

STATISTICAL ANALYSIS OF STUDIED SELF-CONSOLIDATING CONCRETES

The purpose of this chapter is to present statistical analysis that evaluated the role of mixture constituents and proportions on the studied self-consolidating concretes. Additionally, the statistical relationship amongst compressive strength and transport properties were developed. Finally, classifications for transport properties of the studied SCCs are presented.

6.1 Linear Relationship Between Compressive Strength and Transport Properties

Linear regression with multiple variables was performed on compressive strength and transport properties which included volume of voids, capillary primary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion. Multiple linear regression attempts to fit a linear equation as a relationship between two or more explanatory variables and a response variable (Boston University School of Public Health 2013). The linear equation is composed of a fit term and a residual term. The fit term describes the explanatory variables and can be denoted in the following form: $\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_p x_p$, where $x_{1,}$ x_2 etc. are the multiple explanatory variables and p is the number of explanatory variables in the equation. The residual term defines the deviation from observed dependent variable values, y, from their means. Significant tests can be utilized to determine whether an explanatory variable is significant to the multiple linear regression models. The p-value is associated with a two-sided test and if an explanatory variable has a p-value closer to zero, it is more than likely significant to the model (Boston University School of Public Health 2013).

The R-Squared (R^2) value is used as an indicator of how well the observed data is fitted to the regression line. Higher R-Squared values generally signify better fits of linear models with data (Frost 2013). With multiple variables, the R-Square value can be misleading as additional variables will increase the R-Square value regardless of better or worse fit to the model. The adjusted R-Square value accounts for the number of predictors in the model and only increases if the new variable improves the model (Frost 2013).

To achieve the best linear equation between dependent and independent variables, Microsoft Excel Regression was implemented. The program provided R-Squared values, adjusted R-Squared values, explanatory variable coefficients, explanatory variable p-values, and residual plots. These statistical tools were implemented to analyze the effects of SCC mixture variables on the studied SCC's compressive strength and transport properties. The selected explanatory variables were WTP (water-to-powder ratio), LP (percent of limestone powder replacing cementitious materials), SIZE (average mean particle size of the powder matrix), CA (coarse aggregate percent volume, FA (mortar percent volume), HRWRA (admixtures dosage in kg/m^3), and AGE (SCC curing age). Correlations between these explanatory variables are presented in Table 6.2. If two explanatory variables had a correlation of one, only one explanatory variable was selected for a multiple linear regression model. By performing multiple linear regressions with the chosen mixture variables, it was possible to examine statistically what factors affected individual tests.

An example of a multiple linear regression model of rapid migration results is presented in the Appendix C. All explanatory variables were initially selected for the first trial and the R-squared and adjusted R-squared values were recorded. Explanatory variables with relatively high p-values were omitted and regression analysis was performed again. This process was repeated until the optimum adjusted R-squared value was obtained for the model. Some explanatory variables had p-values higher than zero but were found to be significant to optimizing the adjusted R-squared value. Table 6.3 demonstrates the final regression analysis with the highest adjusted R-squared value obtained for each individual test.

Table 6.1: Equations for studied tests derived from multiple linear regression analysis.

Equation No.	
1	Compressive Strength (MPa)= 0.1847AGE -2.275SIZE+ 86.11345
2	Volume of Voids (%)= 243.1653WTP -0.01227AGE+ 0.85408SIZE – 22.03
3	Primary Capillary Absorption= -0.02078AGE+ 23.384WTP – 3.52
4	Water Penetration Depth (mm)= 6.15 CA + 6.08FA- 0.038AGE – 4.381HRWRA – 594.419
5	Rapid Chloride Penetration (coulombs)= -45.1645AGE – 1,198.98HRWRA-7,298
6	Rapid Migration Coefficient (10^{-12})=0.10597LP-0.13623AGE-4.34HRWRA+21.89
7	Chloride Diffusion Coefficient (10^{-12})= 0.00750AGE- 7.7WTP-13.0

Table 6.2: Correlation among mixture variables

	LP	SIZE	WTP	AGE	HRWRA	CA
SIZE	-0.72	1.00				
WTP	-1.00	0.73	1.00			
AGE	0.00	0.18	0.00	1.00		
HRWRA	0.96	-0.86	-0.96	-0.07	1.00	
CA	1.00	-0.72	-1.00	0.00	0.96	1.00
FA	-0.99	0.73	1.00	0.01	-0.95	-0.99

The adjusted R-squared value remained between 0.80 and 0.98 for all studied tests indicating relatively high fit to the regression model. Equations for the individual tests were derived from the significant explanatory variables and their coefficients. These significant explanatory variables can give insight of which factors greatly affected the individual test. Table 6.1 demonstrates the equations for the studied tests determined by the regression analysis. These equations were derived in certain ranges for the studied tests and mixture variables and the acceptable ranges for which the equations are valid are shown in Table 6.3.

Table 6.3: Limits of applicability for tests and mixture variables for derived equations

Test	Limits of applicability	Mixture Variables	Limits of applicability
Compressive Strength	55.9-90.2 MPa	WTP	0.32-0.45 ratio
Volume of Voids	5.47-15.16 % volume	LP	0-30 % replacement
Capillary Absorption	0.76-7.55 mm/s$^{1/2}$	SIZE	10.71-14.97 microns
Water Penetration	5.48-12.63 mm	CA	26.31-28.86 % volume
Rapid Chloride Penetration	936.7-5651 coulombs	FA	71.44-73.69
Rapid Migration	3.83-14.4 (10^{-12})	HRWRA	0.87-1.87 kg/m3
Chloride Diffusion	3.103-9.88 (10^{-12})	AGE	28-90, 28- 180 days

Table 6.4: Adjusted R^2 Values and Significant Variables of Compressive Strength and Transport Properties

Test	R^2 Square Value	Adjusted R^2 Square Value	Significant Variables	Variable Coefficients	p-values
1. Compressive Strength	0.951	0.947	Intercept	86.113	1.26E-13
			AGE	0.185	3.13E-17
			SIZE	-2.275	2.73E-05
2. Volume of Voids	0.8825	0.8604	Intercept	-22.03	2.31E-06
			WTP	53.80	3.67E-05
			AGE	-0.01227	0.173
			SIZE	0.85408	0.012
3. Capillary Absorption	0.8811	0.859	Intercept	-3.52	0.082
			AGE	-0.02078	1.13E-05
			WTP	23.384	0.00043
4. Water Penetration	0.8383	0.7952	Intercept	-594.419	0.0267
			CA	6.15	0.018112
			FA	6.0832	0.027442
			AGE	-.038	9.25E-06
			HRWRA	-4.381	0.036288
5. Rapid Chloride Penetration	0.952	0.9439	Intercept	-7298	2.7E-12
			AGE	-45.1645	2.3E-11
			HRWRA	-1477.17	3.89E-05
6. Rapid Migration	0.982	0.979	Intercept	21.89	6.1E-11
			AGE	-0.13623	2E-15
			HRWRA	-4.34	0.0096
			LP	1.0597	0.0523
7. Chloride Diffusion	0.958	0.9512	Intercept	1.3E-11	7.54E-07
			AGE	-7.5E-14	6.52E-09
			WTP	-7.7E-12	0.0393

6.2 Correlations Among Compressive Strength and Transport Property Tests

The purpose of this section was to observe if any correlations among the compressive strength and studied transport property tests existed. This may be of significance as trends among the tests could be influenced by similar SCC mixture variables. Correlations are associations between two variables where the association indicates that as one variable's value changes, the other variable's value should also change. Weak correlations indicate the value of one variable only changes occasionally while strong correlations indicate the change in value should occur more frequently. Correlation between two variables may indicate an association, however, it is not causation. If one variable changes, it does not imply the other variable will change (Pease and Bull 1996).

Microsoft Excel was used to determine the correlations among the test results of the studied SCCs. The correlations among the studied compressive strength (CS) and transport properties which included volume of voids (VOV), capillary primary absorption (CA), water penetration depth (WP), rapid chloride penetration test (RCPT), rapid migration test (RMT), and chloride diffusion (CD) are shown in Table 6.7. Blank spaces shown in the table were left intentionally to avoid repetition of the same correlation value. If the absolute correlation value was closer to 1, it indicated a strong correlation while a value closer to 0 indicated a weak correlation. Positive values indicated a positive correlation where changes in value should be observed in the two variables in the same direction. When the correlation value was negative, the two variables should change in opposite directions.

Table 6.5: Correlations among compressive strength and transport property tests

Correlation	CS	VOV	CA	WP	RCPT	RMT
VOV	-0.31					
CA	-0.86	0.71				
WP	-0.80	0.59	0.80			
RCPT	-0.94	0.41	0.92	0.82		
RMT	-0.95	0.22	0.82	0.74	0.95	
CD	-0.92	0.09	0.68	0.61	0.81	0.93

It was observed that the rapid chloride penetration test (RCPT) had moderate positive correlation with water penetration and chloride diffusion. This indicated that as the rapid chloride penetration decreased, a somewhat similar decrease maybe observed in the two other transport property results. RCPT results had the highest positive correlation with RMT and capillary absorption results with correlation values of 0.95 and 0.92, respectively. The high correlation may be a result of rapid chloride penetration, rapid migration, and capillary absorption being similarly affected by modification to the pore structure. Lastly, RCPT and compressive strength had a high negative correlation between the two studied tests which indicated any decrease or increase observed in RCPT may reflect the opposite trend for compressive strength results. This correlation appears plausible as a decrease in pore structure should decrease permeability and increase strength. The correlation between RCPT and the compressive strength and transport properties are shown in Figures 6.1 through 6.3.

Rapid migration results exhibited relatively positive correlation with capillary absorption and water penetration results. Strongest rapid migration test correlations were found with rapid chloride penetration test, chloride diffusion and compressive strength. As discussed previously, similar modifications to pore structure by limestone powder are expected to produce similar trends among the tests. Rapid chloride penetration and chloride diffusion correlations with rapid migration results were 0.95 and 0.93, respectively. The similar chloride binding capacity that should exist for both rapid migration and chloride diffusion may be a result of their high correlation. The negative correlation between rapid migration results and compressive strengths of the studied

SCCs was 0.95. The correlations of rapid migration results with chloride diffusion results and compressive strengths of the studied SCCs are shown in Figures 6.4 and 6.5.

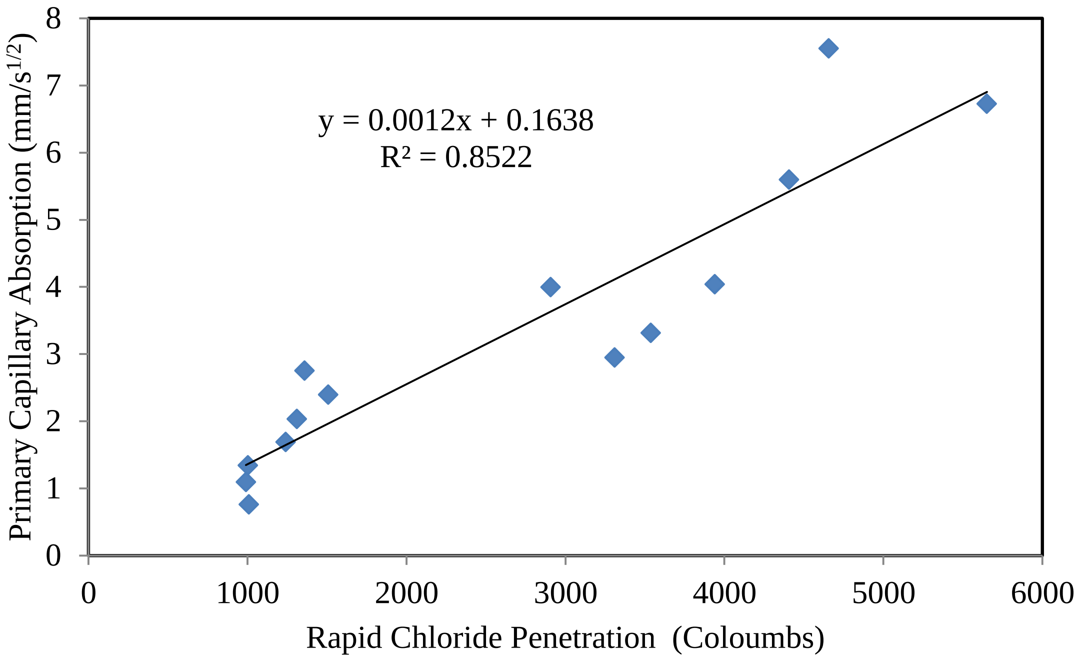

Figure 6.1: Correlation (0.92) between RCPT and Primary Capillary Absorption results of the Studied SCCs

Correlations between compressive strength with both capillary absorption and water penetration appeared to be moderately strong with values of -0.86 and -0.80, respectively. Lastly, the correlation between water penetration and capillary absorption was moderately strong with a value of 0.80. These correlations are expected as many of the transport and mechanical tests are dependent on concrete pore structure. Less porous concretes with little penetration to water and other outside substances should historically have higher strengths.

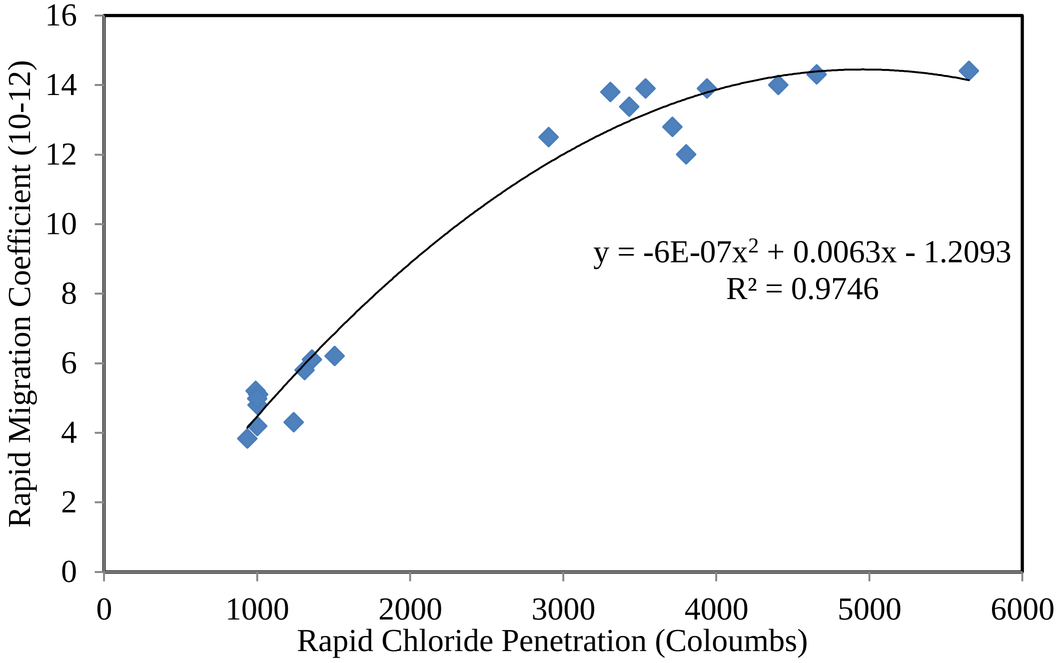

Figure 6.2: Correlation (0.95) between RCPT results and RMT results of the studied SCCs

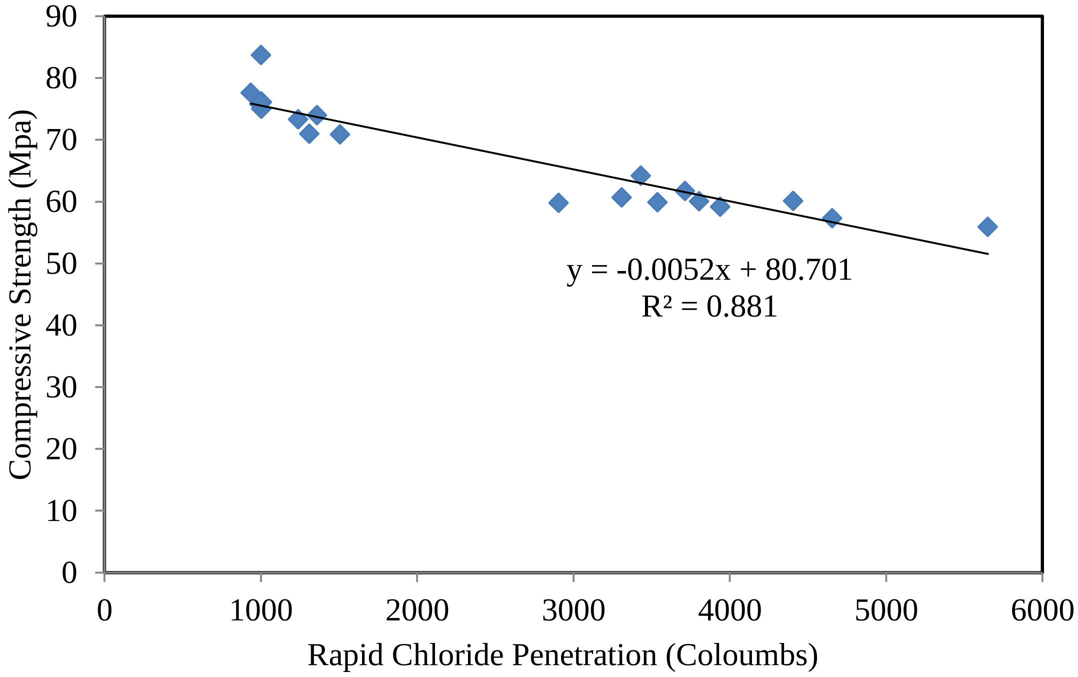

Figure 6.3: Correlation (-0.94) between RCPT results and compressive strenght of the studied SCCs

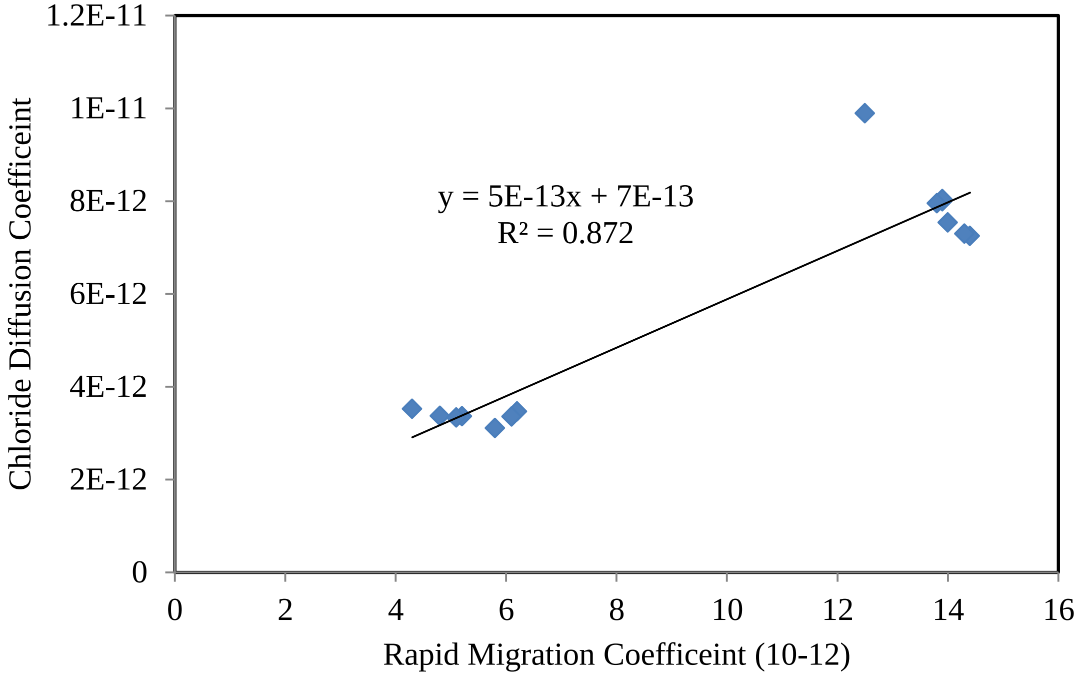

Figure 6.4: Correlation (0.93) between RMT results and Chloride Diffusion of the studied SCCs

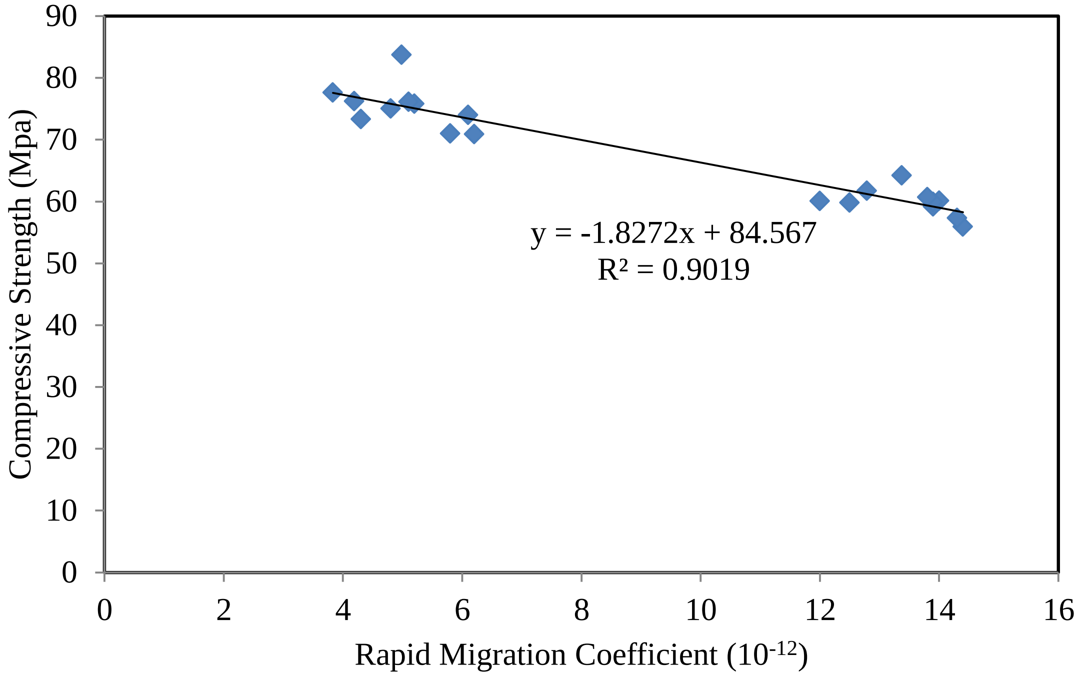

Figure 6.5: Correlation (-0.95) between RMT results and Compressive Strength of the studied SCCs

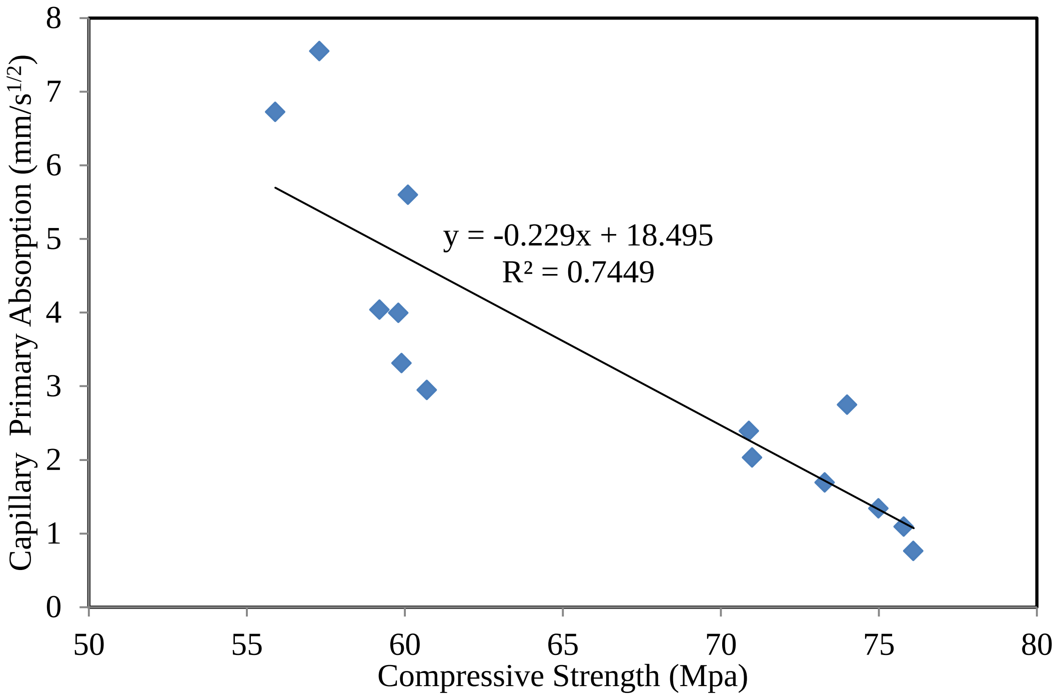

Figure 6.6: Correlation (-0.86) between Compressive Strength and Capillary Primary Absorption of the studied SCCs

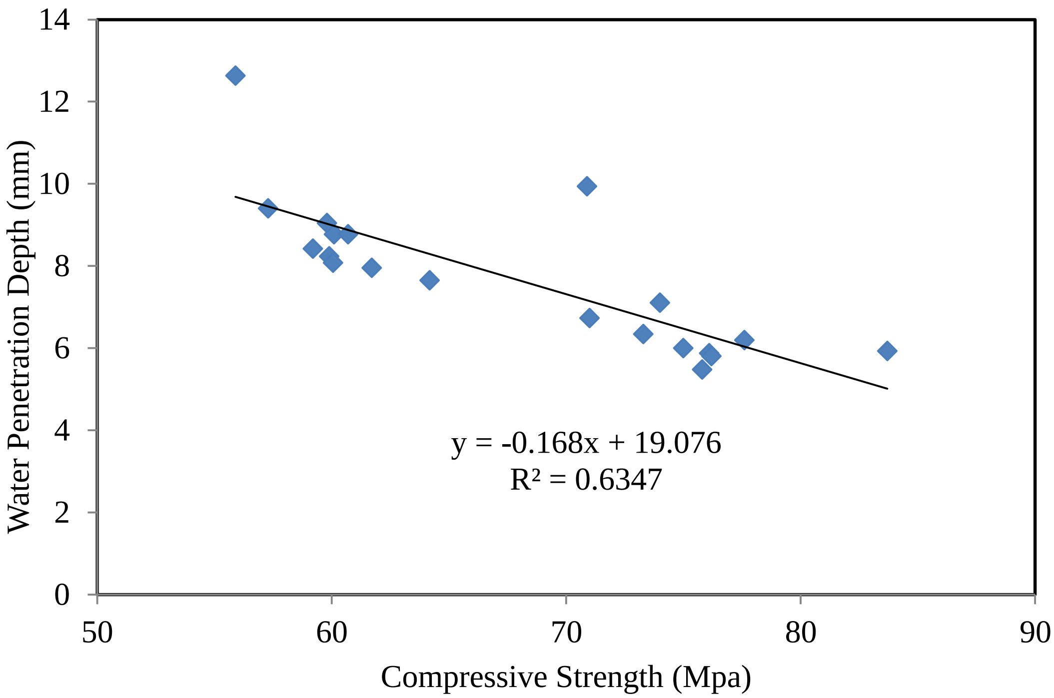

Figure 6.7: Correlation (-0.80) between Compressive Strength and Water Penetration depth of the studied SCCs

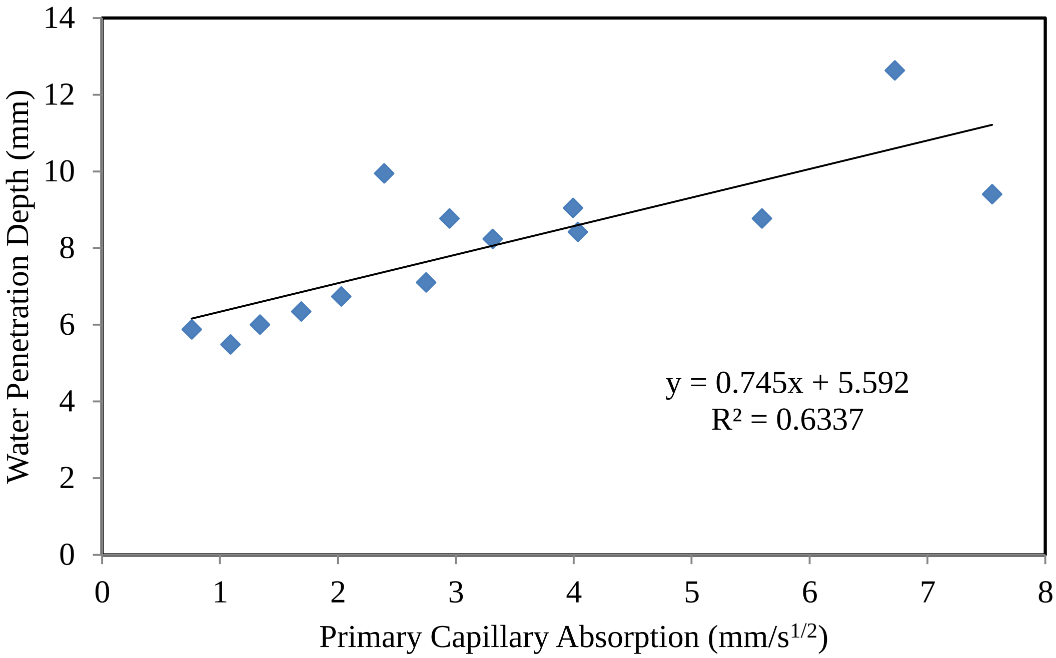

Figure 6.8: Correlation between Capillary Primary Absorption and Water Penetration Depth of the Studied SCCs

6.3 Classifications for Transport Properties of the Studied SCCs

Certain transport properties which were evaluated in previous chapters have suggested classification ranges to quantify the extent of chloride ion penetrability or durability of concrete. Transport properties which had established classifications were rapid chloride penetration test, rapid migration test, and volume of air voids. Table 6.6 demonstrates the rapid chloride penetration test's range of charge passed and to which class of chloride ion penetrability the charge passed belongs to. Presented in Table 6.7 are the studied SCC mixtures at 28- and 90-day curing along with the SCC mixture's chloride ion penetrability based on the criteria stated in Table 6.6.

Table 6.6: Rapid Chloride Penetration Range of Chloride Ion Penetrability Based on Charge Passed (Whiting 1981)

Charge passed	Chloride ion penetrability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible

Table 6.7: Individual SCC Chloride Ion Penetrability Rating for 28- and 90-day curing

Mixture	28-day	Chloride Ion Penetrability	90-day	Chloride Ion Penetrability
Control	5651	High	1507.3	Low
L8-5	4656.3	High	1359.2	Low
L8-10	4407	High	1310	Low
L8-15	3939.3	Moderate	1239.6	Low
L8-20	3538	Moderate	1003.8	Low
L8-25	3309.5	Moderate	990.5	Very Low
L8-30	2906.3	Moderate	1008.3	Low
L3-10	3805	Moderate	936.7	Very Low
L3-15	3715	Moderate	1001.3	Low
L3-20	3432	Moderate	1000.7	Low

From examining the 28-day curing RCPT results, the chloride ion penetrability classifications for the control SCC, Mixture L8-5 and Mixture L8-10 were deemed High. Once the L8 limestone powder substituted 15% or more by weight of the cementitious materials, the rapid chloride ion penetrability classification became Moderate. All studied L3 limestone powder contained SCCs produced chloride ion penetrability ratings of Moderate. It appeared that L8 limestone powder produced SCCs that effectively resisted chloride penetration with limestone powder replacing the cementitious materials by 15% or higher by weight. This could have been due to better pore structure or dilution of the pore solution as discussed previously in Chapter 4. L3 limestone powder at 10 percent replacing the cementitious materials produced better resistance to chloride ion penetrability as compared to that of the control SCC. Early age reactivity of the smaller limestone powder may have contributed to the better chloride resistance.

The 90-day curing RCPT results indicated that all studied SCC mixtures produced ratings of either Low or Very Low chloride ion penetrability. This signified fly ash’s latent reactivity was critical to the chloride ion penetrability classification. Of the L8 limestone powder contained SCCs, only Mixture L8-25 produced a chloride penetrability classification of Very Low. Observing the RCPT results, Mixtures L8-20, L8-25, and L8-30 had similar charges passed at 90-day curing. However, the cutoff range for Very Low chloride ion penetrability rating was 1,000 coulombs passed. It was surmised that higher L8 limestone powder percent replacing cementitious materials produced chloride penetrability of practically Very Low. Examining the L3 limestone powder contained SCCs, Mixture L3-10 had a Very Low classification while Mixtures L3-15 and L3-20 both had Low classifications. The RCPT values of the L3 limestone powder contained SCC mixtures were very similar and bordered the cutoff range of 1,000 coulombs. The inclusion of L3 limestone powder at 10 percent or higher replacing cementitious materials produced nearly Very Low chloride ion penetrability at 90-day curing.

Tang (1996) reported chloride ingress resistance criteria for rapid migration coefficients. The chloride ion rapid migration coefficient criteria are shown in Table 6.8 and the studied SCC mixtures 28- and 90-day curing RMT results along with their criteria are shown in Table 6.9.

Table 6.8: Chloride Ingress Resistance Criteria based on Rapid Migration Coefficients (Tang 1996)

Rapid Migration Coefficient	Criteria
$< 2 \times 10^{-12}$	very good resistance against chloride ingress
$<8 \times 10^{-12}$	good resistance against chloride ingress
$<16 \times 10^{-12}$	moderate resistance against chloride ingress
$>16 \times 10^{-12}$	not suitable for aggressive environment

Table 6.9: Individual SCC Mixtures RMT Criteria for 28- and 90-day curing

Mixture	28-day	Criteria	90-day	Criteria
Control	14.4	Moderate	6.2	Good
L8-5	14.3	Moderate	6.1	Good
L8-10	14	Moderate	5.8	Good
L8-15	13.9	Moderate	4.3	Good
L8-20	13.9	Moderate	4.8	Good
L8-25	13.8	Moderate	5.2	Good
L8-30	12.5	Moderate	5.1	Good
L3-10	12	Moderate	3.83	Good
L3-15	12.79	Moderate	4.19	Good
L3-20	13.37	Moderate	4.98	Good

The 28-day curing RMT results demonstrated no change in the RMT criteria rating and all studied SCC mixtures had a Moderate resistant to chloride ingress. This demonstrated the inclusion of limestone powder did not significantly modify the pore structure at 28 days to where the chloride resistance would be drastically improved.

The rapid migration coefficient criteria for all studied SCC mixtures at 90-day curing was classified as Good and did not alter with further L3 or L8 limestone powder percent replacing cementitious materials. The difference in rapid migration criteria between 28- and 90-day curing however confirmed that fly ash’s latent reactivity greatly improved chloride ingress resistance.

VicRoads (2013) established a classification for concrete durability based on the apparent volume of permeable voids (AVPV) as a percentage of bulk material's volume. The durability classification was used for vibrated concrete, rodded concrete, and cores of concrete. It was assumed that self-consolidating concrete had similar durability classifications as vibrated cylinders due to SCC's improved consolidation. The durability classification provided by VicRoads is shown in Table 6.10. The studied SCC mixtures volume of voids at 28- and 90-day curing and their respective durability rating are shown in Table 6.11.

Table 6.10: Durability Classification Based on Apparent Volume of Permeable Voids (VicRoads 2013)

Durability classification indicator	Vibrated cylinders (AVPV %)	Rodded cylinders (AVPV%)	Cores (AVPV %)
1 Excellent	< 11	<12	<14
2 Good	11-13	12-14	14-16
3 Normal	13-14	14-15	16-17
4 Marginal	14-16	15-17	17-19
5 Bad	> 16	>17	>19

Table 6.11: Individual SCC Mixtures Durability Classification based on Volume of Voids for 28- and 90-day curing

Mixture	28-day	Criteria	90-day	Criteria
Control	15.16	Marginal	12.86	Good
L8-5	14.13	Marginal	12.56	Good
L8-10	13.84	Normal	11.4	Good
L8-15	9.6	Excellent	7.12	Excellent
L8-20	8.8	Excellent	6.59	Excellent
L8-25	6.12	Excellent	6.23	Excellent
L8-30	5.96	Excellent	5.47	Excellent
L3-10	9.25	Excellent	10.69	Excellent
L3-15	6.68	Excellent	7.21	Excellent
L3-20	5.58	Excellent	7.38	Excellent

The improvement in the studied SCCs' durability classification with both L8 and L3 limestone powder increasing content was apparent at 28-day curing results. The control SCC and Mixture L8-5 had Marginal durability classification. With 10 percent of L8 limestone powder substituting a portion of the cementitious materials, the durability classification became Normal. With further percent of L8 limestone powder replacing the cementitious materials, the durability classification was Excellent for remaining L8 limestone powder contained SCCs. This indicated that the inclusion of L8 limestone powder at 15 percent or higher replacing the cementitious materials provided a higher durability indicator than compared to that of the control SCC. All studied L3 contained SCCs produced a classification of Excellent which signified that 10 percent L3 limestone powder replacing a portion of cementitious materials provided a potentially more durable concrete than the control SCC.

The 90-day curing volume of voids results demonstrated the control SCC and Mixture L8-5 and Mixture L8-10 had classifications which improved with age and were classified as Good. The remaining L8 limestone powder contained SCCs had durability indicator classifications of Excellent at 90-day curing. This demonstrated that lower limestone powder content SCCs had improvement with longer curing likely due to their larger fly ash content. However, 15 percent or higher L8 limestone powder replacing a portion of cementitious materials provided a potential for Excellent durability regardless of the curing age. Similar to 28-day curing results, all studied L3 limestone powder contained SCCs demonstrated Excellent durability indicator classification.

6.4 Conclusions

Based on the statistical analysis performed in this chapter, the following conclusions can be made:

(a) Multiple linear regression models were performed on the transport property and compressive test results as dependent variables. Each regression model was optimized for the highest adjusted R-squared value obtained. Explanatory variables included limestone powder percent replacement of cementitious materials, mean powder particle size, water-to-powder ratio, admixture dosage, coarse aggregate percent volume, fine aggregate percent volume, and curing age. By analyzing the explanatory variables that were significant to the regression model, it was possible to examine what variables statistically affected the individual test results.

(b) Correlations amongst the studied tests which included compressive strength, volume of voids, capillary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion were found. It was found rapid chloride penetration results had strongest correlations with capillary absorption and rapid migration results. Rapid migration results had a strongest correlation with chloride diffusion and rapid chloride penetration results. Lastly, compressive strength had negative strong correlations with rapid chloride penetration, rapid migration, capillary absorption, and water penetration results. The correlations may be a result of similar modification by limestone powder on pore structure and in the case of rapid migration and chloride diffusion, chloride binding capacity.

(c) The classification for the transport property tests rapid chloride penetration, rapid migration, and volume of voids were examined for the studied SCCs. It was found inclusion of 15 % or higher L8 limestone powder and 10% or higher L3 limestone powder replacement of a portion of cementitious materials improved rapid chloride penetration and volume of voids criteria chloride ion penetrability and durability classification. Inclusion of both limestone powders marginally improved rapid migration coefficient results, however did not change rapid migration criteria.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This study was intended to evaluate the influence of limestone powder content and size on transport properties of self-consolidating concretes. Limestone powder was used to partially replace a portion of the cementitious materials (Portland cement and fly ash) at varying percentages by weight ranging from 5 to 30%. Two limestone powder sizes, namely, L8 limestone powder which had a mean particle size of 8 microns and L3 limestone powder which had a mean particle size of 3 microns were used. Fresh (slump flow, VSI, T_{50} flow time, and J-Ring) and bulk characteristics (demolded unit weight and compressive strength) of the investigated SCCs were evaluated. Transport properties (absorption, capillary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion) of the studied SCCs were also examined. Finally, statistical analyses were performed to establish the most suitable relationships between the compressive strength and the selected transport properties with independent variables. The main results and conclusions of the study are presented below.

7.1.1 Influence of Limestone Powder on Flow Properties and Admixture Requirement of Self-Consolidating Concretes

High-range water reducing admixture (HRWRA) was used in this study to achieve target flow properties of the studied self-consolidating concretes. Target flow properties included a slump flow of 625 ± 25 mm (25 ± 1 inch), a VSI of 0 (highly stable) to 1 (stable), and J-Ring of less than 50 mm (2 inches). A viscosity modifying agent was found unnecessary for the studied SCCs due to their high powder content which provided adequate viscosity.

The dosage of a high-range water reducer admixture (HRWRA) was adjusted for SCCs in order to meet the previously stated target flow properties. It was found increasing limestone powder content required a higher dosage of HRWRA to meet the target flow properties. This was due to the reducing water-to-powder ratio with increasing limestone powder content in order to maintain a uniform water-to-cementitious materials for all studied SCCs. L3 limestone powder contained SCCs required additional HRWRA as compared to that of L8 limestone powder contained SCCs due to L3 limestone powder's narrower size distribution which increased the water demand.

The particle size distributions for the control SCC and SCCs containing either L3 or L8 limestone powder replacing a portion of the cementitious materials were plotted. It was apparent that increasing L8 limestone powder content produced a finer size distribution for the studied SCCs matrix as compared to that of the control SCC. Furthermore, L3 limestone powder greatly improved the size distribution when compared to either the control SCC or L8 limestone powder contained SCCs. Lastly, to examine whether carboaluminate hydrates found in previous studies were present in SCCs containing L3 or L8 limestone powder, the X-ray diffraction test was utilized. It was found that 90-day cured pastes containing either L3 or L8 limestone powder contained a form of carboaluminate hydrate which was not present in the control paste (cement and fly ash). The availability of the carboaluminate hydrate has contributed to improving the pore structure which, in turn, enhanced the capillary absorption, rapid migration, and chloride diffusion of the investigated limestone powder contained SCCs.

7.1.2 Influence of Limestone Powder as a Partial Replacement of Cementitious Materials on Compressive Strength and Transport Properties of Self-Consolidating Concrete

Limestone powder, denoted as L8, which had a mean a particle size of 8 microns was used to replace a portion of the cementitious materials at levels of 5, 10, 15, 20, 25, and 30% by weight. The compressive strength and selected transport properties were evaluated for the L8 limestone powder contained SCCs and compared to a control SCC (cement and fly ash). The subsections to follow describe the conclusions of the first part of this study.

7.1.2.1 Compressive Strength of the Studied SCCs

Increasing L8 limestone powder content produced marginal compressive strength gain at all curing ages as compared to that of the control SCC. For 28-day cured SCCs, the strength gain compared to the control SCC ranged between 2 and 9% for L8 limestone powder contained SCCs. Compressive strength of the studied L8 limestone powder contained SCCs at 90-day curing and 180-day curing also displayed a marginal compressive strength improvement with limestone powder inclusion of 2 to 8% when compared to that found for the control SCC. A uniform water-to-cementitious materials ratio used for all studied SCCs resulted in similar compressive strength for all curing ages. The marginal strength improvement can be attributed to limestone powder providing better particle packing, additional use of superplasticizer for L8 limestone powder contained SCCs, and higher coarse aggregate content with increasing limestone powder content. Between 28 and 90 days, a strength gain of 25% was observed for the studied SCCs. The strength gain between 90 and 180 days curing was slightly less and averaged at 17%. The higher strength gain between 28 and 90 days was a result of fly ash's latent reactivity which supplied additional hydrates to improve compressive strength.

7.1.2.2 Absorption of the Studied SCCS

Absorption testing included three aspects; absorption after immersion, absorption after immersion and boiling, and the volume of voids. Absorption after immersion was determined to be a function of capillary suction while the latter two are a function of capillary suction and porous voids in the concrete system.

The absorption after immersion results were found to decrease with increasing limestone powder content as compared to the control SCC at 28- and 90-day curing. Up to 10% replacement of cementitious materials with limestone powder produced an average of 20% reduction in absorption after immersion for 28-and 90-day cured SCCs. When limestone powder substituted 15 and 20% of the cementitious materials, the reduction in absorption after immersion was 48 and 55%, respectively, for both curing ages. Further increase of the limestone powder content with 25 and 30% replacement of cementitious materials for both curing ages produced on the whole a significant reduction of 74%. Limestone powder's smaller size filled voids between coarser cement and fly ash particles which in turn reduced water absorption after immersion. Also, limestone powder modified the hydration products by supplying ions which decreased the void system (Daimon and Sakai 1998). Reduction in absorption after immersion between 28 and 90 days was higher (average of 23%) for the control SCC and SCCs containing up to

10% limestone powder by weight of cementitious materials. This finding can be attributed to the improved capillary void structure through additional hydrates provided by fly ash.

Both absorption after immersion and boiling and the volume of voids decreased with inclusion of L8 limestone powder. Similar to absorption after immersion results, up to 10% replacement of cementitious materials with limestone powder had a reduction in 28- and 90-day volume of voids by 10% compared to that of the control SCC and further reduced to approximately 43% for 15 and 20% replacement of cementitious materials. When limestone powder replaced 25 and 30% by weight of the cementitious materials, the average reduction compared to that of the control SCC was 57%. This behavior is attributed to the same explanation given for the results of absorption after immersion of limestone powder contained SCCs. Other contributing factors which effectively reduced the volume of voids in the SCCs were lower water-to-powder ratio and higher HRWRA dosage with increasing limestone powder substituting a portion of the cementitious materials. On the whole, an increase in curing age (i.e. from 28 to 90 days) had a similar effect on limestone powder contained SCCs. The average reduction in absorption after immersion and boiling and volume of voids between the two curing ages were 17 and 14%, respectively. This reduction between the curing ages was a result of fly ash's reactivity which supplied additional calcium silicate hydrates, resulting in lower volume of voids and absorption.

7.1.2.3 Capillary Absorption of the Studied SCCs

The capillary primary absorption of the studied L8 limestone powder contained SCCs decreased at 28- and 180-day curing as compared to the control SCC with the exception of limestone powder replacing 5% of the cementitious materials. For up to 10% replacement of cementitious materials with limestone powder, an average of nearly 16% reduction in capillary absorption as compared to the control SCC was obtained for both curing ages of 28 and 180 days. This reduction significantly increased by an average of 47% for 28-day cured SCCs with an inclusion of limestone powder by 15% weight of cementitious materials and it remained unchanged thereafter. At 180-day curing, there was a steady increase in capillary absorption by an average of 50%, 24%, and 25% for each 5% increase in limestone powder content ranging from 15 to 30% by weight of cementitious materials. This trend can be explained physically through limestone powder's ability to fill voids and chemically through the formation of carboaluminate hydrate which both contributed to the reduction of the capillary void structure. The difference between 28- and 180-day curing remained similar for both control and limestone powder contained SCCs at an average of 65%. The reduction in capillary absorption between curing ages was a result of continued cement hydration and latent fly ash reactivity which both supplied additional hydrates to effectively occupy capillary voids.

7.1.2.4 Water Penetration of the Studied SCCs

The water penetration depth of the studied SCCs decreased with the inclusion of L8 limestone powder. At 28-day curing, there was an observed reduction of 25% from that of the control SCC with limestone powder replacing 5% by weight of cementitious materials. The reduction compared to the control SCC remained between 28 and 35% with each incremental 5% replacement of cementitious materials by weight with limestone powder. The 90-day cured SCC samples observed a 28% reduction for 5%

replacement of cementitious materials with limestone powder and further reduction between 32 and 45% compared to the control SCC with additional limestone powder substituting a portion of the cementitious materials. It appeared that the limestone powder produced an effect at 5% replacement of the cementitious materials to where water penetration was drastically reduced. Potentially, heterogeneous nucleation with the introduction of limestone powder modified the CH structure due to disoriented crystallization and further limestone powder content marginally improved the water penetration depth by means of filler effect. The decrease in water penetration depth between 28 and 90 days averaged 27% for the control and limestone powder contained SCCs and was a result of fly ash's contribution to reduce the void structure.

7.1.2.5 Rapid Chloride Penetration of the Studied SCCs

At 28-day curing, the studied self-consolidating concretes had a reduction in RCPT results with increasing limestone powder content. With a 5% replacement of cementitious materials, the RCPT charge passed decreased approximately 18% compared to that of the control SCC. In comparison with that of the control SCC, additional incremental weight increase of limestone powder by 5% of cementitious materials resulted in the reduction in charge passed by nearly 5%. For the 90-day cured samples, increasing limestone powder content up to 20% of the cementitious materials decreased the RCPT results. An additional increase in the limestone powder content was unable to further reduce the rapid chloride penetration. Between the two curing ages, the reduction in the charge passed was between 60% and 70% for the control and L8 limestone powder contained SCCs.

Reduction in the charge passed of SCCs containing limestone powder with an average size of 8 microns compared to the control SCC was a function of the pore solutions' conductivity dilution with increasing limestone powder content. Limestone powder also filled voids with its smaller size and supplied carboalumiante hydrates which improved the pore structure. The improvement to the pore structure can improve the charge passed but not as significantly as the decrease in pore solution conductivity. Fly ash's latent reactivity appeared to have the greatest impact on reducing the charge passed between 28 and 90 days curing, as a result of fly ash providing CSH structures to improve pore structure and dilute pore solution conductivity.

7.1.2.6 Rapid Migration of the Studied SCCs

The 28-day curing rapid migration coefficients of the studied SCCs decreased marginally with the inclusion of limestone powder. When compared to that of the control SCC, inclusion of limestone powder ranging between 5 to 25% by weight replacement of cementitious materials produced a marginal reduction of 4% in rapid migration coefficient. Replacement of cementitious materials with 30% limestone powder produced a reduction of nearly 12% compared to that of the control SCC. The reduction however may be a function of testing mechanisms as the voltage selected is based off a measured charge cutoff criteria. 90-day RMT results had a more notable reduction with least rapid migration coefficient observed for the limestone powder contained SCC replacing 15% by weight of cementitious materials. Between 28- and 90-day curing, there was a significant decrease in the rapid migration coefficient of the control SCC and SCCs containing limestone powder ranging between 55 and 65%.

It appeared that at 28-day curing, the formation of the carboaluminate hydrate may have been limited by the small amount of aluminates in Portland cement (4.25%) for limestone powder to react with. At 90-day curing, the fly ash was reactive which released additional aluminates (22.22%) to react with limestone powder to produce sufficient carboaluminate capable of enhancing pore structure and reduction of the rapid migration coefficient. The fly ash at later age provided more silicate hydrates which significantly decreased the pore structure, resulting in a sizeable difference in the rapid migration coefficient between the two curing ages.

7.1.2.7 Chloride Diffusion of the Studied SCCs

Chloride diffusion was a function of both chloride binding capacity which was largely affected by cement's C_3A phase and to a lesser extent concrete pore structure. The chloride diffusion coefficients of the 28-day cured SCCs remained independent of the limestone powder content and marginally increased by an average of 7%. The 90-day curing chloride diffusion coefficients slightly decreased by an average 4% with inclusion of limestone powder regardless of the substitution level of cementitious materials by limestone powder. Between 28 and 90 days curing, the chloride diffusion coefficients decreased by an average of 55% for all studied SCCs.

Limestone may have been reactive at 28-day curing and formed the carboaluminate hydrate which consumed the C_3A phase to eventually reduce the chloride binding capacity and to increase the chloride diffusion coefficient. At 90-day, fly ash released additional aluminates (22.22%) into the system which enhanced the chloride binding capacity and the pore structure through means of calcium aluminates and calcium silicates. Limestone powder then reacted with fly ash which modified the pore structure without reducing the chloride binding capacity. The coarse aggregate content also created an interface effect at both curing days which increased the chloride diffusion coefficient. The increase was later alleviated by the fly ash's contributions at 90 days.

7.1.3 Influence of Limestone Powder Size on Transport Properties of Self-Consolidating Concrete

To compare the effects of limestone powder size on the compressive strength and transport properties of self-consolidating concrete, a finer gradation of limestone powder designated as L3 was used to partially replace the cementitious materials at levels of 10, 15, and 20% by weight. L3 limestone powder had a mean particle size of 3 microns as compared to that of L8 limestone which had an average particle size of 8 microns. Transport properties studied for this part of the study included absorption, water penetration, rapid chloride penetration, and rapid migration. The conclusions are presented below in the following subsections.

7.1.3.1 Compressive Strength of the Studied L3 Limestone Powder Contained SCCs

The compressive strength of the L3 limestone powder contained SCCs generally increased as compared to L8 limestone powder contained SCCs at 28 days. The increase of 4% and 7% in compressive strength was obtained when L3 limestone powder replaced 15 and 20% by weight of cementitious materials. At 90-day curing, SCCs containing L3 limestone powder improved the compressive strength by an average 6% as compared to L8 limestone powder contained SCCs. The strength gain for L3 limestone powder, as compared to L8 limestone powder, can be attributed to the L3 limestone powder's smaller size being more capable of filling voids, early age reactivity due to its smaller size, and additional HRWRA (superplasticizer) required to meet the target flow properties. All of these factors had led to a denser pore structure and, hence, to an increase in compressive strength of the SCCs containing the smaller size limestone powder.

Between 28- and 90-day curing, the strength gain (23 to 30%) of the L3 limestone powder contained SCCs was comparable to that obtained for the SCCs containing L8 limestone powder (23 to 25%). The slightly higher strength between curing ages for L3 limestone powder contained SCCs may be due to the higher reactivity of the smaller size limestone powder with fly ash which provided additional hydrates to occupy pore space and to increase compressive strength.

7.1.3.2 Absorption of the Studied L3 Limestone Powder Contained SCCs

At 28-day curing, the absorption after immersion, absorption after immersion and boiling, and the volume of voids decreased with the inclusion of L3 limestone powder when compared to those of the equivalent SCCs prepared with L8 limestone powder. The reduction in absorption after immersion, absorption after immersion and boiling, and volume of voids of 28-day cured L3 limestone powder contained SCCs decreased by an average 47%, 31%, and 30%, respectively, as compared to those of the SCCs containing coarser limestone powder. At 90-day curing, the reduction in volume of voids between the two limestone powder sizes was 15% for limestone powder replacing 10% by weight of cementitious materials. With 15 and 20% replacement of cementitious materials with limestone powder, the volume of voids for the two type of limestone powder size were similar.

At 28-day curing, L3 limestone powder's smaller size allowed for less voids to reduce the absorption after immersion, absorption after immersion and boiling, and volume of voids. The smaller limestone powder assists for a better reactivity with both cement and fly ash at 28 days and produce non-soluble hydrates which decreased the void volume. The SCCs at 90 days may have exhibited similar volume of voids at 15 and 20% by weight replacement of cementitious materials with limestone powder due to the pore structure being sufficiently occupied by hydrates.

The difference in absorption after immersion and boiling and the volume of voids between 28- and 90- day curing of the L3 limestone powder contained SCCs was minimal. On the other hand, the SCCs containing L8 limestone powder had an average reduction in volume of voids of 22%. This opposing trend may be attributed to the L3 limestone powder providing sufficient filling of the voids by both physical and chemical means at earlier curing ages.

7.1.3.3 Water Penetration of the Studied L3 Limestone Powder Contained SCCs

L3 limestone powder contained SCCs demonstrated a marginally lower water penetration depths at 28-day curing as compared to their equivalent L8 limestone powder contained SCCs. The average reduction in water penetration depth was 8, 5, and 7% for L3 limestone powder replacing 10, 15, and 20% by weight of the cementitious materials, respectively. At 90-day curing, there was a marginal difference in water penetration depth between the two limestone powder sizes replacing 10 and 15% by weight of cementitious materials. Once the limestone powder content reached 20% by weight of cementitious materials, the two limestone powder sizes had a similar water penetration depth.

At 28-day curing, L3 limestone powder offered lower water penetration depths as compared to L8 limestone powder contained SCCs due to its smaller size which provided a better filler effect. With additional curing (i.e. 90 days) and limestone powder content, the void structure became sufficiently occupied and independent of limestone powder size. The decrease in curing ages for the two limestone powder contained SCCs water penetration depths were comparable (23 to 27%) and were a result of fly ash's pozzolanic reaction improving the void structure and water penetration, independent of limestone powder size.

7.1.3.4 Rapid Chloride Penetration of the Studied L3 Limestone Powder Contained SCCs

The rapid chloride penetration is a function of primarily concrete pore solution and to a lesser extent pore structure. L3 limestone powder contained SCCs provided lower RCPT values by 14% at 28-day curing for limestone powder replacing 10% of the cementitious materials than compared to Mixture L8-10 (10% by weight of cementitious materials with L8 limestone powder). The reduction was marginal when comparing the two limestone powder contents for 15 % and 20% replacing the cementitious materials. 90-day curing results demonstrated a similar trend where 10% and 15% of L3 limestone powder replacing cementitious materials produced lower RCPT values of 28 and 19%, respectively. With 20% replacement of cementitious materials, L3 and L8 limestone powder had comparable RCPT values.

At the lower replacement of cementitious materials (i.e., 10 to 15%), L3 limestone powder contained SCCs allowed for less charge passed as compared to the equivalent SCCs containing L8 limestone powder. This finding is attributed to the higher reactivity of L3 limestone powder due to its smaller size. However, increasing L3 limestone powder content did not produce increasing RCPT reduction between the two limestone powder types. This can be due to the reduced fly ash content, as a result of an increase in limestone powder content, which limited formation of additional calcium silicates and carboaluminate hydrates. The differences in charge passed between the two curing ages of the two sets of limestone powder contained SCCs were comparable. The contribution of fly ash in improving the pore structure and pore solution conductivity was largely unaffected by limestone powder size.

7.1.3.5 Rapid Migration of the Studied L3 Limestone Powder Contained SCCs

The rapid migration coefficient was found to be a function of the pore structure and was unaffected by the pore solution from previous studies (Stanish 2000). The rapid migration coefficient at both 28- and 90-days curing improved for L3 limestone contained SCCs compared to that of L8 limestone powder contained SCCs for lower replacement of cementitious materials level (i.e., 10%). For the 28-day cured SCCs, Mixtures L3-10 (10% by weight of cementitious materials) and Mixture L3-15 (15% by weight of cementitious materials) had 14% and 9% reduction, respectively, as compared to their those of equivalent L8 limestone powder contained SCCs. The reduction for L3 limestone powder replacing 20% by weight of cementitious materials was only 4%. The RMT results of 90-day curing presented a similar trend where limestone powder replacing 10% of the cementitious materials provided a reduction of 34% as compared to that produced by the equivalent SCC containing L8 limestone powder. With increasing L3 limestone powder content (i.e., 15 and 20% by weight of cementitious materials), the reduction between the two limestone powder sizes became marginal. Between 28 and 90 days curing, Mixtures L3-10 and L8-10 had reductions in rapid migration coefficient of 68 and 58%, respectively. Once L3 limestone powder replaced 20% of the cementitious materials, the reduction in rapid migration coefficient between the two limestone powder types was similar.

The smaller size of L3 limestone powder can react with fly ash and cement more readily than L8 limestone powder to provide additional carboaluminates which modified the pore structure and reduced the rapid migration coefficient. With increasing limestone powder content, the fly ash content was reduced to where this modification was limited. Optimum rapid migration coefficient for L3 limestone powder was found at 10% partial replacement of cementitious materials and for L8 limestone powder at 15% partial replacement of cementitious materials. The larger improvement between curing ages for Mixture L3-10 as compared to Mixture L8-10 was also a result of L3 limestone powder's smaller size being more readily reactive with fly ash as compared to L8 limestone powder's coarser size.

7.1.4 Statistical Analysis of Studied Self-Consolidating Concretes

Multiple linear regression models were performed on the transport property tests and compressive strength results. Each test regression model was optimized for the highest adjusted R-squared value obtained. Explanatory variables included limestone powder percent replacement of cementitious materials, mean powder particle size, water-to-powder ratio, admixture dosage, coarse aggregate percent volume, mortar percent volume, and age. By analyzing the explanatory variables that were significant to the regression model, it was possible to examine what variables statistically affected the individual test results.

Correlations among all studied tests including compressive strength, volume of voids, capillary absorption, water penetration, rapid chloride penetration, rapid migration, and chloride diffusion were performed. It was found rapid chloride penetration results had strong correlations with capillary absorption and rapid migration. Rapid migration had a strong correlation with chloride diffusion. Lastly, compressive strength had an inverse strong correlation with rapid chloride penetration, rapid migration, capillary absorption, and water penetration results.

The classification for chloride ion penetrability, chloride ingress, and durability indicator was also analyzed for the studied limestone powder contained SCCs. It was found that inclusion of 15 % or higher L8 limestone powder and 10% or higher L3 limestone powder substituting a portion of cementitious materials provided a positive improvement in chloride ion penetrability and durability indicator. The studied SCCs did not have a change in their chloride ingress classification with the inclusion of either L3 or L8 limestone powder. The difference between the 28- and 90-day curing resulted in a positive improvement of the rapid chloride penetration and rapid migration for all studied SCCs regardless of limestone powder content.

7.2 Recommendations

Future studies on the inclusion of limestone powder as a partial replacement of cementitious materials may include:

(1) Evaluation of durability of limestone powder contained SCCs and its relation to transport properties

To establish a relationship between transport properties and the durability of SCCs containing limestone powder, the durability of SCCs can be evaluated. Chemical (sulfate attack, alkali silica reactivity, and acid resistance) and physical (abrasion testing) durability testing can be implemented. From the findings, a suitable transport property index can be established that properly predicts long-term durability of limestone powder contained SCCs.

(2) The implementation of a SCC series with Portland cement as the only cementitious materials.

To examine whether or not the synergetic effect between limestone powder and fly ash contributed to the observed results, a "control" series that only implements cement as cementitious materials can be utilized. L3 and L8 limestone powder can be used to replace a portion of Portland cement at the levels of 5, 10, 15, 20, 25, and 30% by weight. How the studied compressive strength and transport property test results differ from the studied fly ash and cement SCCs may prove the fly ash's significance to test results.

(3) Comparison of transport properties of limestone contained SCCs to that of limestone contained vibratory-placed concretes

Since self-consolidating concrete is considered a relatively new type of concrete, its properties as compared to traditional concrete are an area of great interest. A series of traditionally vibrated concretes containing the same cement and fly ash content with a constant water-to-cementitious materials ratio can be examined. Both L3 and L8 limestone powder can replace the cement and fly ash at the same levels of 5, 10, 15, 20, 25, and 30%. The results obtained can demonstrate how transport properties of SCCs with limestone powder compare to those of traditionally vibrated concretes.

APPENDIX A
LITERATURE REVIEW OF TRADTIONAL AND SELF-CONSOLIDATING CONCRETES WITH INCORPORRATION OF MINERAL ADMIXTURES

Table A.1: Flow, Hardened, and Transport Properties of Traditional Concrete with Incorporation of Limestone Cement

Author	Mineral Admixture Incorporated	Objective	Methodology	Findings
Bonavetti, 2000	Limestone blended with cement	Examine effect of duration of initial curing on mechanical properties and chloride penetration of concretes containing limestone blended cements	Three concrete mixtures W/cm = 0.5 Three different initial curing regimens (full, wet, and air curing) Testing- Compressive Strength, Tensile Strength, Modulus of Elasticity, and Chloride Ion Penetration	Limestone blended cements less affected by cessation of moist curing at early ages due to accelerated hydration. Concretes cured 7 days have similar mechanical properties and chloride penetration resistance with and without limestone filler
Bonavetti, 2003	Limestone filler (up to 20%)	Examine effect of limestone filler on degree of hydration, volume of hydration products, and optimal replacement.	Six concrete mixtures w/cm = 0.30 or 0.34 Testing- Compressive Strength	Compressive strength slightly reduces at 28 days for limestone filler cements. Concrete strength is dependent on gel-space ratio. Gel-space ratio affected by degree of hydration, dilution, and increase of effective w/c ratio
Dhir et. al. (2007)	Limestone (LS)	Assess performance of concretes containing limestone in relation to concrete's mechanical	PC/LS ratios of 100/0, 85/15, 75/25, 65/35, and 55/45 were used. Properties evaluated	15% partial limestone replacement was found to be similar to reference concrete for cube

		and durability properties.	were cube strength, flexural strength, modulus of elasticity, creep and drying shrinkage, initial surface absorption, carbonation resistance, chloride diffusion, freeze/thaw scaling, and abrasion resistance. w/c ranged from 0.45 to 0.79.	strength. 25% LS partial replacement was found to have suitable properties as well for initial surface absorption and chloride diffusion.
Ramezanianpout et. al. (2009)	Limestone powder (LP)	Evaluate limestone powder in various amounts on concrete's compressive strength, water penetration, sorptivity, electrical resistivity, and rapid chloride permeability.	PC partially replaced by 5, 10,15, and 20% LP. Curing days were 28, 90, and 180-days. Water to cement/LP of 0.37, 0.45, and 0.55. Total cement + LP content of 350 kg/m^3	Compressive strength and electrical resistivity decrease with increasing LP partial replacement. Sorptivity increased with increasing LP partial replacement. 10% limestone contained PC had lower water penetration depths. 10% LP PC at w/b of 0.37 or 0.45 and 15% at w/b of 0.55 displayed adequate rapid chloride penetration results.

Table A.2: Effects on SCC’s Fresh, Hardened, and Transport Properties by Use of Mineral Admixtures

Author	Mineral Admixture Incorporated	Objective	Methodology	Findings
Khayat, 1999	Silica Fume, Fly ash, Slag	Emphasize the workability requirements of self-consolidating concrete. Evaluate proportioning principals of SCC to provide excellent deformability and adequate viscosity	Six SCCs, one concrete Ternary mixture of Silica fume, fly ash or slag. w/cm varied from 0.41, 0.35, 0.50, and 0.38 with or without incorporation of VEA Field oriented tests used to evaluate deformability, filling capacity, and stability	All trial SCCs exhibit low yield value and satisfactory cohesiveness. Binary or ternary mixtures containing high volumes of pozzolanic or nonpozzolanic fillers (limestone powder) can be incorporated to reduce cement content, heat of hydration, and shrinkage
Zhu and Bartos, 2003	Fine limestone powder, pulverized fly ash (PFA)	Examine permeation properties of SCC compared to traditional concrete with same strength grade	Two grades of concrete strength, 40 MPa and 60 MPa Three SCC and two traditional concrete for each strength containing either PFA, limestone powder, or viscosity agent Testing includes oxygen permeability, capillary absorption, and chloride diffusivity	SCCs had lower oxygen permeability and sorptivity than traditional concretes PFA resulted in lower values of chloride diffusivity for both SCC and traditional Viscosity-agent contained SCC had highest oxygen permeability, sorptivity, and chloride diffusivity out of three SCCs

Zhu and Gibbs (2005)	Limestone powder, chalk powder	Investigates the strength and superplasticizer demand of limestone powder or chalk powder-contained SCCs.	Three levels of powder addition (55%, 44%, and 25%) Three w/c ratio of 0.69, 0.57, 0.42 Fresh properties- slump flow and J-ring Compressive strength at 7,28, and 90 days	Fineness of additional limestone powder or chalk powder affected superplasticizer dosage All SCC mixes containing limestone powder or chalk powder had greater strength than conventional concrete at same w/c
Sahmaran et. al., 2006	Fly ash (FA), Brick powder (BP), Limestone powder (LP), Kaolinite (K)	Evaluate mineral additives and chemical admixtures' effectiveness in producing self-compacting mortars	43 mixtures of self-compacting mortars Constant water and total powder content Workability- mini V-funnel and min slump flow test Hardened properties- ultrasonic pulse velocity and compressive strength at 28 and 56 days	Use of fly ash and limestone powder improved workability properties. Brick powder and kaolinite adversely affect workability Found reduction in strength when part of cement is replaced with mineral additives
Boel et. al., 2007	Limestone filler, fly ash	Examine the transport properties of limestone filler or fly ash contained self-compacting mortars through water and gas transport	Eight SCCs and one traditional concrete Varying superplasticizer Transport properties; water permeability, capillary suction, water vapour diffusion, and gas permeability , Mercury intrusion	Fly ash produces lower transport properties compared with limestone filler. Lowering the water to cement ratio and lowering the cement to powder content at a constant water to cement

			porosimetry	ratio also lowers the transport properties
Sonebi and Ibrahim, 2007	Limestone filler, pulverized fly ash (PFA)	Study the transport properties of medium strength SCC, compare mineral and chemical admixtures	Three SCCs and two traditional concretes Superplasticizer dosage varied Transport properties; water permeability, capillary absorption, air permeability, and in-situ chloride diffusion	Pulverized fly ash SCC mixtures had lower transport properties than traditional concretes. Limestone- contained SCCs also had lower transport properties but not as low as fly ash. VMA SCC had greatest sorptivity, air/water permeability, and chloride migration.
Koehler and Fowler, 2007	Three samples of limestone powder, dolomitic limestone, granite, traprock, fly ash	Use of microfines (limestone powder, dolomitic limestone, granite,traprock) as partial replacement for both fine aggregate and powder content for mortars and concretes.	SCC Mortar- Replacement of fine aggregate content at 5%, 10%, 15%, and 20%. Replacement of powder content at 15% HRWRA demand for 9-inche mini slump flow test, compressive strength, and drying shrinkage. SCC- Replacement of both fine aggregate and powder content 15%. Properties tested; compressive strength, modulus of elasticity,	Mortar- partial replacement of fine aggregate by microfines increased HRWRA demand. HRWRA demand was less when the microfines replaced the powder content. Drying shirinkage was found to increase when partially replacing fine aggregates. Concrete- HRWRA increased for all mixtures with microfines. Compressive and

			flexural strength, rapid chloride permeability, drying shrinkage, abrasion loss.	flexural strength unchanged with constant water to cementitious ratio. Rapid chloride permeability decreased for constant water to cementitious materials.
Bhattacharya et. al., 2008	Slag (SL), fly ash (FA) , silica fume (SF), limestone powder (LP)	Evaluate SCC fresh and cracking properties using crushed limestone, fly ash, slag, silica fume, and limestone powder	Ten SCC mixtures using various combinations of aggregates and chemical/mineral admixtures w/cm constant 0.40 except two mixtures Fresh properties; slump flow, J-ring, column segregation test, L-box Compressive strength at 7 and 28 days	Limestone powder-contained SCCs had higher compressive strength due to lower water powder ratio. Limestone powder SCCs also had the highest paste volume. SL + SF, FA +SF, and LP had all consistent slump flow values
De Schutter et. al., 2008	Limestone filler	Study the transport behavior of potentially aggressive media and durability behavior of SCC	Three SCC and one traditional concrete Varying w/c and superplasticizer amount Testing; water absorption by immersion, water permeability, gas permeability, freezing and thawing in combination with de-	SCC water permeability and gas permeability is slightly lower than traditional concrete. Water absorption by immersion is comparable with traditional concrete. SCC and TC also have comparable resistance to freezing and thawing.

			icing salts, and testing of alkali silica reactivity	SCC appears to exhibit higher expansion than traditional concrete
Sahmaran et. al., 2009	High-lime fly ash, low-lime fly ash, limestone powder	Evaluate high volumes of high-lime and low-lime fly ash partial replacement effects on SCC transport and mechanical properties	11 SCC mixtures with w/cm between 0.30 and 0.35. Varying water content to achieve fresh properties. Constant HRWR dosage Compressive strength at 7, 28, 90, 180, and 365 days Split tensile strength at 28, 90, and 180. Drying shrinkage at 365 days. Transport properties; absorption, sorptivity, and rapid chloride permeability	Compressive strength of both high-lime and low-lime fly ash were found to be acceptable. High volumes of fly ash replacement resulted in 28 day strength reduction, but were offset at later ages. Drying shrinkage was reduced for both low-lime and high-lime fly ash. Low-lime fly ash seemed especially beneficial to transport properties.
Surabhi et. al. , 2009	Limestone powder, fly ash	SCC fresh and hardened properties evaluated with partial replacement of limestone powder	Constant fly ash content, replacement of cement at 10%, 20%, 25%, and 30% Water to powder kept constant as well as superplasticizer dosage Fresh properties; slump flow test, v-funnel test, U-box test Hardened properties; cube compressive strength, cylinder	Limestone powder can be an effective mineral admixture in SCC. SCC workability was found to improve with 20% replacement of cement. Compressive strength increases at 7 and 28 days up to 20% limestone powder replacement. Further addition reduces

			compressive, strength splitting tensile strength, flexural strength, and modulus of elasticity	strength. All other hardened properties improve with limestone powder incorporation.
Tomasiello and Felitti, 2010	Electric arc furnaces (EAF) slag, limestone filler, fly ash	Examine the use of EAF slag as replacement of fine aggregate in SCC	Five SCCs, constant cement content; varying limestone filler and fly ash Fresh properties; slump flow, J-ring, V-funnel, and L-box. Hardened properties; 24 hour and 28 day compressive strength, bulk density	All SCCs met workability requirements and mixture performed relatively equal for all fresh and hardened properties.
Uysal and Yilmaz, 2011	Limestone powder (LP), basalt powder (BP), marble powder (MP)	Investigate influence of LP, BP, and MP on SCC fresh and hardened properties	One control and nine SCC mixtures that incorporate LP, BP, and MP at 10%, 20%, and 30% replacement of cement. Constant water to powder ratio of 0.33 Fresh properties; Slump flow, L-box, T_{50}, unit weight, air void content Hardened properties; compressive strength, ultrasonic pulse velocity, static and dynamic elastic modulus	LP, BP, and MP partial replacement of cement had a positive impact on SCC workability. MP was found to improve overall workability the most. The highest compressive strengths were also found for MP mixtures. Addition of any type of mineral admixture decreases the static and dynamic modulu.
Barbhuiya, 2011	Fly ash, dolomite	Examine the potential to	Five SCCs, constant	Acceptable fresh and

	powder	use fly ash and dolomite powder in production of SCC.	powder and cement content, constant water to powder ratio, superplasticizer amount varied. Fresh properties; Slump flow, L-box, V-funnel Hardened properties; compressive strength, density	hardened properties can be achieved by the addition of fly ash and dolomite powder. All five SCCs were also found to have satisfactory compressive strength for structural applications. Dolomite powder was found to increase the density

APPENDIX B

INDIVIDUAL SCC SAMPLE RESULTS

L8 limestone powder contained SCC results

Table B4.1: 28-, 90-, and 180-day average compressive strength of studied L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
Control	56.74	57.22	55.81	53.80	55.89
L8-5	57.10	57.47	-	-	57.29
L8-10	60.20	60.04	-	-	60.12
L8-15	59.23	59.65	58.81	-	59.23
L8-20	62.23	58.64	58.87	-	59.91
L8-25	61.73	62.50	59.13	59.59	60.74
L8-30	60.12	59.47	59.81	-	59.80
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
Control	68.29	75.12	69.32	-	70.91
L8-5	76.15	75.57	70.19	-	73.97
L8-10	74.33	70.68	68.08	-	71.03
L8-15	76.31	68.80	74.88	-	73.33
L8-20	72.07	77.19	75.61	-	74.96
L8-25	73.13	75.57	78.72	-	75.81
L8-30	72.94	74.36	80.94	-	76.08
180-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
Control	84.66	81.57	84.35	-	83.53
L8-5	87.45	85.14	83.32	-	85.31
L8-10	87.85	86.48		-	87.16
L8-15	86.55	88.82		-	87.68
L8-20	86.87	80.10		-	86.87
L8-25	91.11	88.56	90.05	-	89.91
L8-30	88.87	90.02	91.68	-	90.19

Table B4.2: 28- and 90-day average absorption after immersion (AAI) (percent) of L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	6.21	5.35	6.38	-	-	-	-	-	-	-	-	-	5.98
L8-5	6.28	4.66	6.13	-	-	-	-	-	-	-	-	-	5.69
L8-10	4.50	6.07	4.51	-	-	-	-	-	-	-	-	-	5.03
L8-15	5.71	6.13	6.19	1.89	1.59	0.69	1.39	2.07	1.88	1.76	-	-	2.93
L8-20	2.25	2.53	2.75	-	-	-	-	-	-	-	-	-	2.51
L8-25	1.83	1.17	0.79	-	-	-	-	-	-	-	-	-	1.50
L8-30	2.04	0.99	2.51	1.89	1.59	0.69	1.39	-	-	-	-	-	1.39
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	5.06	3.26	4.26	-	-	-	-	-	-	-	-	-	4.66
L8-5	5.18	5.51	5.11	2.48	5.31	-	-	-	-	-	-	-	4.72
L8-10	2.14	2.93	2.84	5.80	3.73	-	-	-	-	-	-	-	3.49
L8-15	4.15	2.99	2.00	4.40	4.59	2.06	1.73	0.75	1.52	2.25	2.04	1.91	2.53
L8-20	2.37	2.13	1.63	1.99	2.77	-	-	-	-	-	-	-	2.18
L8-25	2.68	1.54	1.29	1.58	-	-	-	-	-	-	-	-	1.29
L8-30	1.27	2.41	3.23	1.01	1.19	1.57	1.52	2.13	1.59	-	-	-	1.16

Table B4.3: 28- and 90-day average absorption after immersion and boiling (percent) of L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	6.49	6.62	6.68	-	-	-	-	-	-	-	-	-	6.59
L8-5	6.45	5.65	6.27	-	-	-	-	-	-	-	-	-	6.12
L8-10	5.91	6.25	5.72	-	-	-	-	-	-	-	-	-	5.96
L8-15	5.92	6.53	6.43	3.27	3.63	2.62	3.17	2.94	3.15	3.27	-	-	4.09
L8-20	3.27	3.71	4.25	-	-	-	-	-	-	-	-	-	3.74
L8-25	2.71	2.43	2.17	-	-	-	-	-	-	-	-	-	2.44
L8-30	3.03	2.55	3.73	3.27	3.63	2.62	3.17	-	-	-	-	-	2.59
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	5.36	4.85	5.31	-	-	-	-	-	-	-	-	-	5.17
L8-5	5.56	5.67	5.40	3.19	5.12	-	-	-	-	-	-	-	4.99
L8-10	3.62	4.99	4.98	5.62	5.21	-	-	-	-	-	-	-	4.88
L8-15	4.70	4.02	2.77	4.69	4.78	3.41	2.86	1.24	2.51	3.72	3.38	3.17	3.44
L8-20	2.55	2.61	1.73	2.47	3.13	-	-	-	-	-	-	-	2.50
L8-25	2.89	2.20	2.12	2.37	-	-	-	-	-	-	-	-	2.40
L8-30	1.38	2.43	3.32	2.01	2.15	1.77	1.71	2.40	1.79	-	-	-	2.11

Table B4.4: 28- and 90-day average volume of voids (percent) of L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	15.01	15.16	15.33	-	-	-	-	-	-	-	-	-	15.16
L8-5	14.86	13.02	14.52	-	-	-	-	-	-	-	-	-	14.13
L8-10	13.70	14.45	13.37	-	-	-	-	-	-	-	-	-	13.84
L8-15	13.84	15.04	14.84	6.95	8.47	6.35	8.56	6.90	7.42	7.62	-	-	9.60
L8-20	7.69	8.71	9.99	-	-	-	-	-	-	-	-	-	8.80
L8-25	6.45	5.79	5.14	-	-	-	-	-	-	-	-	-	6.12
L8-30	5.66	5.66	6.56	5.96	-	-	-	-	-	-	-	-	5.96
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Sample 9	Sample 10	Sample 11	Sample 12	Average
Control	12.53	11.29	13.19	-	-	-	-	-	-	-	-	-	12.86
L8-5	13.04	13.19	12.66	9.64	14.26	-	-	-	-	-	-	-	12.56
L8-10	8.48	11.62	11.63	13.11	12.14	-	-	-	-	-	-	-	11.40
L8-15	11.09	9.43	6.50	11.12	11.18	4.80	5.85	4.39	5.91	4.77	5.13	5.27	7.12
L8-20	7.22	7.15	5.13	5.95	7.50	-	-	-	-	-	-	-	6.59
L8-25	7.66	5.95	5.71	5.61	-	-	-	-	-	-	-	-	6.23
L8-30	4.30	6.82	8.96	4.79	5.13	4.56	4.56	5.28	4.85	-	-	-	5.47

Table B4.5: 28- and 180-day average capillary absorption of L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Average
Control	7.29	6.16	5.09	6.73
L8-5	8.08	7.19	7.38	7.55
L8-10	5.64	6.06	5.09	5.60
L8-15	4.71	3.84	3.56	4.04
L8-20	3.48	2.83	3.63	3.31
L8-25	2.77	3.20	2.87	2.95
L8-30	4.08	4.20	3.71	4.00
180-day	Sample 1	Sample 2	Sample 3	Average
Control	2.26	2.39	2.53	2.39
L8-5	2.75	2.87	-	2.75
L8-10	2.00	2.06	-	2.03
L8-15	1.60	1.78	-	1.69
L8-20	1.17	1.51	1.89	1.34
L8-25	1.29	0.89	-	1.09
L8-30	0.17	0.63	1.49	0.76

Table B4.6: 28 and 90-day average water penetration depths (mm) of studied L8 limestone powder SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Control	14.35	10.41	12.75	12.95	12.67	12.63
L8-5	9.42	9.19	9.58	-	-	9.40
L8-10	8.99	8.66	8.66	-	-	8.77
L8-15	8.33	8.31	8.61	-	-	8.42
L8-20	8.20	8.43	8.05	-	-	8.23
L8-25	8.53	9.17	8.61	-	-	8.77
L8-30	9.11	8.96	-	-	-	9.04
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
Control	9.80	9.55	10.46	-	-	9.94
L8-5	6.99	7.37	6.93	-	-	7.10
L8-10	6.45	6.50	7.24	-	-	6.73
L8-15	6.22	6.55	6.25	-	-	6.34
L8-20	6.25	6.05	5.72	-	-	6.00
L8-25	5.54	5.46	5.44	-	-	5.48
L8-30	6.17	5.92	5.82	-	-	5.87

Table B4.7: 28- and 90-day average RCPT (coulombs) of L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Average
Control	5679	4938	6118	5869	-	-	-	-	5651
L8-5	4624	4373	4972	-	-	-	-	-	4656.33
L8-10	4836	4124	4434	4234	-	-	-	-	4407
L8-15	4088	3804	3926	-	-	-	-	-	3939.33
L8-20	3451	3664	3573	3464	-	-	-	-	3538
L8-25	3203	3416	-	-	-	-	-	-	3309.5
L8-30	2924	2762	2987	2952	-	-	-	-	2906.25
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Average
Control	1420	1677	1425	-	-	-	-	-	1507.33
L8-5	1331	1364	1481	1261	-	-	-	-	1359.25
L8-10	1221	1332	1314	1373	-	-	-	-	1310
L8-15	1208	1240	1271	-	-	-	-	-	1239.667
L8-20	1142	910	993	1015	979	984	-	-	1003.833
L8-25	1019	1011	935	966	1005	1089	868	1031	990.5
L8-30	958	1030	1072	1034	1002	954	-	-	1008.333

Table B4.8: 28- and 90-day average RMT results of the studied L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Average
Control	14.66	14.06	-	14.36
L8-5	14.21	14.74	13.87	14.27
L8-10	13.98	14.12	13.98	14.03
L8-15	14.03	13.45	14.49	13.99
L8-20	12.94	14.51	14.37	13.94
L8-25	13.29	14.52	13.54	13.78
L8-30	12.80	12.63	12.12	12.52
90-day	Sample 1	Sample 2	Sample 3	Average
Control	6.45	6.35	5.74	6.18
L8-5	6.51	5.55	6.46	6.17
L8-10	5.70	5.81	5.91	5.81
L8-15	4.09	4.59	4.34	4.34
L8-20	5.28	4.53	4.56	4.79
L8-25	5.29	5.01	5.22	5.17
L8-30	5.14	5.17	4.94	5.08

Table B4.10: 28- and 90-day average chloride diffusion coefficients of studied L8 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Average
Control	7.25E-12	-	-	7.25E-12
L8-5	7.87E-12	4.23E-12	9.79E-12	7.3E-12
L8-10	7.75E-12	1.08E-11	4.09E-12	7.54E-12
L8-15	7.99E-12	-	-	7.99E-12
L8-20	8.04E-12	-	-	8.04E-12
L8-25	8.75E-12	6.87E-12	8.23E-12	7.95E-12
L8-30	1.3E-11	6.8E-12	-	9.89E-12
90-day	Sample 1	Sample 2	Sample 3	Average
Control	3.63E-12	3.47E-12	-	3.47E-12
L8-5	3.35E-12	-	-	3.35E-12
L8-10	3.1E-12	-	-	3.1E-12
L8-15	2.78E-12	2.28E-12	5.5E-12	3.52E-12
L8-20	3.44E-12	3.29E-12	-	3.37E-12
L8-25	2.51E-12	4.22E-12	-	3.37E-12
L8-30	3.26E-12	3.4E-12	-	3.33E-12

B.2 L3 limestone powder contained SCCs results

Table B5.1: 28- and 90-day average compressive strength (MPa) of L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Average
L3-10	63.1	57.5	59.6	60.1
L3-15	64.0	59.5	61.6	61.7
L3-20	61.3	65.9	65.3	64.2
90-day	Sample 1	Sample 2	Sample 3	Average
L3-10	76.9	82.2	73.6	77.6
L3-15	78.8	71.0	78.8	76.2
L3-20	78.0	89.4	83.6	83.7

Table B5.2: 28- and 90-day average absorption after immersion (percent) of L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	2.49	2.69	-	-	2.59
L3-15	1.66	1.54	-	-	1.60
L3-20	1.28	1.43	-	-	1.355
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	2.63	3.14	2.14	-	2.64
L3-15	1.73	2.01	-	-	1.87
L3-20	1.57	-	-	-	1.57

Table B5.3: 28- and 90-day average absorption after immersion and boiling results (percent) of the studied L3 limestone powder contained SCCs

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	3.79	4.47	-	-	4.13
L3-15	2.71	3.29	-	-	3.00
L3-20	2.45	-		-	2.45
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	4.28	3.96	-	-	4.12
L3-15	3.10	2.86	3.04	-	3.00
L3-20	2.85	-	-	-	2.85

Table B5.4: 28- and 90-day average volume of voids (percent) of the studied L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	8.87	10.40	-	-	9.63
L3-15	6.41	7.79	-	-	7.10
L3-20	5.87	5.57		-	5.87
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Average
L3-10	9.21	10.06	-	-	9.64
L3-15	6.78	7.18	-	-	6.98
L3-20	6.83	6.82	-	-	6.83

Table B5.5: 28- and 90-day average water penetration depths (mm) of the studied L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Average
L3-10	8.12	8.07	8.04	8.08
L3-15	7.82	8.01	8.02	7.95
L3-20	7.86	7.46	7.64	7.65
90-day	Sample 1	Sample 2	Sample 3	Average
L3-10	5.94	6.20	6.42	6.19
L3-15	6.07	5.76	-	5.915
L3-20	6.12	5.53	-	5.825

Table B5.6: 28- and 90-day average RCPT results of the studied L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
L3-10	4060	3819	3783	3813	-	-	3805
L3-15	3721	3811	4230	3613	-	-	3715
L3-20	3419	3860	3321	3555	-	-	3432
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Average
L3-10	946	934	930	922	926	959	936.7
L3-15	661	988	972	1044	-	-	1001.3
L3-20	986	725	966	1050	877	-	1000.7

Table B5.7: 28- and 90-day average RMT results of the studied L3 limestone powder contained SCC individual samples

28-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
L3-10	11.75	12.62	11.64	-	-	12.00
L3-15	14.70	14.30	12.84	11.02	11.09	12.79
L3-20	12.81	13.68	13.10	13.82	13.42	13.37
90-day	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average
L3-10	4.32	3.50	3.52	3.98	-	3.83
L3-15	3.97	3.80	4.61	4.38	-	4.19
L3-20	5.38	4.81	4.74	-	-	4.98

APPENDIX C

MULTIPLE LINEAR REGRESSION EXAMPLE CALCULATION

For this section of the appendix, a sample calculation for the multiple linear regression model for rapid migration results is presented.

Table C6.1: Table of RMT dependent variables and independent variables for SCC mixtures

RMT	AGE	HRWRA	CA	LP	FA	Size	WTP
14.4	28	0.87	26.31	0	73.69	14.9741	0.45
14.3	28	1.03	26.73	5	73.27	14.53975	0.43
14	28	1.22	27.15	10	72.84	14.09362	0.41
13.9	28	1.44	27.58	15	72.42	13.68496	0.38
13.9	28	1.55	28.01	20	71.99	13.26806	0.36
13.8	28	1.58	28.43	25	71.57	12.86237	0.34
12.5	28	1.87	28.86	30	71.44	12.38779	0.32
6.2	90	0.87	26.31	0	73.69	14.9741	0.45
6.1	90	1.03	26.73	5	73.27	14.53975	0.43
5.8	90	1.22	27.15	10	72.84	14.09362	0.41
4.3	90	1.44	27.58	15	72.42	13.68496	0.38
4.8	90	1.55	28.01	20	71.99	13.26806	0.36
5.2	90	1.58	28.43	25	71.57	12.86237	0.34
5.1	90	1.87	28.86	30	71.44	12.38779	0.32
12	28	1.34	27.15	10	72.84	13.00276	0.41
12.79	28	1.54	27.58	15	72.42	11.89724	0.38
13.37	28	1.76	28.01	20	71.99	10.71305	0.36
3.83	90	1.34	27.15	10	72.84	13.00276	0.41
4.19	90	1.54	27.58	15	72.42	11.89724	0.38
4.98	90	1.76	28.01	20	71.99	10.71305	0.36

Table C6.2: RMT Multiple Linear Regression Excel Output Trial 1

Trial 1
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99375
R Square	0.987539
Adjusted R Square	0.98027
Standard Error	0.618528
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	7	363.8349	51.97	135.8	1.82E-10
Residual	12	4.590922	0.382		
Total	19	368.4258			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2376.98	1350.976	-1.759	0.103	-5320.51	566.54	-5320.51	566.540
WP	28.6085	80.5132	0.355	0.728	-146.815	204.03	-146.81	204.031
AGE	-0.13623	0.00446	-30.53	9.55E-13	-0.14595	-0.126	-0.1459	-0.1265
HRWRA	-4.94213	3.855404	-1.281	0.224	-13.3423	3.4580	-13.342	3.45807
Size	-0.07437	0.41412	-0.179	0.860	-0.97667	0.8279	-0.9766	0.82792
CA	96.3316	54.8274	1.756	0.104	-23.1272	215.79	-23.127	215.790
LP	-8.11207	4.60438	-1.761	0.103	-18.1441	1.9200	-18.144	1.92001
FA	-1.9868	2.923321	-0.67	0.509	-8.35617	4.3825	-8.3561	4.38257

Table C6.3: RMT Multiple Linear Regression Excel Output Trial 2

Trial 2
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.993623
R Square	0.987288
Adjusted R Square	0.982748
Standard Error	0.578394
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	363.7423	72.74845	217.4582	9.39E-13
Residual	14	4.68356	0.334		
Total	19	368.4258			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2099.3	959.8425	-2.18	0.046	-4158.04	-40.729	-4158.0	-40.729
AGE	-0.1362	0.004172	-32.6	1.29E-14	-0.14517	-0.1272	-0.1451	-0.1272
HRWRA	-4.5523	1.364101	-3.33	0.004	-7.47806	-1.6266	-7.4780	-1.6266
CA	85.123	37.32045	2.280	0.038	5.078759	165.16	5.07875	165.167
LP	-7.2604	3.211844	-2.26	0.040	-14.1491	-0.3716	-14.149	-0.3716
FA	-1.5972	1.849743	-0.86	0.402	-5.56454	2.3700	-5.5645	2.37007

Table C6.4: RMT Multiple Linear Regression Excel Output Trial 3

Trial 3
SUMMARY
OUTPUT

Regression Statistics	
Multiple R	0.993283
R Square	0.986611
Adjusted R Square	0.98304
Standard Error	0.573469
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	363.4928	90.87321	276.3225	7.5E-14
Residual	15	4.932998	0.328867		
Total	19	368.4258			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-2024.1	947.7379	-2.13	0.049	-4044.19	-4.0785	-4044.1	-4.0785
AGE	-0.1362	0.004137	-32.9	2.09E-15	-0.14504	-0.1274	-0.1450	-0.1274
HRWRA	-4.3615	1.3346	-3.26	0.005	-7.20627	-1.5168	-7.2062	-1.5168
CA	77.784	36.030	2.158	0.047	0.987487	154.58	0.98748	154.581
LP	-6.5156	3.067515	-2.12	0.050	-13.053	0.022	-13.053	0.02263

Table C6.5: RMT Multiple Linear Regression Excel Output Trial 4

SUMMARY OUTPUT

Trial 4

Regression Statistics	
Multiple R	0.991186
R Square	0.98245
Adjusted R Square	0.97916
Standard Error	0.635695
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	361.96	120.6534	298.5669	2.98E-14
Residual	16	6.4657	0.4041		
Total	19	368.42			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	21.89427	1.4378	15.227	6.1E-11	18.84615	24.94239	18.84615	24.94239
AGE	-0.13623	0.0045	-29.70	2E-15	-0.14595	-0.126	-0.14595	-0.126
HRWRA	-4.34754	1.4794	-2.938	0.0096	-7.48378	-1.211	-7.48378	-1.211
LP	0.10597	0.0505	2.0954	0.0523	-0.00124	0.2131	-0.00124	0.2131

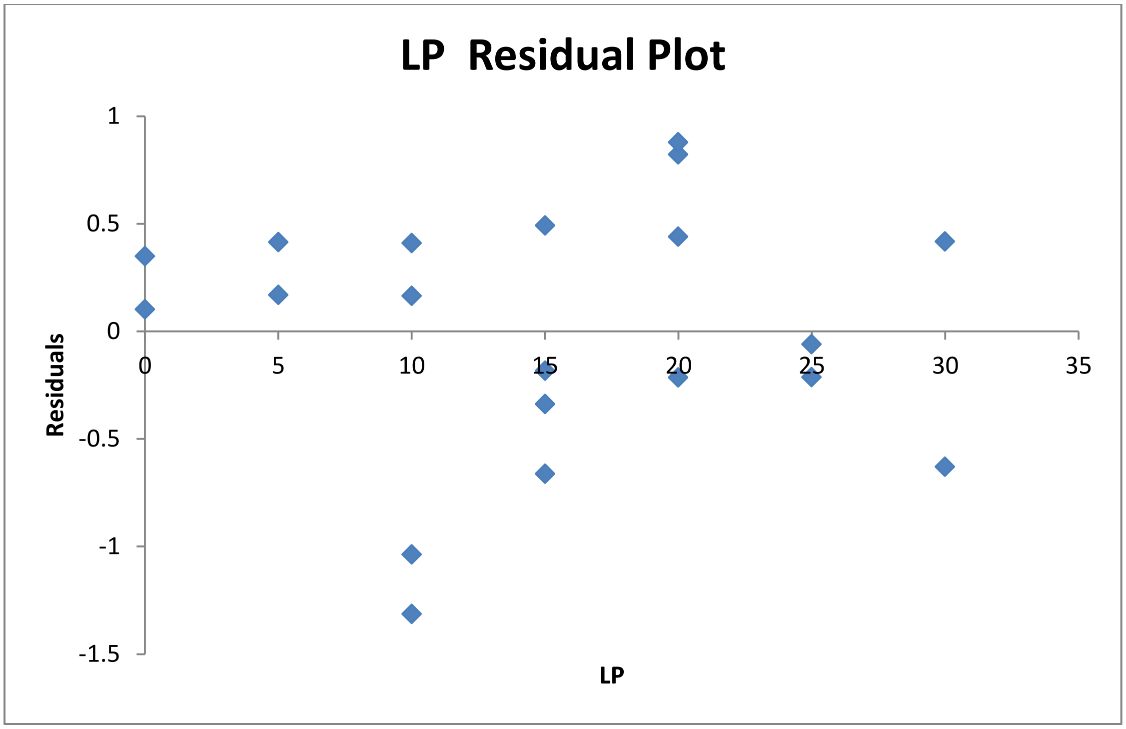

Figure C6.1: Limestone Powder Percent Replacing (LP) Residual Plot

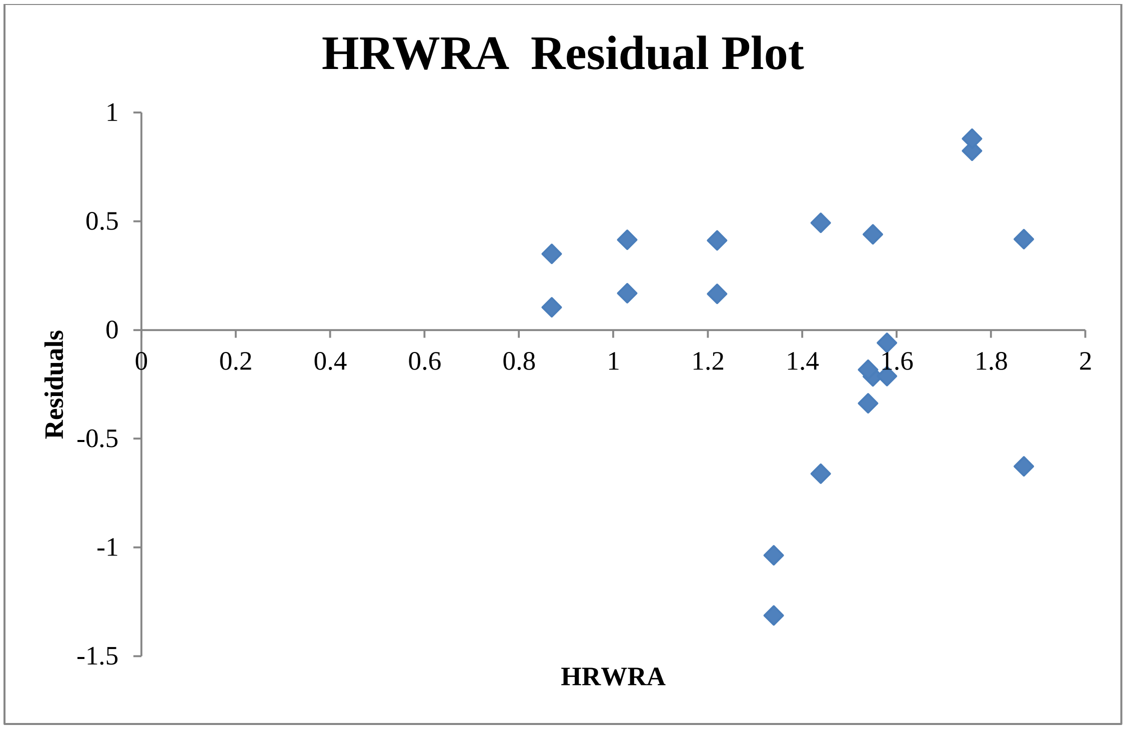

Figure C6.2: HRWRA dosage Residual Plot

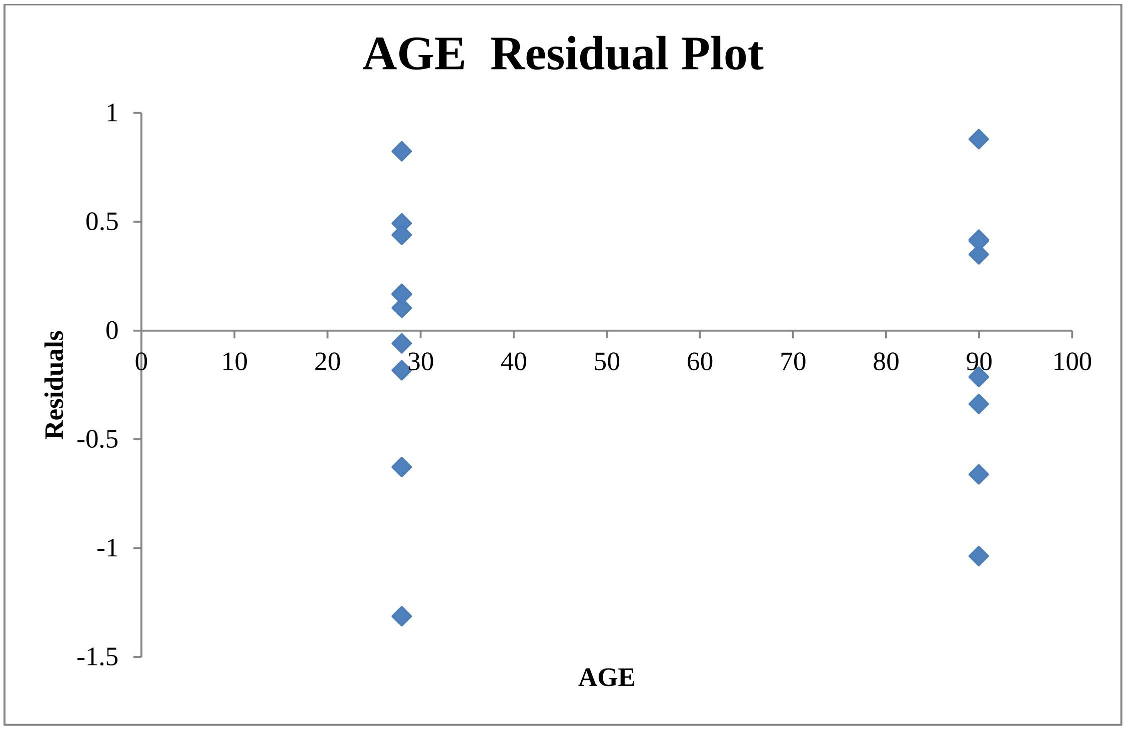

Figure C6.3: Curing age in days (AGE) Residual Plot

Table C6.6: Residuals of the Linear Regression Model

Observation	*Predicted RMT*	*Residuals*	*Standard Residuals*
1	14.29759	0.10241	0.175554
2	14.13184	0.168164	0.288271
3	13.83566	0.164344	0.281723
4	13.40905	0.490951	0.8416
5	13.46067	0.439328	0.753107
6	13.8601	-0.0601	-0.10302
7	13.12916	-0.62916	-1.07853
8	5.85159	0.34841	0.597254
9	5.685836	0.414164	0.709971
10	5.389656	0.410344	0.703423
11	4.963049	-0.66305	-1.13662
12	5.014672	-0.21467	-0.368
13	5.414097	-0.2141	-0.36701
14	4.683164	0.416836	0.714551
15	13.31395	-1.31395	-2.25241
16	12.9743	-0.1843	-0.31592
17	12.54769	0.822311	1.409626
18	4.867951	-1.03795	-1.77928
19	4.528296	-0.3383	-0.57992
20	4.101689	0.878311	1.505622

Table C6.7: Tabulation of Excel Regression Trial Runs

Trial	R Square Value	Adjusted R Square Value	Variables	Coefficient	P-value
1	0.987539	0.98027	Intercept	-2376.98	0.103945
			WP	28.60851	0.728512
			AGE	-0.13623	9.55E-13
			HRWRA	-4.94213	0.224101
			Size	-0.07437	0.860467
			CA	96.33164	0.104379
			LP	-8.11207	0.103531
			FA	-1.9868	0.509632
2	0.987288	0.982748		-2099.39	0.046193
			AGE	-0.13623	1.29E-14
			HRWRA	-4.55236	0.004886
			CA	85.12317	0.038728
			LP	-7.26041	0.040248
			FA	-1.59723	0.40242
3	0.986611	0.98304	Intercept	-2024.13	0.049595
			AGE	-0.13623	2.09E-15
			HRWRA	-4.36158	0.005188
			CA	77.78442	0.047471
			LP	-6.51562	0.050702
4	0.98245	0.97916	Intercept	21.89427	6.1E-11
			AGE	-0.13623	2E-15
			HRWRA	-4.34754	0.009635
			LP	0.10597	0.052397

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