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Prescriptive Mixture Design of Self-Consolidating Concrete

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16. Abstract

This research studied the influence of aggregate size, admixture source, hauling time, temperature and pumping on the fresh and hardened properties of three distinct groups of self-consolidating concretes (SCC.) The first phase of investigation compared dosages of admixtures and properties of the variants. The second phase evaluated the influence of hauling times, temperature and pumping on the concrete.

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PRESCRIPTIVE MIXTURE DESIGN OF SELF-CONSOLIDATING CONCRETE

NDOT RESEARCH
Agreement No: P077-06-803

Report Submitted to
Nevada Department of Transportation
Research Division
ATTN: Dr. Tie He
1263 S. Stewart Street
Carson City, NV 89712

By
Nader Ghafoori, Ph.D., P.E., Professor and Chairman

and

Hamidou Diawara, MSc, Doctorate student and Research assistant

University of Nevada, Las Vegas

Civil and Environmental Engineering Department

4505 Maryland Parkway

Box 454015

Las Vegas, Nevada 89154-4015

Phone: (702)895-3701

Fax: (702)895-3936

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ABSTRACT OF THE REPORT

PRESCRIPTIVE MIXTURE DESIGN
OF SELF-CONSOLIDATING CONCRETE

The research investigation presented herein was intended to study the influence of parameters such as aggregate size, admixture source, hauling time, temperature and pumping on the fresh and hardened properties of three distinct groups of self-consolidating concretes (SCC). Within each group, the selected self-consolidating concretes were made with a constant water-to-cementitious materials ratio, a uniform cementitious materials (cement and fly ash) content, and a constant coarse-to-fine aggregate ratio that provided the optimum aggregate gradation. Three coarse aggregate sizes (ASTM C 33 #8, #7, and #67) obtained from two different quarries were investigated. Four sources of polycarboxylate-based high range water reducing admixtures (HRWRA), along with their corresponding viscosity modifying admixtures (VMA), were used. All raw materials were evaluated for their physico-chemical characteristics.

The investigation presented herein was divided into two major phases. The first phase aimed at: (1) comparing the optimum dosage requirement of four different sources of polycarboxylate-based HRWRA and VMA in attaining the target slump flow of 20 inches (508 mm), 25 inches (635 mm), and 28 inches (711 mm), T_{50} of 2 seconds or more, and a visual stability index (VSI) of 0 (Highly stable concrete) or 1 (Stable concrete), (2) evaluating the flow ability/viscosity, the dynamic stability, the passing ability, the filling ability, and the static segregation resistance of trial self-consolidating concretes, and (3) examining the properties of the selected SCCs as related to air content, bleeding, time of setting, adiabatic temperature, demolded unit weight, compressive strength and modulus of elasticity.

In the second phase, the influences of hauling time, temperature and pumping on fresh performances of the selected self-consolidating concretes were evaluated. Seven

different temperatures 109, 96, 83, 70, 57, 44 and 31 °F (43, 36, 28, 21, 14, 7 and -0.5 °C) and nine different hauling times (10, 20, 30, 40, 50, 60, 70, 80 and 90 minutes) were used to determine the loss in unconfined workability, dynamic stability, and flowability rate of the designed matrices. The adverse influence of the above-mentioned variables was remediated by providing sufficient initial optimum admixture dosages (overdosing method) that resulted in achieving the intended fresh properties of the designed SCCs for different hauling times and temperatures. Moreover, the second phase of the study addressed the effect of pumping at various distances of 100, 200 and 300 ft (30, 60 and 90 m) on the flow ability, passing ability, stability, rheology (yield stress and plastic viscosity), air content and air void characteristics of the selected self-consolidating concretes.

For the test results of this study the following conclusions can be drawn:

- Irrespective of the self-consolidating concrete groups, the optimum dosages requirement of HRWRA in obtaining a uniform slump flow and visual stability index was highest for the source A, followed by the sources C, B, and D in descending order. On the other hand, the required VMA dosage was highest for the source A and remained uniform for the sources B, C, and D. With proper proportioning, self-consolidating concrete with acceptable flow ability, plastic viscosity, dynamic and static stabilities, passing ability, and filling ability can be achieved with any of the four selected admixture sources.
- The fresh performance of self-consolidating concrete was affected by hauling time. The effects were manifested in the form of loss in flow ability, and gain in plastic viscosity and dynamic stability. A remediation technique consisting of admixture overdosing was able to produce SCCs with a similar flow ability, plastic viscosity, dynamic stability, and passing ability to those obtained at the control hauling time.
- The fresh performance of self-consolidating concrete was affected by hot temperatures in the form of significant decrease in unconfined workability, substantial increase in flow rate or plastic viscosity per inference, and improvement in dynamic stability of the freshly-mixed SCCs. The cold temperature affected the fresh performance of the selected self-consolidating concretes by a marginal gain in flow ability, small variation in flow rate, and an increase in the resistance to segregation from VSI of 1 to 0

for the matrices only made with slump flow of 28 inches (711mm), when compared to those obtained under the control temperature. The VSI of the trial SCCs prepared with slump flows of 20 and 25 inches (508 and 635 mm) were unaffected by the selected cold temperatures. A remediation method by way of admixture overdosing was successful to reverse the change in fresh properties of the selected self-consolidating concretes in elevated temperatures. The selected self-consolidating concretes did not require any remediation in cold temperatures.

- The pumping adversely affected the fresh performance of the self-consolidating concrete by decreasing the unconfined workability, flow rate, and passing ability; and by increasing the dynamic segregation resistance. The impact of pumping on the rheological properties of self-consolidating concrete was manifested by a moderate increase in relative yield stress and a significant decrease in relative plastic viscosity. In general, irrespective of the slump flow and pumping distance, the air content remained unaffected by the pumping action. However, the air voids characteristics were affected by the pumping without exceeding the recommend limits. The pumping generated larger sizes of the air bubbles (or lower specific area) accompanied with increases in the spacing factors.

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GLOSSARY

The intent of this glossary is to define terminologies used in this report. The following definitions apply:

Admixture: Material added during the mixing process of concrete in small quantities related to the mass of cementitious binder to modify the properties of fresh or hardened concrete

Binder: The combined Portland cement and fly ash

Bingham fluid: A fluid characterized by a non-null yield stress and a constant viscosity regardless of flow rate

Confined flowability: The ability of a fresh concrete to flow in a form characterized by a low ratio of horizontal form surface to total form surface

Dynamic stability: The characteristic of a fresh SCC mixture that ensures uniform distribution of all solid particles and air voids as the SCC is being transported and placed

Filling ability: The confined workability or the ability of fresh concrete to flow into and fill all spaces within the formwork under its own weight

Flow ability: The ease of flow of fresh concrete when unconfined by formwork and/or reinforcement

High range water reducing admixture: Admixture added to fresh concrete to increase its fluidity

Mortar: The fraction of the concrete comprising paste plus those aggregates passing #4 sieve (0.187 in. (4.75 mm))

Mortar Halo: A concentration of mortar that can form at the perimeter of the slump flow patty

Paste: The fraction of the concrete comprising powder, water and air, plus admixture, if applicable

Passing ability: The ability of fresh concrete to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking

Powder: Material of particle size passing the No. 100 sieve (0.006 in. (0.15 mm))

Self-consolidating concrete (SCC): Concrete that is able to flow and consolidate under its own weight, completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity and without the need for any additional compaction

Segregation resistance: The ability of concrete to remain homogeneous in composition while in its fresh state

Slump flow: The mean diameter of the spread of fresh concrete using a conventional slump cone

Rheological properties: Properties dealing with the deformation and flow of the fluid fresh SCC mixture.

Thixotropy: The tendency of a material (e.g. SCC) to progressively lose fluidity when allowed to rest undisturbed but to regain its fluidity when energy is applied

Unconfined workability: The ability of a fresh concrete to flow in a form characterized by a high ratio of horizontal form surface to total form surface

Viscosity: The resistance to flow of a material (e.g. SCC) once flow has started.

Viscosity Modifying Admixture (VMA): Admixture added to fresh concrete to increase cohesion and segregation resistance.

Yield point of concrete: The force needed to start the concrete moving.

RESEARCH OBJECTIVES

The aim of this study was: (1) to prepare a document describing self-consolidating concrete specifications and acceptance criteria, (2) to develop appropriate self-consolidating concretes using local raw materials to meet the required specifications for fresh and hardened characteristics, and (3) to examine the influence of construction-related variables (hauling distance (hauling time), temperature, and pumping) on fresh performance of the trial self-consolidating concretes.

In order to achieve the stated objectives, this investigation was divided into seven (7) tasks as described below:

- Task 1: Development of self-consolidating concrete specifications and acceptance criteria;
- Task 2: Preparation and appraisal of raw materials;
- Task 3: Mixture development of self-consolidating concretes;
- Task 4: Influence of hauling time on flow ability, flow rate, and stability of designed self-consolidating concretes;
- Task 5: Influence of temperature on flow ability, flow rate, and stability of designed self-consolidating concretes; and
- Task 6: Influence of pumping on flow ability, flow rate, stability, rheology, air content, and air void characteristics of designed self-consolidating concretes.

TASK 1

DEVELOPMENT OF SELF-CONSOLIDATING CONCRETE SPECIFICATIONS/ACCEPTANCE CRITERIA AND TEST METHODS

The objective of Task 1 is to develop specifications/acceptance criteria and test methods of self-consolidating concrete (SCC). It also presents overviews of self-consolidating concrete, its components, and physico-chemical properties of different ingredients used in its production.

1.1 DEVELOPMENTS OF SELF-CONSOLIDATING CONCRETE SPECIFICATIONS / ACCEPTANCE CRITERIA AND TEST METHODS

The development of self-consolidating concrete (SCC) in Japan in the late 1980s was followed by several uses in many other countries in Asia, Europe and more recently in the United States. However, the lack of standard specifications and test methods has slowed down the wider use of SCC. In response to this situation several European and American organizations have collected and used information on self-consolidating concrete to develop guidelines. A number of United States Departments of Transportation (US-DOTs) have also taken an active role in developing self-consolidating concrete specification and quality control/assurance manuals

The document presented in appendix A of the report serves as specifications and test methods relevant to the use of self-consolidating concrete for the Nevada Department of Transportation. The preparation of the document began by contacting the Department of Transportation of the fifty (50) States for information and documents pertaining to specifications and acceptance criteria of self-consolidating concrete. Additionally, other relevant publications such as Precast/Prestressed Concrete Institute’s Standard Specification for self-consolidating concrete (PCI), the European Guideline for SCC, and the Japan Society of Civil Engineers' (JSCE) Standard Specification for Design and Construction of Concrete Structures were also acquired.

Inquiries made to various Departments of Transportation revealed that eighteen (18) States have had or have on-going SCC projects. Only ten (10) States (Colorado, Delaware, Florida, Illinois, Maine, Missouri, Nebraska, North Carolina, Pennsylvania and Utah) have developed SCC specifications. A copy of their specifications was acquired. All collected materials were thoroughly examined and their information was used to prepare the draft document in its present form.

1.2 GENERAL BACKGROUND ON SELF-CONSOLIDATING CONCRETE

Self-consolidating concrete (SCC) is a highly flowable non-segregating matrix that can spread into place, fill the formwork, and encapsulate the reinforcement without mechanical consolidation[1]. Self-consolidating concrete provides better consolidation around reinforcement, reduces noise due to the elimination of vibration, improves surface appearance, enhances working conditions and safety, and reduces in-place cost when compared to vibratory-placed concrete.

Self-consolidating concrete (SCC) was first developed in Japan in the late 1980's, by Okamura and his coworkers, to reduce the labor required to properly place concrete[2]. Their initial motivation stemmed from durability considerations. Under or over consolidation of concrete was common in Japan, due to lack of skilled workers, compromising the durability of concrete structures. Insufficient consolidation led to excessive occurrence of entrapped air and other flaws, especially adjacent to rebars and other confined areas, whereas excessive vibration resulted in considerable segregation, external and internal bleeding and destruction of the air void system. Shortly after Japan, the use of self-consolidating concretes spread rapidly in Europe. The use of SCC has been promoted in the United States by various public and private entities only in the most recent years.

The main idea behind modern self-consolidating concrete is to produce a matrix with low yield value and adequate viscosity that can easily be spread without any densification effort. This type of concrete is typically proportioned with a relatively high content of cementitious materials and sufficient chemical admixtures, leading to a relatively high initial material cost. Increases in cost can be tolerated in high-value added applications, especially when cost savings can be realized from using self-consolidating concrete; given the reduced effort in concrete placement, the reduction in construction time and labor cost and greater flexibility in placement operation (particularly in highly-congested reinforced areas), scheduling, and procuring the required resource[2,3,4].

A review of the related literature revealed a number of investigations detailing the mixture constituents and proportions in SCC construction applications. While considerable variations have been shown, several factors common to the majority of the trial SCC matrices are still apparent. Self-consolidating concrete is characterized by a slump flow of 20 to 33 inches (508 to 850 mm)[5]. Binding materials contents such as cementitious and pozzolanic materials are high, typically 650 - 925 lb/yd^3 (380 - 550 kg/m^3), but use of Portland cement exclusively is reported to result in inadequate cohesion or segregation resistance. In that respect, the utilization of fly ash, silica fume, and ground granulated blast furnace slag as pozzolanic additives were found beneficial in multiple ways that impact properties, such as: workability, bleeding and segregations, air content, heat of hydration, setting time, finishability, pumpability, plastic shrinkage cracking, strength and stiffness, permeability, and durability[4,6].

The fluidity is provided by high range water reducing admixtures, most based either on polycarboxylate, naphthalene, or melamine formaldehyde, modified to provide extended retention of fluidity and set times and to control all important viscosity of the matrix. By far, polycarboxylate-based high range water reducing admixtures are the most widely used for developing and proportioning SCC. Strong segregation resistance can be achieved at the water-to-cementitious materials ratio of 0.3 – 0.4 (or higher) if an appropriate quantity of Viscosity Modifying Admixture (VMA) is added in addition to the superplasticizer[7]. The use of a VMA is not always necessary, but VMA can be advantageous when using lower powder contents and gap-graded or demanding aggregates[8]. Factors that influence the fluidity of self-consolidating concrete are: (1) fine and coarse aggregates grading, aggregates shape and surface texture, (2) fine aggregate-to-paste ratio, (3) fine aggregate volume-to-total-aggregate volume ratio, (4) cementitious materials type and factor, (5) water-to-cementitious materials ratio, (6) admixtures type and dosage, (8) environmental condition (i.e., temperature), and (9) delivery method and transportation duration[1,3,6,8].

The objective of this literature review is to present an overview of the type and physico-chemical properties of different ingredients used in manufacturing of self-consolidating concrete. The influence of those raw materials on the fresh and hardened performances of SCC is also discussed.

1.2.1 Aggregates

The importance of using the right type and quality of aggregate cannot be overemphasized since the coarse and fine aggregates generally occupy 60% to 75% of the concrete volume (70% to 85% by weight)[9]. It has been customary to consider aggregates as inert and inexpensive material. This belief is abandoned nowadays, because the aggregate physical, thermal, and chemical properties have a great influence on the concrete fresh and hardened properties. Aggregates must meet certain standard for optimum engineering use: they must be clean; hard; string; durable; and free of absorbed chemicals, coatings of clay, and other fine materials in amounts that could affect hydration and bond of the cement paste[9]. In the case of self-consolidating concrete, a great attention is given to the aggregate types, grading, and coarse-to-fine aggregate ratio due to their critical role in mixture performance. Other characteristics such as shape, texture, bulk density, specific gravity, porosity, bond and strength also influence the overall performance of SCC mixtures. The mineralogical and petrographical compositions of aggregate greatly impact its bulk density[10]. The important minerals found in aggregate are: silica minerals (quartz, opal, chalcedony, etc.), carbonate minerals, sulfate mineral, iron sulfide minerals, ferromagnesian minerals, zeolites, iron oxide minerals, clay minerals, etc. The presence of some unstable forms of silica can adversely affect the performance of the concrete[10]. An overview of the main properties of aggregates is presented below:

1.2.1.1 Grading

The particle size distribution or grading of aggregates is provided by the American Society of Testing Material (ASTM C 33[11]). Aggregate grading is determined by sieve analysis. There are seven standard sieves for fine aggregate, with the openings ranging from No. 100 sieve to 3/8 inch (150 µm to 9.5 mm) and thirteen standard sieves for coarse aggregate, with opening ranging from 0.046 inch to 4 inches (1.18 mm to 100 mm). The grading and grading limits are usually expressed as the percentage of material passing each sieve.

1.2.1.2 Shape and texture

The grading, shape, and surface texture can affect strongly the fresh and hardened properties of concrete. In fact, as reported by several researches, finer particles require more water to wet their larger specific surface, whilst the irregular shape and rougher texture of an angular aggregate decrease the concrete workability[10]. Several shapes of aggregates exist, the most common ones are[9,10,12]:

- Well rounded: no original faces left
- Rounded: faces almost gone
- Subrounded: considerable wear, faces reduced in area

- Subangular: some wear face untouched
- Angular: little evidence of wear
- Irregular: partly shaped by attrition
- Flat or Flaky: thickness smaller relative to the other two dimensions
- Elongated: usually angular, and the length is considerably larger than the other two dimensions
- Flaky and elongated: length considerably larger than width, and width considerably larger than thickness. Flaky, elongated or flaky and elongated shaped aggregate particles should be avoided or limited to a maximum of 15 % by weight of the total aggregate.

The surface texture of an aggregate is based on the degree to which the particle surfaces are polished (dull, smooth or rough). It depends on the hardness, grain size and pore characteristic. Aggregate's surface texture can be classified as follow: [9,11,12]

- Glassy: conchoidal fracture
- Smooth: water-worn, or smooth due to fracture of laminated or fine-grained rock
- Granular: fracture showing less or more uniform rounded grains
- Rough: rough fracture of fine – or medium – grained rock
- Crystalline: containing easily visible crystalline constituents
- Honeycombed: with visible pores and cavities.

1.2.1.3 Bulk density or unit weight

The bulk density or bulk unit weight of an aggregate is the mass or weight of the aggregate required to fill a container of a specified unit volume[9]. Depending on the bulk density, aggregates can be classified as normal-weight (95 to 105 lb/ft^3 (1520 to 1680 kg/m^3)), lightweight (less than 70 lb/ft^3 (1120 kg/m^3)) or heavyweight (more than 130 lb/ft^3 (2080 kg/m^3)). For special need, aggregate with a lighter or heavier density can be used to make the corresponding lightweight or heavyweight concretes[10].

1.2.1.4 Specific gravity

The ASTM C 12713 defines specific gravity as the ratio of mass (or weight in air) of a unit volume of aggregate to the mass of the same volume of water at the stated temperature. Specific gravity, also referred to as relative density, is used for mixture proportioning as the volume occupied by the aggregate in the absolute volume method of concrete mixture design. Most natural aggregate have specific gravity between 2.4 and 2.9[9].

1.2.1.5 Porosity and absorption

The internal structure of an aggregate particle is made up of solid matter and voids that may or may not contain water. The voids or pores vary in size over a wide range, but even the smallest pores are larger than the gel pore in the cement paste[10]. The porosity and absorption of aggregate influence aggregate's specific gravity, bond with cement paste, and concrete's durability. The amount of water added for concrete batching should be adjusted, because of the absorption and the moisture content, in order to accurately meet the water requirement of the mix design. The coarse and fine aggregates generally have absorption levels (moisture contents at Saturated Surface Dry (SSD)) in the range of 0.2% to 4% and 0.2% to 2%, respectively[9].

1.2.1.6 Bond

Bond between aggregate and cement matrix considerably influences the strength of concrete (especially flexural strength). Great bond is provided by rougher texture and larger surface area of angular aggregate. Generally, texture characteristics which permit no penetration of the surface of the particle by the paste are not conducive to the formation of good bond. Thus, softer, porous and mineralogically heterogeneous particles result in a better bond[9,12].

1.2.1.7 Strength

It is well established that the compression resistance of concrete cannot significantly exceed that of the aggregate contained therein. The strength of an aggregate is rarely tested and generally does not influence the strength of conventional concrete as much as the strength of the paste and the paste-aggregate bond[9]. However aggregate strength becomes important in high-strength concrete. The information about aggregate strength can be obtained from indirect tests, such as crushing strength and performance of aggregate in concrete. Aggregates crushing strength ranges from 12000 psi (80 MPa) to 30000 psi (200 MPa)[10].

1.2.2 Portland cement

Joseph Aspin, an English mason, is known as the inventor of Portland cement in 1824[9]. Naturally occurring calcium carbonate materials such as limestone, chalk, marl, and seashells are the common industrial sources of calcium, but clay and dolomite ($CaCO_3 \cdot MgCO_3$) are present as principal impurities. Clays and shales, rather than quartzs or sandstone, are the preferred sources of additional silica for making calcium silicates because quartzitic silica does not react easily[12]. Table 1.1 presents the sources of other raw materials used in the manufacture of Portland cement. The Calcium oxide and the silica are essential, whereas alumina and iron oxides are mainly used to decrease the temperature of manufacturing.

Because of the high number of publications available on Portland cement, this review is brief.

1.2.2.1 Definition

ASTM C 150[13] defines Portland cement as hydraulic cement produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an interground addition. Clinkers are 0.2 to 1 inch (5 to 25 mm) diameter nodules of a sintered material which is produced when a raw mixture of predetermined composition is heated to high temperature.

Hydraulic cements are defined as cements that not only hardened by reacting with water but also form a water-resistant product.

1.2.2.2 Manufacturing process of Portland cement

Cement manufacturing involves the heating, calcining and sintering. In the calcining phase, limestone is converted into lime, releasing carbon dioxide ($CaCO_3 \rightarrow CaO + CO_2$) and clay is converted into silicon dioxide, alumina and iron ($\text{Clay} \rightarrow SiO_2 + Al_2O_3 + Fe_2O_3 + H_2O$). Sintering is the process, in which fine particles of a material become chemically bonded at a temperature that is sufficient for atomic diffusion. Chemically, the produced calcium oxide in the first stage reacts with silicon dioxide and alumina – and iron-bearing compounds to form C_3S and C_2S plus lesser quantities of C_3A, C_4AF, and several other compounds[14,15].

Two processes of manufacture, namely wet and dry, are employed, the latter being more common in North America. The dry process is more energy efficient than the wet process because the water used for slurring must subsequently be evaporated before the clinkering operation. In the dry process the materials are crushed, dried, and

Table 1.1: Source of raw materials used in producing of Portland cement[9].

Lime, CaO	Iron, Fe_2O_3	Silica, SiO_2	Alumina, Al_2O_3	Gypsum, $CaSO_4 \cdot 2H_2O$	Magnesia, MgO
Alkali waste	Blast furnace	Calcium silicate	Aluminum-ore refuse	Anhydrite	Cement rock
Aragonite	Clay	Cement rock	Bauxite	Calcium sulfate	Limestone
Calcite	Iron ore	Clay	Cement rock	Gypsum	Slag
Cement-kiln dust	Mill scale	Fly ash	Clay		
Cement rock	Ore washings	Fuller's earth	Copper slag		
Chalk	Pyrite cinders	Limestone	Fly ash		
Clay	Shale	Loess	Fuller's earth		
Fuller's earth		Marl	Granodiorite		
Limestone		Ore washings	Limestone		
Marble		Quartzite	Loess		
Marl		Rice-hull ash	Ore washings		
Seashells		Sand	Shale		
Shale		Sandstone	Slag		
Slag		Shale	Staurolite		
		Slag			
		Traprock			

then ground in ball mills to a powder which is burnt in its dry condition. In the wet process the materials are first crushed and then ground to form slurry in wash mills. After passing through the wash mills and the slurry silos, the slurry passes to slurry tanks. Samples of the slurry are tested and any correction in the chemical composition is made by changing the proportions of the calcareous and argillaceous constituents. The ground raw material is fed into the upper end of a kiln. Cement kilns may be as large as 18.7 ft (5.7 m) in diameter and about 650 ft (200 m) in length, and with an output of as much as 76 tonnes per hour[16]. The raw mix passes through the kiln at a rate controlled by the slope and rotational speed of the kiln. Burning fuel (powered coal, oil, or gas) is forced into the lower end of the kiln where temperatures of 2600 ^oF to 3000 ^oF (1430 ^oC to 1650 ^oC) change the raw materials chemically into cement clinker. The clinker is cooled and then pulverized. During this operation a small amount, 3 to 5 percent, of retarder (gypsum being the material generally used) is added to regulate the setting time of the cement. The clinker is ground so fine that nearly all of it passes through a No. 200 mesh (0.003 inch (75 microns)) sieve with 40,000 openings per square inch. This extremely fine gray powder is called Portland cement. The temperature of the cement as it comes out the grinding mill can be as high as 158 ^oF (70 ^oC)[9,12,15].

1.2.2.3 Chemistry of Portland cement

The chemistry of Portland cement is very complex. This section is intended to give an overview of the main chemical compounds. The chemical analysis of Portland cement gives its composition in form of oxides. The acidic components of the raw mixture react with the calcium oxide during the burning operation of Portland cement clinker to form principal compounds that make to 90% of cement by weight. Table 1.2 provides the name and the chemical formula of each of these oxides, Table 1.3 presents the primary compounds, their chemical formula and abbreviation, and Table 1.4 presents the main phases of Portland cement and their characterizations.

When cement is mixed with water, a chemical action begins between the various compounds and water. In the initial stage, the small quantity of retarder (gypsum) quickly goes into solution, and is thus able to exert its influence on the other chemical reactions which are starting. These reactions resulted in the formation of various compounds which cause setting and hardening. The four most important being[9,12]:

Table 1.2: Chemical compositions of Portland cement in form of oxide[17]

Name	Chemical Formula	Abbreviation
Lime	CaO	C
Silica	SiO_2	S
Iron	$Fe_2 O_3$	F
Alumina	Al_2O_3	A
Trioxide of sulfur	SO_3	S
Magnesia	MgO	M
Sodium oxide	Na_2O	-
Potassium oxide	K_2O	-
Equivalent Alkalis	$0.342\%Na_2O + 0.658\%K_2O$	-

Table 1.3: Primary chemical compounds of Portland cement[9]

Name	Chemical Formula	Abbreviation
Tricalcium silicate	$3CaO . SiO_2$	C_3S
Dicalcium silicate	$2CaO . SiO_2$	C_2S
Tricalcium aluminate	$3CaO . Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO . Al_2 O_3 . Fe_2 O_3$	C_4AF

Table 1.4: Main phases of Portland cement and their characteristics[15]

Parameter	C_3S	C_2S	C_3A	C_4AF
Reactivity	high	low	very high	low
Impurities	Al_2O_3, Fe_2O_3, MgO	Al_2O_3, Fe_2O_3, Na2O, K_2O, SO_3	Fe_2O_3, Na_2O, K_2O, (MgO)	MgO, SiO_3, TiO_2
Technical name	alite	belite	aluminate phase	ferrite phase
Heat of hydration (j/g)	500	250	1340	420
Contribution to strength	high at early ages	high at late ages	high at very early ages	very low

1.2.2.3.1 Tricalcium silicate (C_3S)

The reaction of this compound commences within a few hours and generates considerable amount of heat. The resulting hydrate from the reaction has a significant influence on the strength of concrete at early age, mainly in the first 14 days. The approximate hydration reactions can be written as follow:

$$2C_3S \quad + \quad 6H \quad \rightarrow \quad C_3S_2H_3 \quad + \quad 3Ca(OH)_2$$

(1.1)

[100] [24] [75] [49]

1.2.2.3.2 Dicalcium silicate (C_2S)

The hydrate of this compound is formed slowly with a low rate of heat evolution. It is mainly responsible for the progressive increase in strength which occurs from 14 to 28 days, and onwards. Cements containing a high C_2S content have a relatively high chemical resistance, a low drying shrinkage, and hence, are the most durable of the Portland cement. The approximate hydration reactions can be written as follow:

$$2C_2S \quad + \quad 4H \quad \rightarrow \quad C_3S_2H_3 \quad + \quad Ca(OH)_2$$

(1.2)

[100] [21] [99] [22]

It can be seen from equations (0.1) and (0.2) that the hydration of C_3S and C_2S generates two forms of hydrates, namely: Portlandite (CH) and the Calcium Silicate Hydrate, CSH-phase (previously referred to as tobermorite). The numbers in the square brackets are the corresponding masses, and on this basis both silicates require approximately the same amount of water for hydration, but C_3S produces more than twice as much $3Ca(OH)_2$ as is formed by the hydration of C_2S.

1.2.2.3.3 Tricalcium aluminate (C_3A)

The amount of C_3A in most concretes is comparatively small. The C_3A compound hydrates very rapidly and produces a considerable amount of heat. It is responsible for the initial stiffening, but contributes least to ultimate strength. It is very vulnerable to sulfate environment and has the tendency to cause cracking due to volume change. The approximate reaction can be written as follows:

$C_3A \quad + \quad 6H \quad \rightarrow \quad C_3AH_6$

(1.3)

[100] [40] [140]

The masses shown in the brackets indicate that a higher proportion of water is required than for the hydration of silicates. The hydration of C_3A is highly influenced by the presence of gypsum. Without gypsum the initial hydration reaction is very quick. C_3A is first converted into unstable phases, further into stable calcium aluminate hydrate phase (C_3AH_6).

$$2C_3A + 21H \Rightarrow C_4AH_{13} \text{ (unstable)} + C_2AH_8 \text{ (unstable)} \qquad (1.4)$$

$$C_4AH_{13} + C_2AH_8 \Rightarrow 2C_3AH_6 \text{ (stable)} + 9H \qquad (1.5)$$

The addition of gypsum makes concrete placeable. In the presence of its dissolved components Ca^{2+} and $H_2SiO_4^{2-}$, C_3A is converted into ettringite, which is a calcium aluminate trisulfate.

$$C_3A + 3Ca^{2+} + 3SO_4^{2-} + 32H \Rightarrow C_3A\cdot 3Cs\cdot H_{32} \text{ (ettringite)} \qquad (1.6)$$

Ettringite has a fibrous morphology consisting of long hexagonal needles. The length of needles strongly depends on the environmental conditions. As it is detailed in the next section (1.2.2.4 - Portland cement hydration), the hydrate phase of ettringite is formed around the C_3A containing grains and protects them from further rapid hydration during the dormant period. During the deceleration period, ettringite becomes unstable due to an insufficient sulfate ion supply. It is converted into calcium aluminate monosulfate[10,15]

$$C_3A\cdot 3Cs\cdot H_{32} + 2C_3A + 4H \Rightarrow 3C_3A\cdot 3Cs\cdot H_{12} \text{ (monosulfate)}$$

(1.7)

1.2.2.3.4 Tetracalcium aluminoferrite (C_4AF)

This compound is of little importance since it has no marked importance on the strength and other hardened properties. It provides the cement its grey color[10,12].

From the above equations it can be seen that the aluminate phases and their hydration products play an important role in the early hydration processes. The relative reactivity of the different mineral phases with water can be classified as C_3A > C_3S >

$C_2S \cong C_4AF$[18]. In order to obtain a desired type of cement or cement with desired properties, type and proportion of the raw materials, and manufacturing process (i.e., mode of burning, speed of cooling, and fineness) should be altered. The ASTM C 150[13], Standard Specifications for Portland cement, identifies eight types of Portland cement as follows:

Type I:	Normal
Type IA:	Normal, air-entrained
Type II:	Moderate sulfate resistance
Type IIA:	Moderate sulfate resistance, air-entrained
Type III:	High early strength
Type IIIA:	High early strength, air-entrained
Type IV:	Low heat of hydration
Type V:	High sulfate resistance

1.2.2.4 Portland cement hydration

Immediately after the first contact of cement with water, various reactions occur through several types of bonding interaction leading to a final dense and stable matrix. Typical representation of cement hydration stages is illustrated in Figure 1.1, which can be obtained by using a conduction calorimeter. As shown in Figure 1.1, it can be seen that the occurrence of hydration with time involves five stages which are:

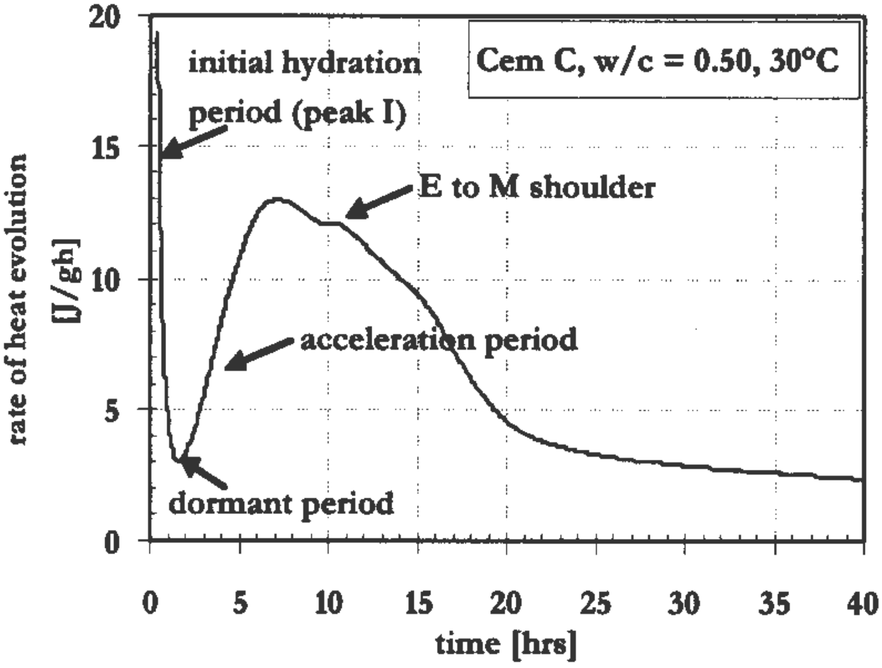


Figure 1.1: The four stages of Portland cement hydration[15]

1.2.2.4.1 Initial hydration

During the initial hydration water wets the cement particles and solubilizes the cement phases. The easily soluble components like alkalis, calcium sulfate phases and free lime are dissolved by the surrounding water[15]. A rapid heat evolution, representing probably the heat of solutions of aluminates and silica, lasting a few minutes (0 to 15) occurs. Na^+, K^+, Ca^{2+}, SO_4^{2-}, and OH^- ions are enriched in the pore water. Meanwhile, Ca^{2+} and $H_2SiO_4^{2-}$ are hydrolyzed from the most reactive cement particles C_3A and C_3S, and C_3A is converted into ettringite (calcium aluminate trisulfate). Besides ettringite, a small amount of calcium silicate hydrate (CSH) gel is formed around the C_3S containing cement grains. The initial heat flux drastically decreases when the solubility of aluminates is depressed in the presence of sulfate in the solution and the cement grains are coated with a protective layer of hydration products[10,12,15,18].

1.2.2.4.2 Induction period or dormant period

The induction period usually lasts 15 minutes to 4 hours, during which the concrete should be transported and placed. This hydration stage is characterized by a very low heat flow. In the early part of the dormant period, reactions of the aluminate and gypsum phases play a predominant role in the setting of the paste. If the solubilization of gypsum (to produce sulfate ion) is too low, flash set may occur (flash set is distinguished from false set in that it evolves considerable heat and the rigidity of the mix cannot be dispelled by further mixing without adding water). False set is caused by the presence of the hemihydrate or anhydrite. If the solubilization of gypsum is too high (because of the presence of hemihydrate form of gypsum, sodium, and potassium sulfates), then extensive growth of gypsum crystals occurs, resulting in false set. The pore water during the induction period consists of alkali hydroxides[10,12,15,19].

1.2.2.4.3 Acceleration and setting period

Near the end of the dormant period, the rate of cement hydration increases sharply because of the disruption of the protective hydrates layer, the nucleation, the growth of calcium silicate hydrates (CHS-phase) and calcium hydroxide (portlandite), and the recrystallization of ettringite leading to setting and hardening[15]. The concrete is no longer placeable. C_2S starts to hydrate. C_3A and to a lesser extent C_4AF continue to hydrate. The paste of a properly retarded cement will retain much of its plasticity before the commencement of this heat cycle and will stiffen and show the initial set (beginning of solidification) before reaching the apex, which corresponds to the final set (complete solidification and beginning of hardening). During the acceleration period the calcium and sulfate ion concentration in the pore water decrease due to the ettringite formation. The acceleration period lasts 4 to 8 hours for most Portland cement [10,12,15,19].

1.2.2.4.4 Deceleration and hardening period

The hardening of the cement paste or concrete occurs during the deceleration period, and can lasts 8 to 24 hours. During this stage the pore volume decreases with increasing time and decreasing water-to-cementitious material ratios. At the end of the deceleration period, the cement hydrated product mainly consists of calcium silicate hydrate (CSH) and portlandite (CH). As shown in Figure 1.1, sometimes a shoulder (conversion of ettringite (E) to monosulfate (M)) is visible at the deceleration period[10,12,15,18].

1.2.2.4.5 Curing period (1 to several weeks)

The last stage of concrete hydration is curing, which consists in maintaining satisfactory moisture content and temperature in concrete for a period of time immediately following placing and finishing so that the desired properties may develop. During curing, concrete properties improve rapidly at early age but continue more slowly thereafter for an indefinite period[10,15].

1.2.3 Chemical admixtures

1.2.3.1 Definition

ACI 116R[20] defines an admixture as a material other than water, aggregates, hydraulic cements, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardening properties and that is added to the batch before or during its mixing.

ACI committee 212-3R[21] lists 19 important purposes for which admixtures are used. The most important contributions are: to increase the plasticity of concrete without increasing the water content, to reduce bleeding and segregation, to retard or accelerate the rate of heat evolution, to increase the durability of concrete to specific exposure condition, to improve pumpability, and to produce colored concrete or colored mortar.

1.2.3.2 Background

The importance of admixture use in concrete was proven since the ancient time. Materials used as admixtures included milk and lard by Romans; eggs during the middle ages in Europe; polished glutinous rice paste, lacquer, tung oil, blackstrap molasses, and extracts from elm soaked in water and boiled bananas by the Chinese; and in Mesoamerica and Peru, cactus juice and latex from rubber plants. The Mayans also used bark extracts and other substances as set retarders to keep stucco workable for a long period of time[20,22]. In the last 70 years or more, considerable research and development have been done and many organic and polymer-based admixtures have been developed for use in various applications in construction. The performance of a chemical admixture depends on its type, chemical composition and dosage; specific surface area of the cement; type and proportions of aggregate; sequence of addition of water and admixture; compatibility of admixtures; water-to-cementitious material ratio; and temperature and conditions of curing[19]. An overview of the main chemical admixtures used in the manufacturing of self-consolidating concrete; including their types, functions, chemical compositions, and mechanism of actions; is presented below.

1.2.3.3 Nomenclature, specification and classification

Admixtures are incorporated in concrete in order to alter one or more of its fresh or hardened properties. They vary considerably in chemical composition and some of them can perform more than one function which makes it difficult to classify them according to their function[12]. For the purpose of the present research, the discussion is confined to the admixtures classified by the American Society for Testing and Material ASTM C 494[23] "Standard Specification for Chemical Admixtures for Concrete," which are:

- Type A, Water-reducing admixtures;
- Type B, Retarding admixtures;
- Type C, Accelerating admixtures;
- Type D, Water-reducing and retarding admixtures;
- Type E, Water-reducing and accelerating admixtures;
- Type F, Water-reducing, high-range, admixtures; and
- Type G, Water-reducing, high-range and retarding admixtures;

Depending on their mechanism of action, chemical admixture can be broadly divided into two groups. The first group begins to act on the cement-water system instantaneously by influencing the surface tension of water and by adsorbing on the surface of cement particles[12]. The second group breaks up into their ionic constituents and affects the chemical reactions between cement compounds and water from several minutes to several hours after addition. For the purpose of presenting detailed description of their function, composition, mechanism of action and application, chemical admixtures are grouped here into two categories, namely: surface-active chemical (air-entraining admixtures, water-reducing admixtures, and viscosity modifying admixtures); and set-controlling admixtures (accelerating and retarding admixtures)[12].

1.2.3.4 Surface-active chemicals

Surface-active chemicals, also called surfactants, cover admixtures that are generally used for air-entrainment or reduction of water in concrete mixtures. They are organic or polymer-based admixtures, which consist essentially of long-chain molecules, one end of which is hydrophilic (water-attracting) and the other hydrophobic (water-repelling). The hydrophilic end contains one or more polar groups, such as $-COO^-$, $-SO_3^-$, or $-NH_3^+$. Anionic admixtures are used in concrete technology either with a nonpolar chain or with a chain containing some polar groups. The admixture with nonpolar chain serves as air-entraining and the one with polar group as water-reducing admixtures. During the cement hydration, the surfactants become adsorbed at the air-water and the cement-water interfaces with an orientation of the molecule that determines whether the predominant effect is the entrainment of air or plasticization of the cement-water system[12].

1.2.3.4.1 Air-entraining admixtures

1.2.3.4.1.1 Function

When an air-entraining surfactant is added to the cement-water system, as a result of the mixing action, it forms and stabilizes air bubbles that become a component of the hardened concrete. The main application of air-entraining admixtures is for concrete mixtures designed to resist against damage from repeated freezing-and-thawing. The air bubbles must have a diameter between 0.0004 to 0.04 inch (10 and 1000 micrometers) and must be present in the proper amount and spacing (spacing factor larger than 0.008 inch (0.200 mm)) to be effective at providing freezing and thawing protection. The term spacing factor represents the maximum distance that the water would have to move before reaching the air void reservoir or safety valve[22]. Entrained air should not be confused with entrapped air.

The concrete air content can be affected by several factors which can be summarized as follows[22]:

- *Cement*: An increase in the fineness or in the cementitious materials content can decrease the air content. An increase in the Alkali content of the cement increases the air content.
- *Fine aggregate*: An increase in the amount of fine fraction passing the No. 100 sieve (0.0059 inch (150 µm)) will decrease the amount of entrained air, while an increase in the middle fraction passing the No. 16 sieve (0.0469 inch (1.18 mm)) but retained on the No. 30 sieve (0.0236 inch (600 µm)) and No. 50 sieve (0.0118 inch (300 µm)), will increase the air content.

- *Coarse aggregate*: Crushed stone concrete may result in lower air than a gravel concrete
- *Water*: Hard water or industrial detergent-contaminated water may reduce the air content.
- *Pozzolans and slag*: Fly ash, silica fume, natural Pozzolans, and ground granulated blast-furnace slag can affect the dosage rate of air-entraining admixtures.
- *Chemical admixtures:* chemical admixtures generally affect the dosage rate of air-entraining admixtures.
- *Temperature*: An increase in concrete temperature will decrease the air content.
- Increase in temperature from 70 to 100 ^{o}F (21 to 38 ^{o}C) may reduce air contents by 25%. Reductions of temperature from 70 to 40 ^{o}F (21 to 4 ^{o}C) may increase air contents by as much as 40%.
- *Concrete mixer*: The type of mixer, the energy of mixing, the state of the mixer blade (worn or coated with hardened concrete buildup), and the loaded volume (under or overloaded) of a mixer can affect the air content.

The incorporation of air-entraining surfactants in concrete mixture can induce some side effect. The most important are: improvement of workability, and reduction of concrete unit weight and strength. An increase of 1% in air content will decrease the compressive strength by about 5% in concrete mixtures with a compressive strength in the range of 3000 to 5000 psi (21 to 35 MPa). Since air-entraining surfactants render the cement particles hydrophobic, an over dose of the admixture would cause an excessive delay in cement hydration[12].

1.2.3.4.1.2 Chemical composition

Surfactants used as air-entraining admixtures generally consist of salts of wood resins, proteinaceous materials and petroleum acids, and some synthetic detergents. They are used in concrete to produce and stabilize tiny air bubbles, which are produced by mixing action. Figure 1.2 presents a typical chemical formula of a nonpolar hydrocarbon chain with an anionic polar group of an air-entraining surfactant.

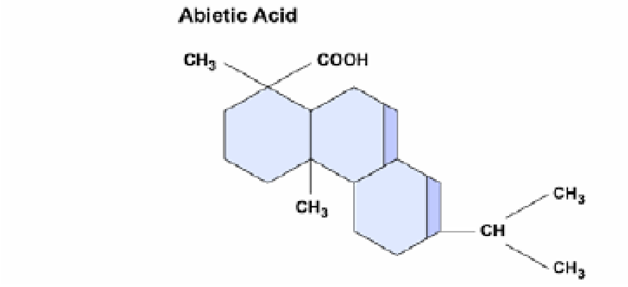


Figure 1.2: Chemical structure of a typical air-entraining surfactant derived from pine oil or tall oil processing[12]

1.2.3.4.1.3 Mechanism of action

The mechanism of action of an air-entrainment admixture consists to lower the surface tension of the water to facilitate bubble formation. Figure 1.3 presents an illustration of the mechanism of air entrainment in concrete. Lea[24] reported a detailed air-entrainment and stabilization actions as follow[12]:

> *At the air-water interface the polar groups are oriented towards the water phase lowering the surfacing tension, promoting bubble formation and counteracting the tendency for the dispersed bubbles to coalesce. At the solid-water interface where directive forces exist in the cement surface, the polar groups become bound to the solid with the nonpolar groups oriented towards the water, making the cement surface hydrophobic so that air can displace water and remain attached to the solid particles as bubbles.*

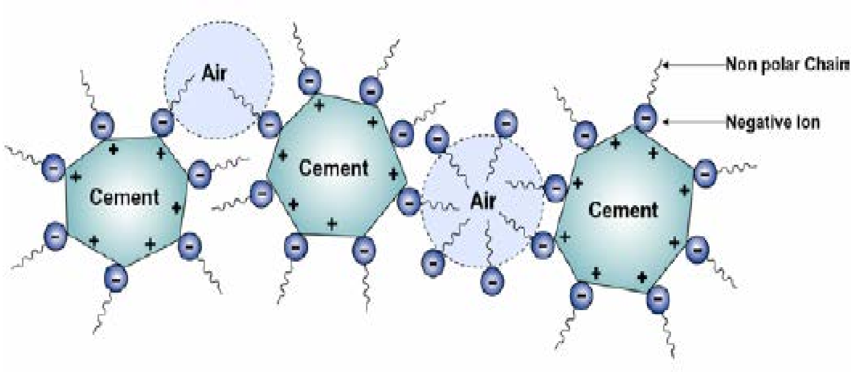


Figure 1.3: Mechanism of air entrainment when an anionic surfactant with a nonpolar hydro-carbon chain is added to the cement paste[12]

1.2.3.4.2 Water-reducing admixtures or normal plasticizers

1.2.3.4.2.1 Function

Water-reducing admixtures (WRA) or plasticizing admixtures are surface-active chemicals consisting of water-soluble organic materials. Depending on their chemical composition, they can perform more than one function. However, their main role is to disperse cement particles which are strongly agglomerated when cement is in contact with water. The main benefits obtained when WRA are used in concrete are: (1) to increase the workability without changing the mixture composition; (2) to reduce the amount of water needed to achieve a given workability, without significantly affecting the air content and the setting characteristics, in order to improve strength and durability; (3) to decrease both water and cement content, without changing the workability, in order to produce a cost-saving. Typically, the use of a water-reducing admixture decreases the required mixing water content by 5 to 12%. It is important that the manufacture's recommended dosage rates should be strictly followed and trial batches with local materials should be performed to determine the proper dosage rate for a given concrete mixture.

1.2.3.4.2.2 Chemical composition

Table 1.5 presents the main ingredients used for making water-reducing admixture. It can be seen that surfactants used as plasticizing admixtures usually are salts, modifications, and derivatives of lignosulfonic acids, hydroxylated carboxylic acids, and polysaccharides, or any combinations of the foregoing three, with or without other subsidiary constituents. Figure 1.4 presents the chemical structure of the most important sulfonated and acrylic polymers used as active ingredients of plasticizing and superplasticizing admixtures.

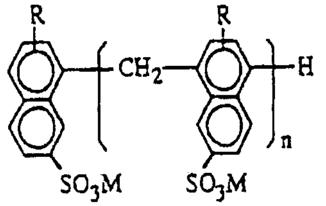
Table 1.5: Main and secondary ingredients in plasticizing and superplasticizing admixtures[25]

Superplasticizers		Plasticizers	
Main ingredients	Secondary ingredients	Main ingredients	Secondary ingredients
SMF	MLS	LS/MLS	TEA
SNF	Retarders	HC	Inorganic salts
AP	Inorganic salts	CH	Defoaming agents
Others	TEA	Others	Anti-bacterial products

SMF, sulfonated melamine formaldehyde; SNF, sulfonated naphtalene formaldehyde; AP, acrylic polymers; MLS, modified form; TEA, triethanolamine; LS, lignosulfonic acid; HC, hydroxycarboxylic acids; CH, carbohydrates.

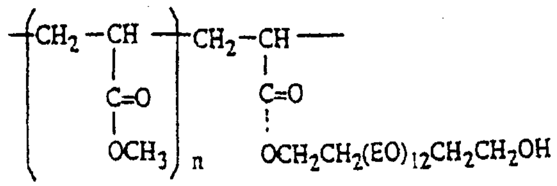
1.2.3.4.2.3 Mechanism of action

The fundamental mechanism of action of plasticizers has been established and reported by several studies[1,9,12,25]. It depends mostly on the surface chemistry. When a small quantity of water is added to the cement, without the presence of surfactant a well-dispersed system is not attained because, first, the water possesses high surface tension (hydrogen-bonded molecular structure), and second, the cement particles tend to cluster together or form flocs (attractive force exists between positively and negatively charged edges, corners, and surfaces when crystalline minerals or compounds are finely grounded)[9,12]. The diagram representing the flocculation system is shown in Figure 1.5. During the flocculation system a faster coagulation of cement grain occurs because C_2S and C_3S have a negative zeta potential while C_3A and C_4AF have a positive zeta



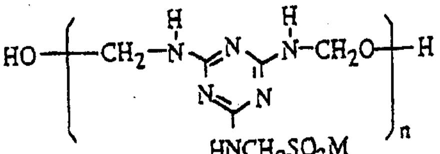
$R=H, CH_3, C_2H_5$
$M=Na$

SNF
(Sulfonated naphtalene formaldehyde)



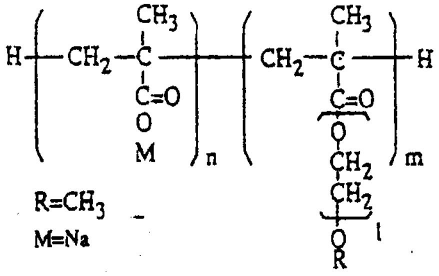
EO: Ethylene oxide

PC
(Polycarboxylate ester)



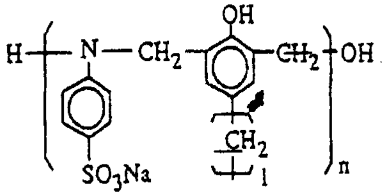
$M=Na$

SMF
(Sulfonated melamine formaldehyde)

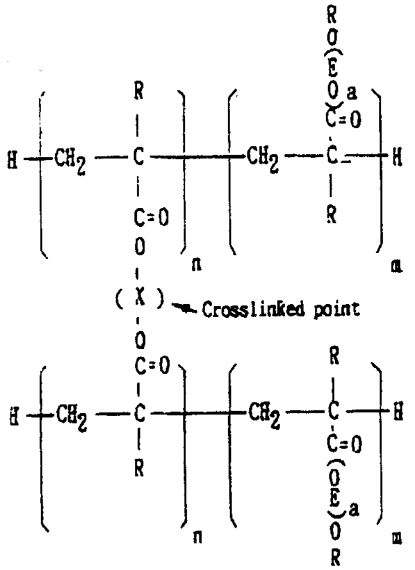


$R=CH_3$
$M=Na$

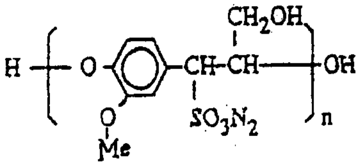
CAE
(Copolymer of carboxylic acrylic acid with acrylic ester)



AS
(Amino-sulfonate polymer)



CLAP
(Cross-linked acrylic polymer)



$Me=CH_3$, $M=Na$

LS
(Lignosulfonate)

Figure 1.4: Chemical structure of sulfonated and acrylic polymers[25]

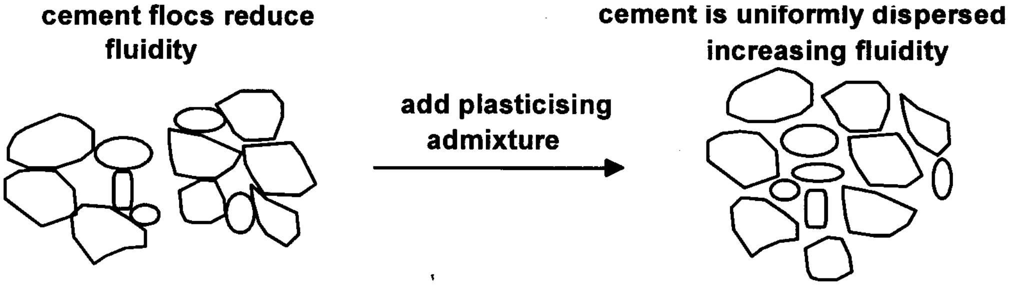


Figure 1.5: Mechanism of flocs of cement break-up[27]

potential[26]. Particle charge can be controlled by modifying the suspending liquid characteristics. Modifications include changing pH of liquid or changing the ionic species in solution. Another direct technique is to use surface active agent which directly adsorb to the surface of colloid and change its characteristics.

The improvement of fresh concrete's fluidity by the incorporation of a water-reducing admixture is considered to be caused by its dissociation in water to give negative charges on the $-COO^-$, $-SO_3^-$, or OH^- groups. Some of these are adsorbed onto the positive sites on the cement particles; others form an outer negative charge around the grain lowering the inter-particle attraction by the electrostatic repulsion mechanisms. An overview of the main physico-chemical effects involved in cement-plasticizer interactions is presented below.

1.2.3.4.2.3.1 Adsorption

The plasticizer has to be adsorbed first to the cement particle surface before being able to play dispersing role. In fact, as reported in section 1.2.2.4 during the hydration of Portland cement the soluble compounds of cement particles such as alkalis, calcium sulfate phase and free lime are dissolved by the surrounding water as soon as cement and water come into contact, and the Ca^{2+} and $H_2SiO_4^{2-}$ ions are hydrolyzed from C_3A and C_3S. The sustainability of this theory has been proven by the chemical analysis of cement particles from an electron spectroscopy for chemical analysis (ESCA, a test used to determine the elements on the sample surface by irradiating the sample with soft x-ray), which showed that calcium ions can be dissolved from the surface of the clinker without destroying the skeletal structure of clinker material, leading to a formation of a

Silicon (SiO_4^{4-}) or Aluminum ($Al_2O_3^{3-}$) rich surface[15]. The dissolved Ca^{2+} ions produce positive charged surface-adsorbed layer around the cement particles. Consequently, in the presence of plasticizer, the hydrophilic end of the molecule chain (i.e. COO^-, SO_3^- for organic molecules, and OH^- for polar functional group of organic molecules (e.g. sugar)) is adsorbed to the cement particles. For the case of polymeric admixtures (e.g. lignosulfonates) containing hydrophobic, polar and ionic groups, the adsorption results from a sum of effect and often stabilize the adsorption rate[18]. Figure 1.6 is a typical representation of an adsorption of organic molecules at the cement-solution interface. This theory was disputed by some researchers since plasticizers are also negatively charged and the surface charge of cement particle is low or even negative because the interstitial cement solution has a pH between 12 and 13. However, even if a surface has an overall negative charge, it carries also positively charged site, and the surface complexation (not adsorption), which does not depend on the overall surface charge, may be the main mechanism binding polycarboxylate to a surface for most of organic admixtures[28].

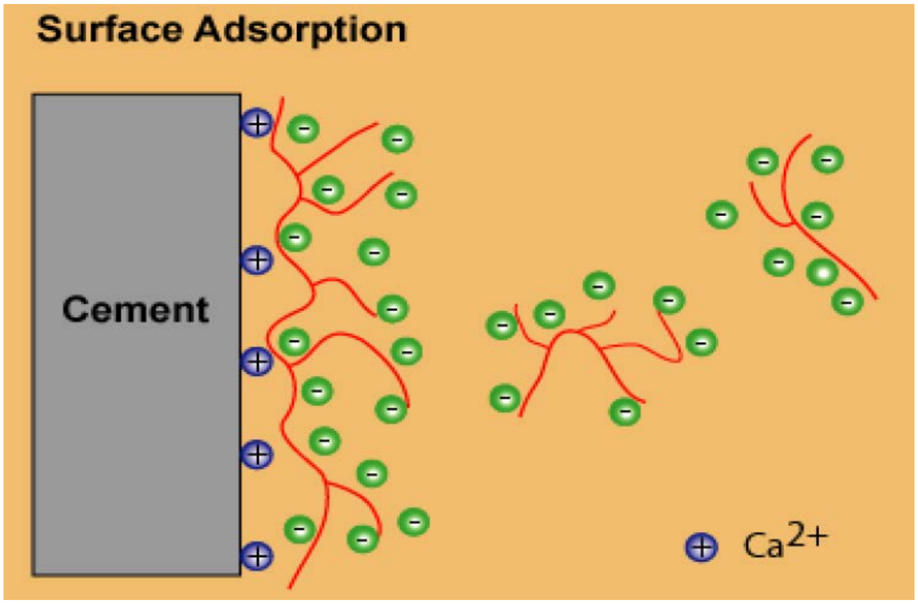


Figure 1.6: Adsorption mechanism of organic molecules at the cement-solution interface[12]

1.2.3.4.2.3.2 Electrostatic repulsion

The second mechanism of action of plasticizer in a concrete mixture is electrostatic repulsion. Electrostatic forces can be either repulsive between particles of identical charges or attractive between particles of opposite charge. As described above, a negative charge is induced by the adsorption of anionic plasticizer resulting in repulsive forces. In fact, the adsorbed anionic surfactants will send a net negative electrical charge to the particle surface (i.e zeta potential) inducing repulsion between neighboring cement particles and increasing their dispersion, thus requiring less water for a given degree of concrete workability. Figure 1.7 shows a typical electrostatic repulsion mechanism.

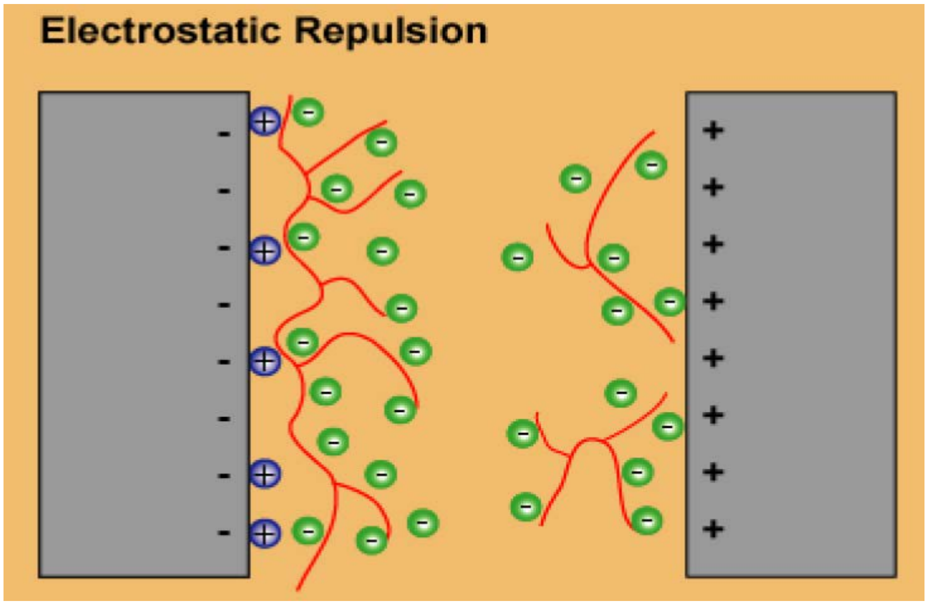


Figure 1.7: Electrostatic repulsion mechanism of organic molecules at the cement-solution interface[12]

1.2.3.4.3 Superplasticizers

1.2.3.4.3.1 Function

Superplasticizers or high range-water reducing admixtures (HRWRA) have similar functions of normal plasticizers but are more powerful in their cement dispersing action and fluidity retention. The use of chemical admixture date from 1930s, but it was not until the 1970s that sulphonated melamine formaldehydes (in Germany) and analogous naphthalene derivatives (in Japan) were developed using reactive polymer[29].

In the early 1990s, superplasticizers or high range water-reducing admixtures (HRWRA) consisting of sulphonated salts of melamine or naphthalene formaldehyde condensates or copolymers of carboxylic acrylic acids were developed in order to improve the dispersibility and the slump retention of melamine and naphthalene type admixtures. HRWRA extends the working life of concrete up to 2 hours, depending on mixture type and environmental condition[30]. They are capable of reducing water requirements at a given workability by up to 30 to 45 %. The increase use of polycarboxylate-type admixture has limited the use of the melamine and naphthalene type admixtures in precast concrete and other high slump concrete application.

1.2.3.4.3.2 Chemical composition

The chemical composition of water-reducing admixture (WRA) and high range water-reducing admixture (HRWRA) are quite different. The main ingredients in superplasticizer are synthetic water-soluble polymers and that of plasticizer are organic products. Table 1.5, shown earlier, presents the main and secondary ingredients used in manufacturing of superplasticizing and plasticizing admixtures. The sulfonated melamine formaldehyde (SMF) and the sulfonated naphthalene formaldehyde (SNF) are ionic linear organic polymers with sulphonate groups at regular intervals. Polycarboxylate (PC) is a generic name given to compounds that are classified into acrylate-based, methacrylate-based, or maleate-based, depending on the type of the main chain[31]. Figure 1.4 represents the formula of unit molecule of different sulfonated and acrylate-based polymers. The superplasticizer is formed by a repetition of these molecular units. For the case of polycarboxylate, at the backbone chain of the above cited polymers, various functional groups (polar or ionic, carboxyl, hydroxyl groups) are attached as side chains. The variations in type and length of the main and side chain of PC-type superplasticizer can affect its dispersibility.

1.2.3.4.3.3 Mechanism of action

The fundamental mechanism of action of superplasticizers has also been established and reported by several studies[1,9,12,25]. Most of HRWRA work in a very similar way to normal WRA. When naphthalene or melamine based-admixture is used, the action dispersing the particle is in most part due to the electrostatic repulsive force. Steric hindrance mechanism is the predominant effect for the polycarbonate-based admixtures mainly composed of an acrylic acid-acrylic acid ester copolymer. Uchikata et al.[32] reported that steric repulsive force is a short-range repulsive force cause by the overlapping of the adsorbed polymers. The steric repulsion effect is mainly attributed to the molecular structure of PC admixtures which is composed of a long straight chain of carbon atoms with the side chains branching from it[32]. Steric interaction occurs if the distance between the adsorbed polymers (as shown in Figure 1.8) is smaller than twice the thickness of superplasticizers[15]. Collerpardi et al.[25] found that the polymers molecules of CAE (see Figure 1.4) on the surface of cement might themselves hinder flocculation into large and irregular agglomeration of cement particles. This mechanism would be in agreement with the relatively smaller number of negative anionic groups COO^- in the CAE copolymer in comparison with those present as SO_3^- in the SMF and SNF polymer.

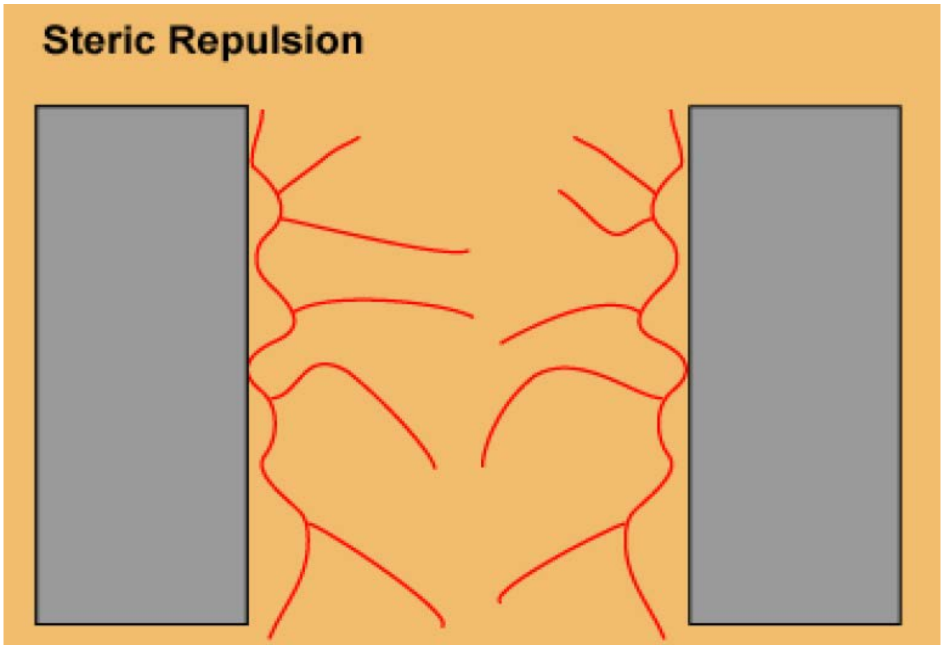


Figure 0.8: Steric hindrance mechanism of synthetic water-soluble polymers at the cement-solution interface[12]

In addition to electrostatic repulsive forces (F_{el}) and steric repulsive forces (F_{st}), it is reported in literature that Van der Waal's forces (F_{vdw}) are also acting between superplasticized-cement particles. Van der Waal's forces include momentary attraction between molecules, diatomic free elements, and individual atoms. They differ from ionic bonding in that they are not stable, but are caused by momentary polarization of the particle[15].

In summary, it can be reported that a superplasticizing admixture's mechanism of action involves adsorption of the polymer's anionic surfactants into the cement particles; electrostatic repulsive forces between neighboring cement particles; steric repulsive forces consisting of short-range repulsive forces caused by the overlapping of the adsorbed polymers; and Van der Waal's forces i.e. momentary attraction between molecules, diatomic free elements, and individual atoms.

1.2.3.4.3.4 Superplasticizer in cement hydrate product

The distribution of superplasticizer polymers can be divided into: (1) polymers in the pore water (P_w), dissolved in the pore water; (2) adsorbed polymers (P_{ads}), located on the hydrating cement surface; and (3) incorporated polymers (P_{inc}), incorporated in the hydrate products[15]. The total superplasticizer content (P_{tot}) which is initially added to the concrete is the sum of the above three portions.

$P_{tot} = P_w + P_{ads} + P_{inc} = P_w + P_{cem}$,

Or $P_{cem} = P_{tot} - P_w$, where:

P_{cem} is the superplasticizer adsorbed or incorporated in the cement hydration product. Andrea[15] reported that since the determination of P_{ads} and P_{inc} is very complicated or impossible, then P_{cem} can be obtained through the total superplasticizer added to the matrix. It is not a direct measure of dispersion or fluidity because it contains P_{ads} and P_{inc}.

1.2.3.4.3.5 Time of addition of superplasticizer

The time of addition of the superplasticizer or plasticizer can affect the duration of its effectiveness. SMF and SNF polymers are adsorbed more, particularly on the C_3A hydration products, when the immediate addition in mixing water is adopted. This effect seems to be related to the production of large amount of ettringite coating on the surface of cement particles during the initial cement hydration (see sections 1.2.2.3 and 1.2.2.4). An increase in superplasticizer dosage is not a solution, because larger amount of admixture than normally needed may retard the time of set by preventing or delaying the hydration product to flocculate. Also the addition of superplasticizer with mixing water causes strong incorporation of the polymer molecules into the C_3A-gypsum system, and leaves only small amounts of polymers for dispersion of C_3S and C_2S. The acrylic polymer-based superplasticizers are proven to be much less independent of the time and method of addition[25].

1.2.3.4.3.6 Effect of chemical structure on polycarboxylate polymer

The modification of the chemical structure of polycarboxylate-based polymer admixture is easier than that of the naphthalene-based[31]. As shown in Figure 1.9, the ratio of the acid and ester can be varied by changing modulus n and m. The higher the acid ratio, the higher the carboxylic group content, and easily the polymer can adsorb to cement particles leading to a higher dispersibility. On the other hand, the higher the ester ratio, the higher the side chain content, therefore, the content of carboxylic group relatively decreases and the polymer cannot so easily adsorb to the cement particles, consequently the dispersibility of the polycarboxylate polymer at the same dosage decreases. In the later case, the remaining molecules adsorbed gradually to cement particles as time elapses, thus increased the fluidity retention[31]. It is discussed in section 0.4.4.2.3 that electrostatic repulsion is one of the main factors involved in plasticizer dispersion and water reduction. Flatt et al.[33] indicated that the electrostatic repulsion is intimately linked to the function of zeta potential and the polycarboxylic acid polymers (PC) induce larger final zeta potential (around -23 mV), while polycarboxylic ester polymer polymers (PE) induce lower potential ranging from -5 to -18 mV. This difference can be attributed to the fact that the PA-polymers are all strong electrolytes, and the PC-polymers are weak or very weak electrolytes. Thus, it is more likely that the dispersion by electrostatic repulsion of PA-polymers can be higher that of PE-polymers.

1.2.3.4.3.7 Effect of cement composition on polycarboxylate polymer

The relative reactivity of the four main mineral phases with water can be classified as $C_3A > C_3S > C_2S \simeq C_4AF$. During the initial cement hydration, because of its high reactivity, the C_3A is converted into ettringite in the presence of the dissolved components Ca^{2+} and $H_2SiO_4^{2-}$ of gypsum. An increase in the cement C_3A content will lead to an increase of the surface area of the hydrate cement product due to the increase

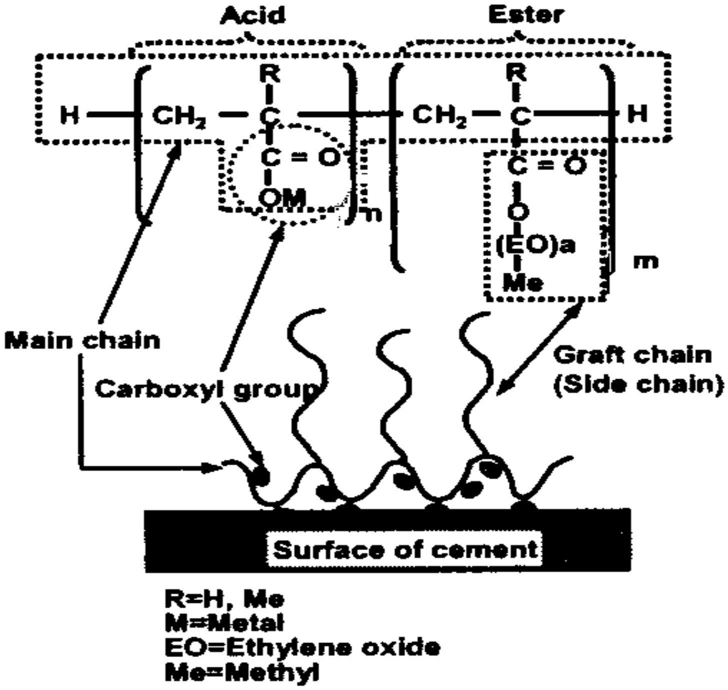


Figure 1.9: Polycarboxylate-cement system: Model of copolymer of acrylic acid and acrylic ester[31]

in formation of ettringite compounds. Therefore, the adsorbed volume of polymer per unit area of cement particle decreases along with its dispersibility[18,31].

Alkali by itself does not affect the performance of a superplasticizer[31], but SO_4^{2-} affects it greatly because its concentration in the liquid phase is varied by the presence of alkali. When the concentration of SO_4^{2-} increases, the main chain of the PC-polymer contracts decreasing the steric hindrance effect. Both SO_4^{2-} and PC polymer competitively adsorb onto the surface of solid phase. The presence of SO_4^{2-} can detach the already adsorbed PC polymer, decreasing the adsorption volume[31].

In summary, it can be reported that the cement composition, especially the C_3A, SO_3 and alkali contents, which control the rate of ettringite formation, may have an effect on cement-admixture interaction. The cement fineness also increases the surface area, decreasing the adsorption for a given superplasticizer dosage.

1.2.3.4.4 Viscosity modifying admixture (VMA)

With the increased use of flowable concretes, such as SCC, to facilitate placement in congested and/or restricted areas, unstable dispersion of cement paste and aggregate particles become recurrent. The tendency of heterogeneous materials to separate increases with the reduction of viscosity, due to an increase fluidity of the concrete, or when the concrete is subjected to a high shear rate, such as that encountered during pumping[34]. Viscosity modifying admixtures (VMA) are relatively new admixtures engineered and formulated to enhance concrete performance by modifying the viscosity and controlling the rheological properties of the concrete mixtures. They were first used in Germany in the mid-1970s, later in Japan in the early 1980s, and in the North America in late 1980s.

1.2.3.4.4.1 Function

The key function of a viscosity modifying admixture (VMA) is to modify the rheological properties of the cement paste, i.e. the yield point and the plastic viscosity. Yield point is the force needed to start the concrete moving. The yield point is related to the workability of the concrete. The plastic viscosity, usually caused by internal friction, describes the resistance of a concrete to flow under external stress and relates to the speed of flow of concrete. The incorporation of VMA in a concrete mixture can improve its rheological properties, cohesion and stability, thixotropic properties, stability during transport and placement, pumpability, finishability, and bleeding[34,35].

1.2.3.4.4.2 Chemical composition

Viscosity modifying admixtures are water-soluble polymers which can be natural, semi-synthetic, and synthetic[36]. Natural polymers include starches, guar gum, locust bean gum, alginates, agar, gum arabic, welan gum, xanthan gum, rhamsan gum, and gellan gum, as well as plant protein. Semi-synthetic polymers include decomposed starch and its derivatives; cellulose-ether derivatives, such as hydroxypropyl methyl cellulose (HPMC), hydroxyethyl cellulose (HEC) and carboxy methyl cellulose (CMC); as well as electrolytes such as sodium alginate and propyleneglycol alginate. Finally, synthetic polymers include polymers based on ethylene, such as polyethylene oxide, polyacrylamide, polyacrylate, and those based on vinyl, such as polyvinyl alcohol.

Some VMAs are based on inorganic materials such as colloidal silica which is amorphous with small insoluble, non-diffusible particles, larger than molecules but small enough to remain suspended in water without setting. By ionic interaction of the silica and calcium from the cement a three dimensional gel is formed which increases the viscosity and/or yield point of the paste[34,35].

The viscosity modifying admixtures commonly used in cement-based system are water-soluble polysaccharides, such as cellulose ether derivatives and microbial-source polysaccharides, such as welan gum, that bind some of the mixing water, thus enhancing viscosity. Acrylic-based polymers, such as partial hydrolysis products of a polyacrylamide copolymer and sodium acrylate, are also employed. Welan gum is an anionic, high molecular weight (around 2 millions g/mol) polysaccharide produced by a controlled aerobic fermentation process. Welan gum is a long-chain biopolymer with sugar backbone substituted with sugar chains[34,35].

Viscosity modifying admixtures can be supplied as a powder blend or liquid-based products to make dosing easier and accurate. The dosage depends on the application but typically ranges from 0.1 to 1.5% by weight of cement. Most VMAs have little effect on other concrete properties in either the fresh or hardened state but some, if used in high dosage, can affect setting time and/or the content and stability of entrained air[35].

1.2.3.4.4.3 Mechanism of action

Khayat[34] reported that the mode of action of VMA in cement-based system can be attributed to adsorption, association, and intertwining.

Adsorption

First, the long-chain polymer molecules adhere to the periphery of water molecules, thus adsorbing and fixing part of the mix water and thereby expanding, and increasing the viscosity of the mix water and cement-based product.

Association

The molecules in adjacent polymer chains can develop attractive forces, thus further blocking the motion of water, causing a gel formation and an increase in viscosity.

Intertwining

At low rates of shear, and especially at high concentrations, the polymer chains can intertwine and entangle, resulting in an increase in the apparent viscosity. Such entanglement can disaggregate, and the polymer chains can align in the direction of the flow at high shear rates, hence resulting in shear thinning.

1.2.3.4.4.4 Classification

Viscosity modifying admixtures can be grouped into two main types based on the mechanism by which they function, namely: thickening-type and binding-type[37].

Thickening-Type VMA

The VMAs in this group function by thickening the concrete, making it very cohesive without significantly affecting the fluidity of the mixture.

Binding-Type VMA

These VMAs function by binding water within the concrete mixture. This mechanism results in an increase in the viscosity of the mixture, while reducing or eliminating concrete bleeding. This type of VMA is more potent in modifying the viscosity of SCC mixture compared to a thickening-type VMA. They also take on the concrete's thixotropic characteristic, which means that fresh concrete may gel up if left in a mixing vessel, truck, or form without agitation. Simply re-mixing the concrete can restore workability.

1.2.3.4.4.5 HRWRA and VMA incompatibility

When using flowable concrete such as SCC, the balance between the yield point and the plastic viscosity is the key in obtaining the appropriate concrete rheology. VMA is used to increase the plastic viscosity but usually causes only a small increase in yield point whereas HRWRAs are used to decrease the yield point. Since HRWRAs are sometimes used in conjunction with a VMA to optimize the yield point[35], their compatibility becomes important. The use of polyalkylaryl sulphonate water-reducing admixture in aqueous solutions containing cellulose VMA was reported to cause an abnormal increase in viscosity[34]. Kawai and Okada[36] also found that the use of hydroxypropyl methyl cellulose (HPMC) in an aqueous solution possessing a pH of 13 and containing a naphthalene-based HRWRA can result in a sharp increase in viscosity when the HPMC and HRWRA contents were respectively greater than 0.8% and 1% by mass of water. This was attributed to the formation of chemical gel resulting from the incompatibility between the two admixtures. Welan gum does not exhibit an incompatibility with either melamine-based or naphthalene-based HRWRAs[34].

1.2.4. Mineral admixtures

1.2.4.1 Nomenclature and Specifications

The mineral admixtures are usually added to concrete in large amounts. Beside cost reduction and workability improvement of the fresh concrete, they can successfully be employed to improve the resistance of concrete to thermal cracking, alkali-aggregate expansion, and sulfate attack. Some mineral admixtures are pozzolanic, some are cementitious and others are both pozzolanic and cementitious. The mineral admixtures can be divided into two main groups: natural materials and by-product materials.

1.2.4.1.1 Natural materials

The natural materials all mostly derived from volcanic rocks and mineral (except diatomaceous earths). They are processed for the sole purpose of producing a pozzolan, by crushing, grinding, and separating the sizes. Based on the principal reactive constituent, the natural material can be classified into volcanic glasses, volcanic tuffs, calcined clays or shales, and diatomaceous earths[9].

1.2.4.1.2 By-product materials

The by-product material mineral admixtures are not the primary products of the industry producing them. They may or may not require any drying or pulverization before use as mineral admixture. The most important by-product materials are described below:

1.2.4.1.2.1 Fly ash

Fly ash is the most widely used supplementary cementitious material in concrete. It is comprised of the non-combustible mineral portion of coal. When coal is consumed in a power plant, it is first ground to the fineness of powder and blown into the boiler where after the consumption of carbon molten particles rich in silica, alumina and calcium are formed. These particles solidify as microscopic, glassy spheres that are collected from the power plant's exhaust[38].

According to ASTM C 618[39], "Standard Specification for Fly Ash and Raw or Calcinated Natural Pozzolan for Use as Mineral Admixture in Portland Cement Concrete," three mains classes of fly ashes exist:

(1) Class F fly ash is normally produced from burning anthracite or bituminous coal. Class F materials are generally low-calcium (less than 10% CaO) fly ashes with carbon

content usually less than 5%, but some may be as high as 10%;

(2) Class C fly ash is normally produced from burning lignite or subbituminous coal. Class C materials are often high-calcium (10% to 30% CaO) fly ashes with carbon contents less than 2%. In addition to being pozzolanic, class C fly ash is also cementitious. When exposed to water they will hydrate and harden in less than 45 minutes. Some fly ashes meet both Class F and Class C classification; and

(3) Class N fly ash, is a natural mineral admixture. It consists of raw or calcinated pozzolans such as diatomaceous earths, opaline cherts and shales, tuffs and volcanic Ashes or pumicite, and calcinated materials such as clays and shales[9].

Most of the fly ash particles are solid spheres and some are hollow cenospheres[9]. The particles sizes vary from less than 0.00004 inch (1 μm) to more than 0.004 inch (100 μm) with the typical particle size measuring less than 0.0008 inch (20 μm). They are generally finer than cement. The surface area is typically 176 to 293 yd^2/lb (300 to 500 m^2/kg), although some fly ash can have surface areas as low as 117 yd^2/lb (200 m^2/kg) and as high as 410 yd^2/lb (700 m^2/kg). For fly ash without close compaction, the bulk density (mass per unit volume including air between particle) can vary from 34 to 54 lb/ft^3 (540 to 860 kg/m^3), whereas with close packed storage or vibration, it can range from 70 to 94 lb/ft^3 (1120 to 1500 kg/m^3)[9].

Chemically, fly ash is a pozzolan. ASTM C 125[40] defines pozzolan as a siliceous, or siliceous and aluminous material which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compound possessing cementitious properties. One of the primary benefits of fly ash is its reaction with available lime and alkali in concrete, producing additional cementitious compounds which allow fly ash concrete to continue to gain strength over time. The following equations illustrate the pozzolanic reaction of fly ash with lime to produce additional calcium silica hydrate (C-S-H) binder

Cement reaction: $$C_3S + H \rightarrow C\text{-}S\text{-}H + CaOH \qquad (1.8)$$

Pozzolanic reaction: $$CaOH + S \rightarrow C\text{-}S\text{-}H \qquad (1.9)$$

Where S is the silica from ash constituents

1.2.4.1.2.2 Silica fume

Silica fume is a by-product of the manufacture of silicon or various silicon alloys produced in submerged electric arc furnaces (ASTM C 1240)[41]. The production of silicon consists of reducing a white quartzite (99.3% SiO_2) to silicon using high quality charcoal in an electric-arc furnace. A mixture of crushed quartzite, charcoal, and wood chips is continuously fed to the top of the furnaces. The furnaces, by rotating very slowly around the carbon electrodes, create electric arcs deep in the furnace bed and hence the high temperature needed to produce molten silicon. The production of ferro-silicon is similar to silicon production; however iron and lime are added to produce iron ferro-silicon. This does not necessarily lead to a reduction in SiO_2 content as ferro-silicon plants often have low carbon content.

Silica fume's particles are spherical in shape. They average 0.15 micron but vary from 0.01 to 1 micron. Its color varies from pale to dark gray and is mostly influenced by the carbon and iron content.

Silica fume is available in several forms according to its bulk density. The main three different forms are:

(1) Undensified form:

In undensified form, the raw silica fume direct from the bag house (10 - 15 pcf (160 - 240 kg/m^3)) is like a dense smoke. Yet because it is so light it almost floats, and handling becomes a major problem. Undensified silica fume is predominantly used in refractory grout, and mortars.

(2) Densified form

The densified form is obtained by blowing air through the fume in a silo to agglomerate the undensified silica fume. This forces the particles to move around other particles and adhere to them by surface force. Densification takes a couple of days with the silica fume's appearance changing. The bulk density increases to about 35 - 42 pcf (561 - 673 kg/m^3) where the grain size increases to about 0.02 inch (0.5 mm). The fineness of silica fume is one of the two characteristics that make its super pozzolanic nature. Hence, it is vital that the agglomerations formed by densification breakdown during mixing. Densified silica fume is well-suited for concrete.

(3) Slurry Form

Slurries are generally made from undensified silica fume. A conditioner (pH neutralizer) is added to stop setting and silica fume is mixed with water (approximately 1:1 weight). Other admixtures (e.g. superplasticizer) may be incorporated to the slurry. The main requirement of silica fume slurry is that it should not settle. Its ability to not settle is dependent on the particle size and added dispersants. Slurry has a unit weight of about 82 pcf (1300 kg/m^3).

(4) Pelletized Form

Water is sprayed onto the undensified silica in a pug to produce pellets. The pellets produced are 3/8 of an inch (10 mm), dustless and do not break down easily during concrete mixing. This form of silica fume is utilized in inter-ground silica fume blended cement.

The chemical composition of silica fume varies depending on the type of plant (silicon or ferro-silicon), the source of materials, and the method of plant operation. The major chemical components of silica fume are: silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and carbon (C). ASTM C 1240[41] requires the following chemical composition:

• SiO_2	85% minimum
• Moisture content	3% maximum
• Loss on ignition	6% maximum

The most important compound of silica fume is the SiO_2 content. The higher the SiO_2 content, the better silica fume performs when used as a mineral admixture in concrete. The primary benefit of silica fume is its pozzolanic reaction during secondary hydration process where it reacts with calcium hydroxide (hydrated lime) of Portland cement to form more C-S-H gel during the pozzolanic reaction. The hydration of silica fume concrete can be explained through equations (1.8) and (1.9) where S represents the silica from silica fume.

In addition to being much finer than cement (100 times finer), silica fume acts as a filler for the spaces between the cement grains. This higher fineness increases the rate at which silica fume hydrates and thus accelerates strength development. Several other physical properties of silica fume contribute to the enhancement of concrete. These include the increase in density of the composite system, the increase in cohesiveness, and the decrease of bleeding due to the high surface area of the particle. However, the addition of silica fume increases the water demand, and unless a water reducer is used, more water is needed to achieve a desirable level of fluidity.

1.2.4.1.2.3 Ground granulated blast furnace slag (GGBFS)

ASTM C 989[42] defines blast furnace slag as a non-metallic product mainly consisting of calcium silicates and other bases that is developed in a molten condition simultaneously with iron in a blast furnace. Ground Granulated Blast Furnace Slag (GGBFS) is a by-product of the steel industry which is obtained when molten slag is quenched rapidly using water jets. GGBFS is granular with very limited crystal formation. It is classified into three grades, namely, 80, 100, and 120, according to the slag activity index which is the average compressive strength of the slag-reference cement cubes (SP), divided by the average compressive strength of the reference cement cube (P), and multiplied by 100.

The primary chemical composition of slag (about 95%) is in the form of silica, alumina, calcium oxide, and magnesia. The remaining 5% consists of manganese, iron, and sulfur. GGBFS becomes highly cementitious in the presence of water by using its SiO_2 to react with the $Ca(OH)_2$ generated by the hydration of cement in order to produce additional calcium silicate hydrate (C-S-H). This process is similar to the hydration of silica fume and fly ash, as shown by equations (1.80 and (1.9), where S represents the silica from GGBFS. The additional C-S-H brought to the matrix by the incorporation of GGBFS increases the concrete strength and durability over time.

TASK 2

PREPARATION AND APPRAISAL OF RAW MATERIALS

The Task 2 of the investigation reports on the preparation and appraisal of the raw materials used to produce self-consolidating concretes.

2.1. INTRODUCTION

Modern concrete technology produces highly engineering materials in which, by the careful selection and proportioning of constituents, their characteristics are designed to fulfill specific needs. The more advanced the concrete becomes; such as self-consolidating concrete, high performance concrete, pumpable concrete; the more sensitive it gets to materials' variations and fluctuations during production and placing. Variations in the moisture content or grading of the aggregates and fluctuations in the fine content of the aggregate are among the major problems encountered in production sites.

2.2. MATERIAL PREPARATION AND APPRAISAL

Self-consolidating concrete is a concrete made mainly with conventional concrete materials such as aggregates, cement, supplementary cementitious materials, admixtures, and water. The description of the raw materials used in this investigation along with their physico-chemical properties are presented below.

2.2.1 Aggregates

Self-consolidating concrete can be considered high-performance concrete in the plastic state[1]. The workability attributes of SCC are characterized with its flow ability, passing ability, filling ability, and stability. Because coarse and fine aggregates generally occupy 60% to 75% of the concrete volume, the selection of aggregate becomes significant in developing concrete that meets the required specifications. Coarse aggregate size, shape, and total volume play a critical role in SCC performance. A rounded coarse aggregate imparts greater filling ability for the same water content when compared with a crushed stone of similar size. Additionally, when all others mixture parameters are equal, a concrete mixture containing well-rounded natural gravel can be used at a higher volume than angular crushed aggregate of the same gradation. The fine aggregate gradation is equally important and should be evaluated for suitability in Portland cement concrete.

For the purpose of this investigation, four distinct sizes of coarse aggregate, provided by three different quarries, were selected. The aggregates were given designations of Q89, R8, R67, and S7 to avoid any commercialization interest. The letters Q, R, and S refer to the quarries in which the aggregates were obtained from, and numbers “89”, “8”, “67”, and “7” indicate their size designations based on the requirement of ASTM C 33[13].

2.2.1.1 Quarry Q

Two distinct deliveries of aggregates from quarry Q were tested in the laboratory. It was determined that the fine aggregate satisfied ASTM C33[13] requirements, whereas the coarse aggregate did the contrary. As a result, the aggregates from the quarry Q were not included in this investigation. It is also important to note that the use of ASTM C 33[13] #89 coarse aggregate is not generally recommended for making self-consolidating concrete partly due to its higher surface area that requires significant dosage of superplasticizers.

2.2.1.2 Quarry R

The aggregates from the Quarry R were also evaluated in the laboratory. The test results revealed that they satisfied the requirements of ASTM C 33[13] fine aggregate, and ASTM C 33[13] #8 or #67 coarse aggregates. The fine aggregate had well-rounded particles that were dense and relatively smooth in nature. The coarse aggregate was crushed stone, angular to irregular shape with a granular surface texture. The physical properties of Quarry R aggregates are shown in Table 2.1, whereas their size distributions are presented in Figures 2.1, 2.2, and 2.3.

2.2.1.3 Quarry S

Samples of fine and coarse aggregates obtained from Quarry S were tested per ASTM C 33[13]. The coarse aggregates satisfied the gradation requirements of ASTM C 33[13] #7 and the fine aggregate remained within the allowable size limit. While the aggregate shape and texture were similar to those of Quarry R, their color and bulk density indicated a different mineralogical origin. The size gradations of these aggregates are presented in Figures 2.4 and 2.5 and their physical properties are given in Table 2.1.

All aggregates were shipped from quarries in an open station truck and were stored in 55-gallon steel drums. Each time, approximately 150 lbs (68 kg) of material were air- dried

Table 2.1: Physical properties of aggregates

Aggregates		Color	Bulk specific gravity (SSD)	Absorption (%)	Dry rodded unit weight (pcf)
Quarry R	Fine aggregates	Yellow dark	2.54	1.50	-
	Coarse aggre. ASTM C33 #8	Gray	2.58	1.40	94.6
	Coarse aggre. ASTM C 33 #67	Gray	2.60	1.00	96.50
Quarry S	Fine aggregates	White	2.78	0.80	-
	Coarse aggre. ASTM C #7	White	2.79	0.60	102.00

1 pcf = 16.02 kg/m^3

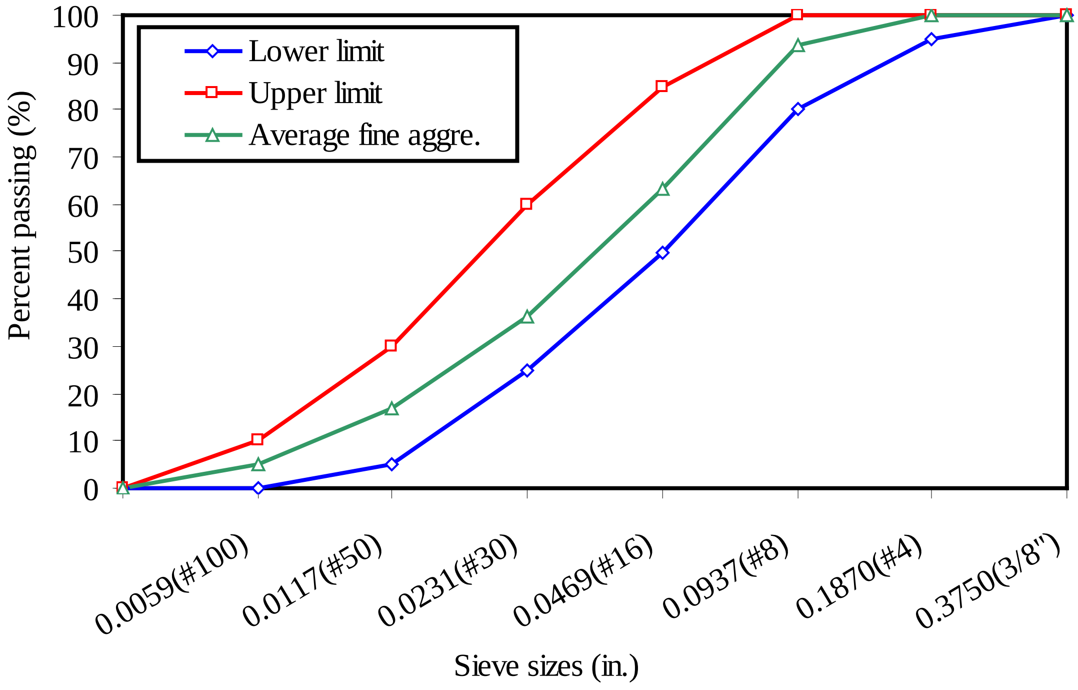


Figure 2.1: Quarry R fine aggregate size distribution

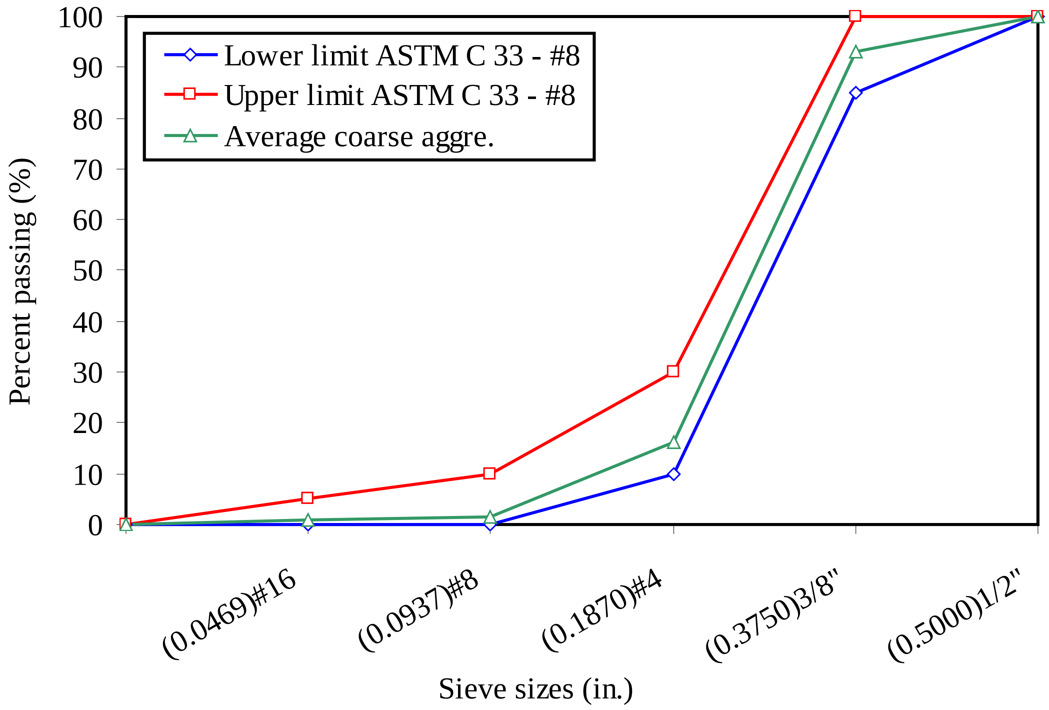


Figure 2.2: Quarry R ASTM C 33 # 8 coarse aggregate size distribution

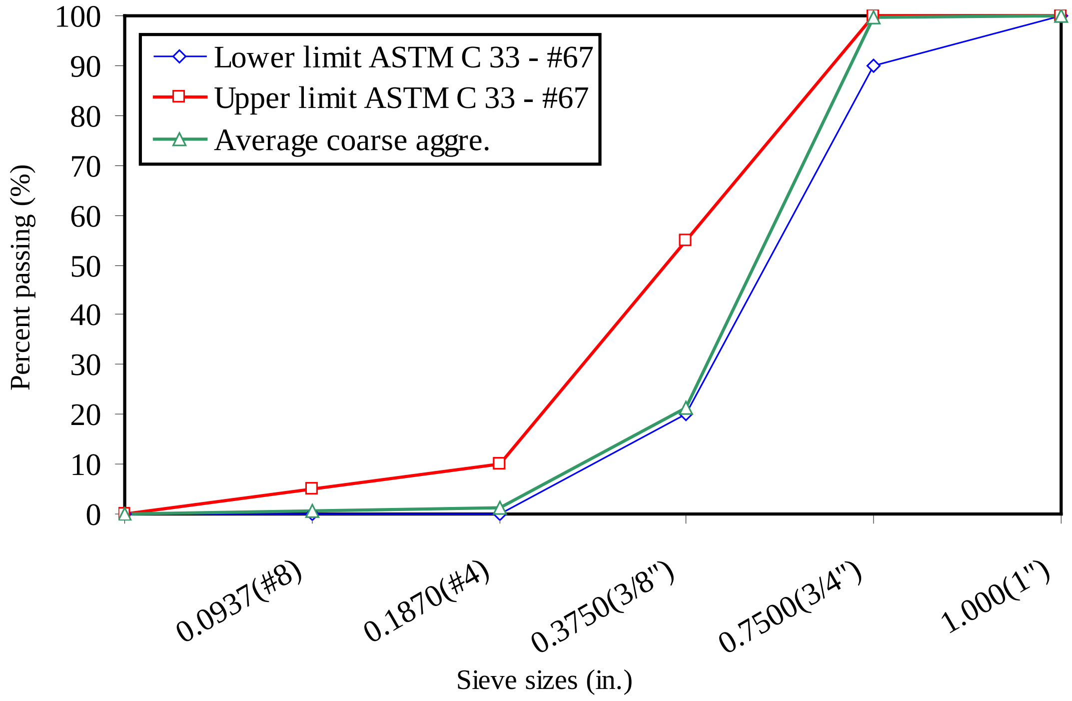


Figure 2.3: Quarry R ASTM C 33 # 67 coarse aggregate size distribution

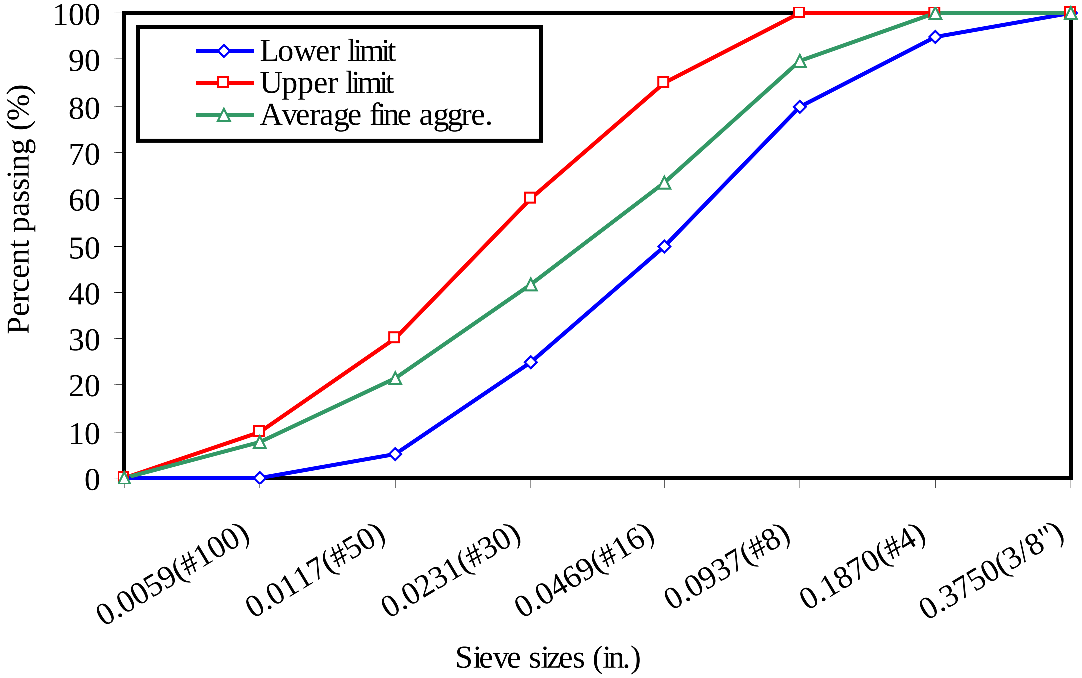


Figure 2.4: Quarry S fine aggregate size distribution

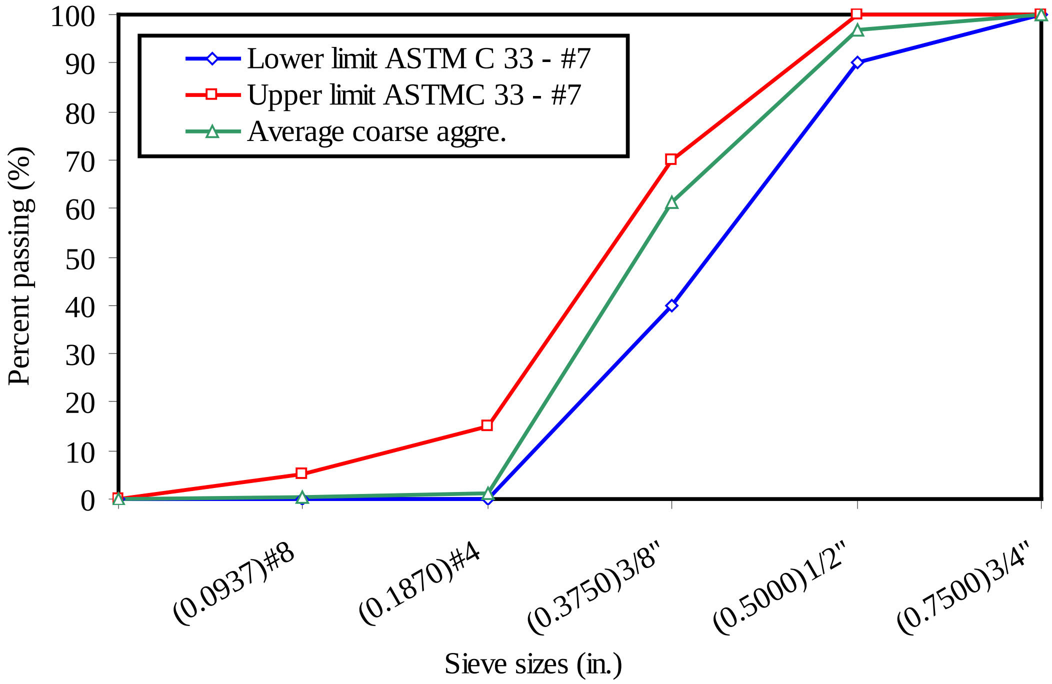


Figure 2.5: Quarry S ASTM C 33 #7 coarse aggregate size distribution

until moisture contents of about 0.10 and 0.15% were obtained for fine and coarse aggregates, respectively. The aggregates were then placed in sealed cans in order to prevent any moisture loss. The moisture content of the aggregates was monitored on a weekly basis.

2.2.2 Portland cement

Portland cements suitable for use in self consolidating concrete should meet one of the following specifications: ASTM C 150[14], C 595[43], or C 1157[44]. Commercially available Type V Portland cement was used in this study. This type of cement is suitable for uses where special properties, such as a sulfate resistance, are required. The cement, obtained from a single supplier, complied with the ASTM C 150[14] specifications and its physico-chemical characteristics are shown in Tables 2.2. These data are the average information provided by the supplier for five different deliveries (average data of five mill certificates). Upon delivery, the Portland cement was placed in plastic bags and stored in sealed cans in the laboratory (room temperature (70 ± 3 ^{o}F (21 ± 2 ^{o}C)), prior to use.

2.2.3 Fly ash

The fly ash used in this investigation was provided by the same supplier as the Portland cement. It was delivered in 55 gallons metallic drums and stored away from the humidity in the laboratory. Its physical and chemical properties are presented in Table 2.2. These data represent the average of five mill certificates obtained upon delivery. The fly ash complied with the ASTM C 618[39], class F specifications.

2.2.4 Water

Throughout this investigation, tap water complying with the requirements of ACI 310[45] “Specifications for Structural Concrete for Buildings” was used.

2.2.5 Chemical Admixtures

Among a variety of commercially available plasticizers and superplasticizers, polycarboxylate-based (PC) high range water reducing admixtures (HRWRA) are most widely used for developing and proportioning self-consolidating concretes[1]. While PC-HRWRA is used to impart fluidity on SCC, a viscosity modifying admixture (VMA) is also used to increase concrete’s cohesiveness (improve segregation resistance). For the purpose of this study, the liquid high range water reducing and viscosity modifying

Table 2.2: Chemical and physical properties of Portland cement and fly ash

Chemical Composition	Portland Cement (%)	Fly Ash (%)
SiO_2	20.64	58.9
AL_2O_3	3.4	20.5
Fe_2O_3	3.4	5.6
CaO	63.5	7.5
MgO	4.7	
SO_3	2.4	0.4
Na_2O equivalent	0.46	-
K_2O		
C_2S	9	-
C_3S	66	-
C_3A	4	-
Loss on Ignition	1.20	0.3
Insoluble residue	0.14	-
Moisture content		0
Fineness Blaine, cm^2/gm	3810	-
Autoclave expansion, %	0.18	0.02
Time of set, minutes		
Initial	96	-
Final	205	-
False Set, %	94	
Air content, %	6.3	-
Compressive strength, (MPa)		
3-day	27.4	-
7-day	33.9	-
28-day	42.7	-
325 sieve passing, (%)	97.9	23.5
Specific gravity	3.15	2.33

1 MPa = 145 psi, 1 kg/m^3 = 0.0624 pcf

admixtures were received from four different manufacturers, designated as A, B, C, and D, in sealed 5.0-gallon plastic containers. They were stored in the laboratory at a temperature of 70 ± 3 °F (21 ± 2 °C). All admixtures were manufactured and formulated to comply with the specifications for chemical admixtures for concrete Type F ASTM C 494[23] for HRWRA, and ASTM C 260[46] for air-entrainment admixture (AEA). Their chemical compositions and types are presented in Tables 2.3 through 2.5. These data are obtained from manufacturer supplied Product Data and Material Safety Data Sheet (MSDS).

Table 2.3: Chemical compositon of high range water reducing admixtures (HRWRA)

Designation	Source A	Source B	Source C	Source D
Chemical type	Polycarboxylate ether	Polycarboxylate	Polycarboxylate	Polycarboxylate
Volatiles (%)	-	60.00%	approx. 70%	approx. 60%
Speific gravity	1.05	1.09	1.02 to 1.10	approx. 1.1
pH	5.0 to 8.0	6.2 to 6.6	5.0 to 7.0	3.0 to 7.0
Water reduction range	20 to 30%	up to 40%	up to 40%	up to 45%

Table 2.4: Chemical compositon of viscosity modifying admixtures (VMA)

Designation	Source A	Source B	Source C	Source D
Chemical type	Polysaccharides	NS and welan gum	Methyl isothiocyanate	NS and melamine polymer
Volatiles (%)	-	56.90%	approx. 80%	-
Speific gravity	1.002	1.207	1.100	1.23
pH	8.0	7.5 to 10.5	n/a	> 8.0

Table 2.5: Chemical compositon of air entrainment admixtures (AEA)

Designation	Source A	Source B	Source C	Source D
Chemical type	Alkybenzene sulfonic acid	Tall oil and glycol ether	Resin and rosin acids, potassium salt	Natural resin solution
Volatiles (%)	-	86.70%	90%	-
Speific gravity	1.0	1.01	1.0 to 1.04	1.0
pH	10.7 to 12.3	10 to 12	9 to 11	7.0 to 9.0

TASK 3

MIXTURE DEVELOPMENT OF SELF-CONSOLIDATING CONCRETE

The present chapter aims at: (1) comparing the optimum dosage requirement of four different sources of polycarboxylate-based High Range Water Reducing Admixture (HRWRA) and Viscosity Modifying Admixture (VMA) in attaining slump flows of 20 inches (508 mm), 25 inches (635 mm), and 28 inches (711 mm); and a visual stability index (VSI) of 0 (highly stable concrete) or 1 (stable concrete), (2) evaluating the flow ability/viscosity, stability, passing ability, and filling ability of three groups of self-consolidating concretes, and (3) examining the properties of the three groups of SCC as related to air content, bleeding, time of setting, adiabatic temperature, demolded unit weight, compressive strength, and static modulus of elasticity.

3.1 Mixture proportion design

The mixture proportions used in the present investigation were developed based on the required engineering properties and mixture economy of various self-consolidating concretes, using the raw materials described in Task 2. Low, medium, and high slump flows, i.e. 20 inches (508 mm), 25 inches (635 mm), and 28 inches (711 mm) non-air entrained self-consolidating concretes were adopted. Factors that guided the selection of the matrix constituents and proportions are summarized below.

3.1.1 Engineering properties

3.1.1.1 Fresh performance

The fresh performance of self-consolidating concrete is characterized by its flow ability, passing ability, filling ability, and stability[1]. The general considerations to achieve the desired fresh performances were:

- Optimum coarse-to-fine aggregate ratio,
- Appropriate water-to-cementitious materials ratio (w/cm) to avoid formation of autogeneous shrinkage. In general, autogenous shrinkage dominates when the w/cm ratio is below 0.40. The shrinkage becomes less dependent on cement content when a w/cm ratio higher than 0.4 is used[47],
- Minimum cementitious materials content, and
- Optimum dosage of the combined HRWRA and VMA.

3.1.1.2 Hardened characteristic

- Strength was not a major consideration since high cementitious material content and low water-to-cementitious materials ratio were used.

- Sulfate durability was provided through Type V Portland cement, fly ash, and low-water-to-cementitious materials ratio. For the purpose of this study, all designed self-consolidating concretes were non-air-entrained.

In accordance with the testing standards related to the required fresh properties, and discussed in section 3.2, the followings target limits were adopted:

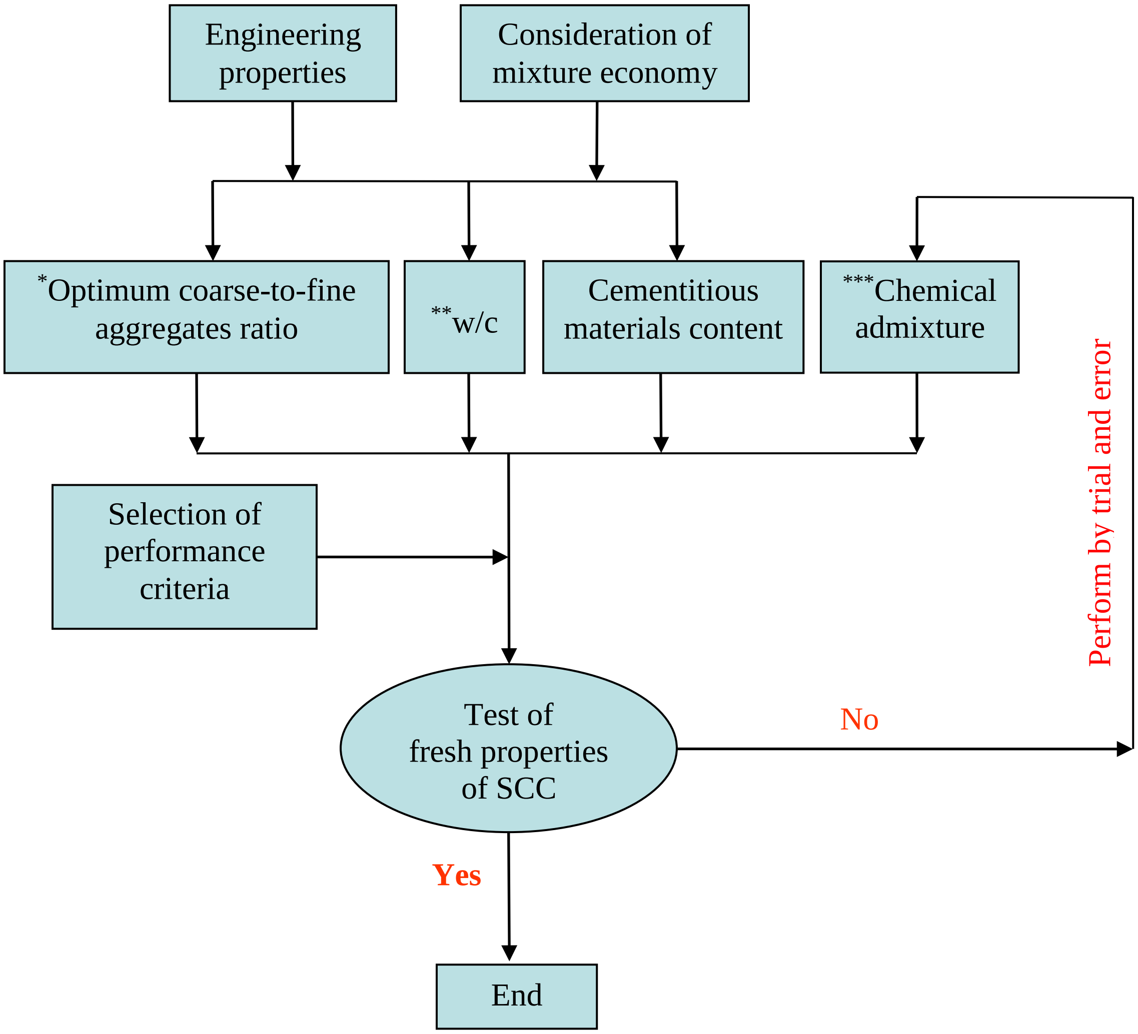
- Slump flow : SF ± 1.0 inch (25.4 mm)
- VSI : 0 to 1 (Highly stable to Stable)
- T_{50} : From 2 to 5 seconds
- J-ring value : SF – J-ring $\leq$ 2.0 inches (50 mm).
- L-box : $0.8 \leq H_2/H_1 \leq 1.0$
- U-box : $H_1 - H_2 \leq 12$ inches (305 mm)
- V-funnel : $t_v \leq 10$ seconds
- Column segregation : SI (segregation index) $\leq$ 15%

3.1.2 Consideration of mixture economy

SCC is typically proportioned with relatively high cementitious materials content and chemical admixtures, leading to a relatively high material cost. To achieve the most economical matrices, the following items were considered:

- Use of minimum possible cement content without sacrificing the desired rheological properties,
- Use of secondary cementitious material to improve fresh properties and mixture economy, and
- Use of minimum dosage of the combined admixtures to produce the intended fresh properties.

The flow chart of Figure 3.1 presents the mixture proportioning methodology of self-consolidating concrete. The mixture constituents and proportions used to produce the matrices are presented in Tables 3.1a through 3.1c. Groups I, II, and III self-consolidating concretes were made with the aggregate groups R8, R67, and S7, respectively. All selected matrices were prepared with a constant water-to-cementitious materials ratio of 0.40 and a uniform cement factor of 658 lb/yd^3 (390.38 kg/m^3). The quantities of fly ash used in the matrices were 25% of cement weight for the groups I and II, and 20 % by weight of cement for the group III.



*Maximum size of aggregate not to exceed ¾ inch (20 mm)
**Water-to-cementitious materials ratio
***Start with manufacturer recommended dosage rate

Figure 3.1: Mixture proportioning methodology of self-consolidating concrete

Table 3.1a: Mixture proportion of group I self-consolidating concretes

Mix No.	Portland cement (pcy)	Fly ash (pcy)	w/cm[1]	Actual water (pcy)	Fine aggre. (pcy)	Coarse aggre. (pcy)	oz / cwt of cm[4]		Paste fraction (%)	Mortar fraction (%)	Volume of coarse aggre. (%)
							HRWRA[2]	VMA[3]			
R8.A.SF20	658.00	164.50	0.40	363.52	1274.10	1401.30	6.30	0.00	36.27	66.44	32.21
R8.B.SF20	658.00	164.50	0.40	363.90	1273.63	1400.79	3.30	0.00	36.19	66.45	32.19
R8.C.SF20	658.00	164.50	0.40	363.70	1273.83	1401.07	5.00	0.00	36.24	66.44	32.20
R8.D.SF20	658.00	164.50	0.40	363.90	1273.62	1400.79	3.30	0.00	36.19	66.45	32.19
R8.A.SF25	658.00	164.50	0.40	362.61	1275.25	1402.58	8.50	5.00	36.44	66.41	32.23
R8.B.SF25	658.00	164.50	0.40	363.46	1274.18	1401.40	5.40	1.00	36.27	66.44	32.21
R8.C.SF25	658.00	164.50	0.40	363.47	1274.17	1401.39	5.80	1.00	36.28	66.44	32.21
R8.D.SF25	658.00	164.50	0.40	363.52	1274.10	1401.31	5.30	0.90	36.26	66.44	32.21
R8.A.SF28	658.00	164.50	0.40	362.00	1276.02	1403.42	10.30	8.00	36.55	66.39	32.25
R8.B.SF28	658.00	164.50	0.40	363.34	1274.33	1401.57	6.10	1.20	36.29	66.43	32.21
R8.C.SF28	658.00	164.50	0.40	363.38	1274.28	1401.51	6.30	1.20	36.30	66.43	32.21
R8.D.SF28	658.00	164.50	0.40	363.40	1274.40	1401.48	6.10	1.00	36.28	66.43	32.21

[1] water-to-cementitious materials ratio, [2] high range water reducing admixture, [3] viscosity modifying admixture,

[4] fluid once per hundred weight of cementitious materials content

1 pcy = 0.594 kg/m^3, 1oz/cwt = 65 ml/100kg

Table 3.1b: Mixture proportion of group II self-consolidating concretes

Mix No.	Portland cement (pcy)	Fly ash (pcy)	w/cm[1]	Actual water (pcy)	Fine aggre. (pcy)	Coarse aggre. (pcy)	oz / cwt of cm[4]		Paste fraction (%)	Mortar fraction (%)	Volume of coarse aggre. (%)
							HRWRA[2]	VMA[3]			
R67.A.SF20	658.00	164.50	0.40	354.80	1412.72	1303.40	5.40	0.00	36.24	68.87	29.72
R67.A.SF25	658.00	164.50	0.40	354.46	1413.18	1303.83	7.00	1.00	36.31	68.86	29.76
R67.A.SF28	658.00	164.50	0.40	353.51	1414.51	1305.05	9.50	6.00	36.49	68.83	29.76

[1] water-to-cementitious materials ratio, [2] high range water reducing admixture, [3] viscosity modifying admixture,

[4] fluid once per hundred weight of cementitious materials content

1 pcy = 0.594 kg/m^3, 1oz/cwt = 65 ml/100kg

Table 3.1c: Mixture proportion of group III self-consolidating concretes

Mix No.	Portland cement (pcy)	Fly ash (pcy)	w/cm[1]	Actual water (pcy)	Fine aggre. (pcy)	Coarse aggre. (pcy)	oz / cwt of cm[4]		Paste fraction (%)	Mortar fraction (%)	Volume of coarse aggre. (%)
							HRWRA[2]	VMA[3]			
S7.A.SF20	658.00	131.60	0.40	332.33	1430.55	1554.56	4.30	0.00	34.60	65.62	33.04
S7.B.SF20	658.00	131.60	0.40	332.58	1430.22	1554.21	2.30	0.00	34.55	65.63	33.03
S7.C.SF20	658.00	131.60	0.40	332.44	1430.41	1554.41	3.50	0.00	34.58	65.63	33.03
S7.D.SF20	658.00	131.60	0.40	332.61	1430.18	1554.16	2.10	0.00	34.54	65.63	33.03
S7.A.SF25	658.00	131.60	0.40	332.12	1430.84	1554.88	5.00	1.00	34.63	65.62	33.05
S7.B.SF25	658.00	131.60	0.40	332.40	1430.46	1554.47	3.20	0.40	34.58	65.62	33.04
S7.C.SF25	658.00	131.60	0.40	332.33	1430.56	1554.57	4.00	0.40	34.60	65.62	33.04
S7.D.SF25	658.00	131.60	0.40	332.44	1430.41	1554.41	3.00	0.40	34.57	65.63	33.04
S7.A.SF28	658.00	131.60	0.40	331.84	1431.22	1555.29	6.60	1.60	34.69	65.61	33.05
S7.B.SF28	658.00	131.60	0.40	332.29	1430.61	1554.63	3.90	0.50	34.60	65.62	33.04
S7.C.SF28	658.00	131.60	0.40	332.22	1430.70	1554.72	4.70	0.50	34.62	65.62	33.04
S7.D.SF28	658.00	131.60	0.40	332.35	1430.53	1554.54	3.60	0.50	34.59	65.62	33.04

[1] water-to-cementitious materials ratio, [2] high range water reducing admixture, [3] viscosity modifying admixture,

[4] fluid once per hundred weight of cementitious materials content

1 pcy = 0.594 kg/m^3, 1oz/cwt = 65 ml/100kg

Particular attention was given to the coarse-to-fine aggregate ratio due to its critical role in generating sufficient amount of mortar for the selected self-consolidating concretes. The ASTM C 29[48] was used to determine the densified unit weight and the calculated void content using different ratios of the combined coarse and fine aggregates. As shown in Figures 3.2a through 3.2c, the optimum volumetric coarse-to-fine aggregate ratios of groups I, II, and III were found at 0.52/0.48 (or 1.083), 0.48/0.52 (or 0.923), and 0.52/0.48 (1.083), respectively. These ratios were subsequently utilized in the proportioning of the concrete constituents.

Four different sources (manufacturers) of polycarboxylate-based high range water reducing admixture (HRWRA), along with their viscosity modifying admixtures (VMA), were used. The optimum quantities of the chemical admixtures used in the selected self-consolidating concretes are shown in Tables 3.1a through 3.1c. They were obtained by evaluating the unconfined workability and dynamic stability of concretes using different trial batches until a satisfactory slump flow of 20 inches (508), 25 inches (635 mm), or 28 inches (711 mm); and a visual stability index of 0 or 1 were attained.

Several combinations of HRWRA and VMA were tested in order to find the minimum dosage needed to achieve the above stated fresh properties. Also reported in Tables 3.1a through 3.1c, are the paste fraction, mortar fraction, and the percentage of coarse aggregate-to-total volume of concrete. These reported fractions were all within the recommended ranges as suggested by the ACI 237[1].

3.2 Mixing procedure, testing and sampling

An electric counter-current pan mixer with a capacity of 1 ft^3 (0.028 m^3) was used to blend concrete components at a rate of 14.5 rpm. Batch volumes of 0.60 to 0.80 ft^3 (0.017 to 0.023m^3) were used for all trial mixtures. The mixing sequence consisted of blending the coarse aggregate with 1/3 of the mixing water for two minutes, followed by the fine aggregate with 1/3 of the mixing water for another two minutes, and the cementitious materials with the remaining 1/3 of the mixing water for three minutes. Finally, the HRWRA and VMA were added and blending of the matrix continued for an additional three minutes, followed by a two-minute rest and resumption of mixing for two additional minutes.

The freshly-mixed self-consolidating concretes were used to determine the

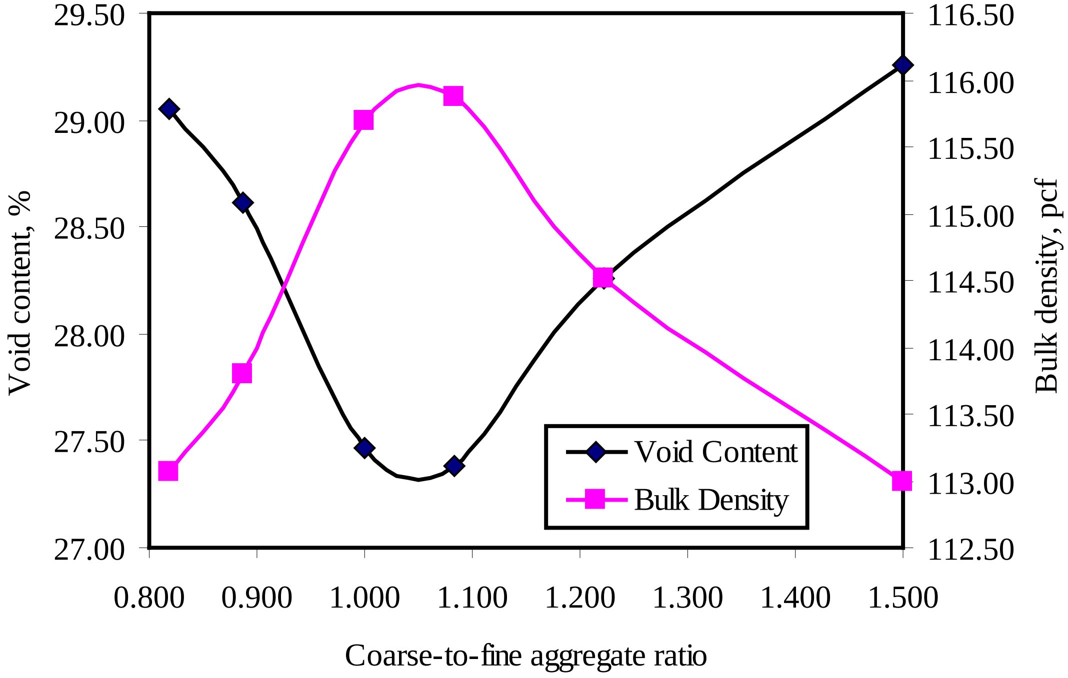


Figure 3.2a: Group I optimum volumetric coarse-to-fine aggregate ratio

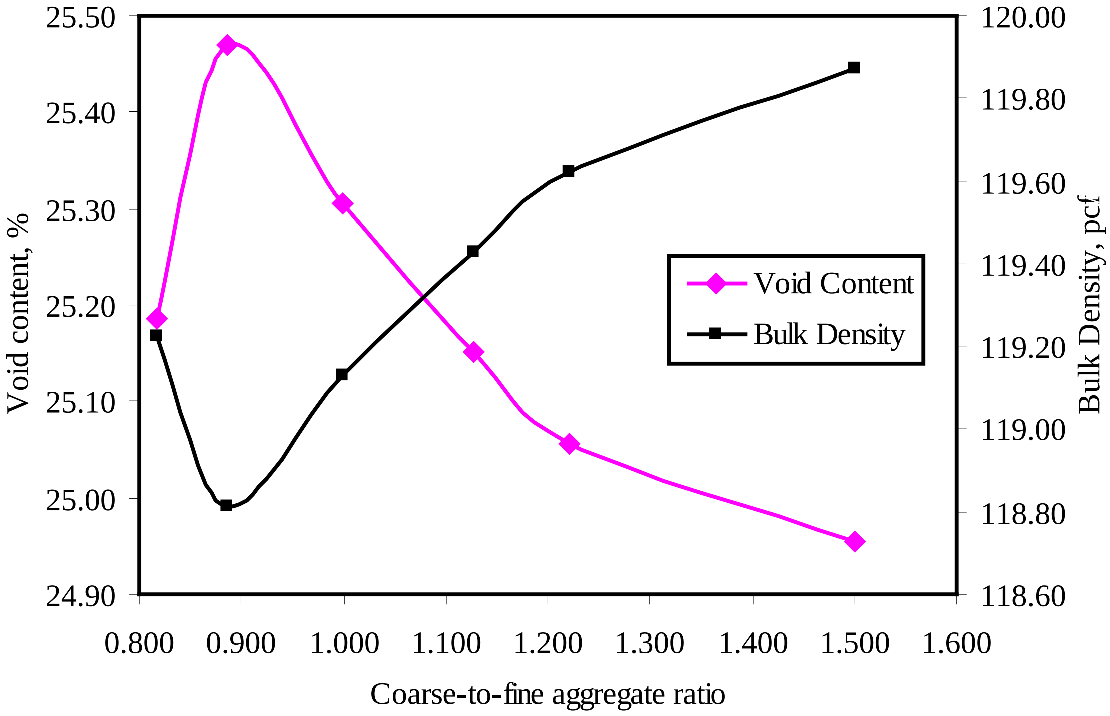


Figure 3.2b: Group II optimum volumetric coarse-to-fine aggregate ratio

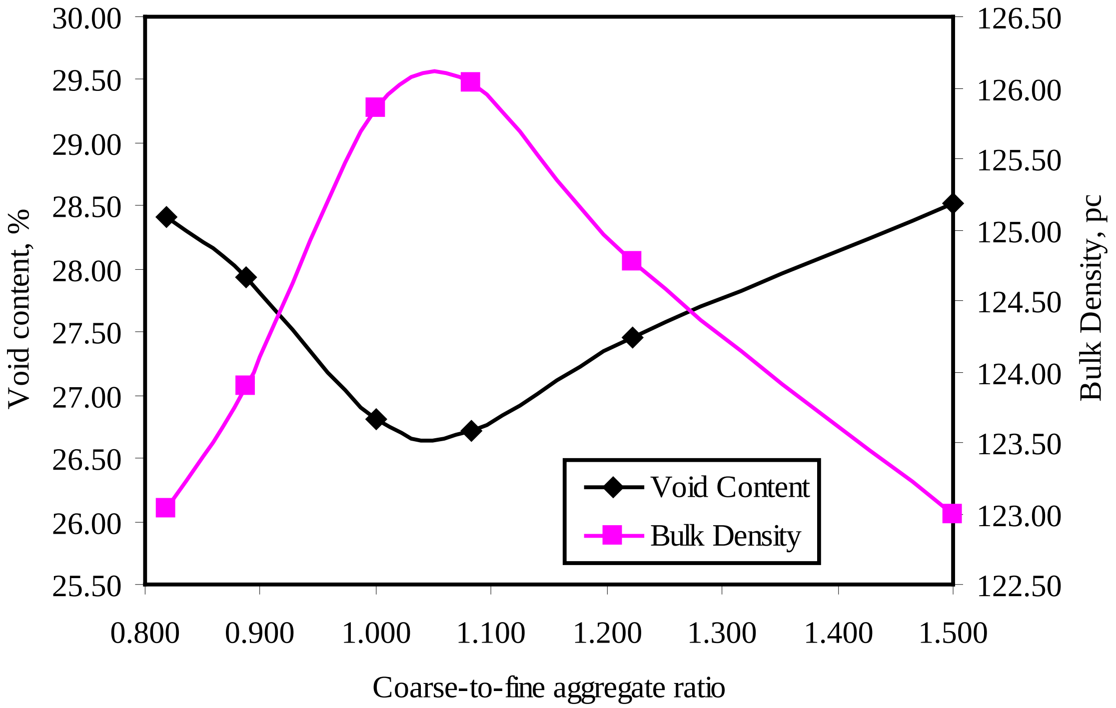


Figure 3.2c: Group III optimum volumetric coarse-to-fine aggregate ratio

unconfined workability, flow rate/plastic viscosity, passing ability, filling ability, and static and dynamic stabilities using slump flow, T_{50}, J-ring, U-box, L-box, V-funnel, visual stability index (VSI), and column segregation tests. The slump flow, T_{50}, VSI; J-ring; and column segregation tests were conducted in accordance with the ASTM C 1611[49], C 1621[50] and C 1610[51], respectively. The V-funnel, U-box, and L-box tests were performed in accordance with the recommendations of the ASTM committee C09.47[52]. The tests on the fresh concretes were conducted immediately after mixing to avoid any variations over time. When a significant discrepancy between two consecutives tests was observed, additional matrices were prepared and tested until reliable results were obtained. Each mixture was repeated at least three times, and the reported test results reflect the average value of a minimum of three tests. Figures 3.3a through 3.3g illustrate the tests performed to evaluate the fresh properties of the selected self-consolidating concretes.

Finally, the air content, bleeding, time of setting, adiabatic temperature, demolded unit-weight, compressive strength, and static modulus of elasticity were evaluated using

a) b)

Figure 3.3: a) Slump flow (unconfined workability) and Visual stability index (VSI, dynamic segregation resistance), and b) J-ring (passing ability) tests

c) d)

Figure 3.3: c) L-box (passing ability) and d) U-box (passing and filling ability) tests

e) f)

Figure 3.3: e) V-funnel (confined workability) and f) Column segregation (static segregation resistance) tests

g) h)

Figure 3.3: g) Adiabatic temperature and h) Setting time tests

ASTM C 173[53], C 232[54], C 403[55], C 1064[56], C 138[57], C 39[58], and C 469[59], respectively. Cylindrical specimens with 4 inches (102 mm) in diameter and 8 inches (204 mm) in height were cast in order to find the hardened characteristics of the self-consolidating concretes. All samples were cured in an isolated curing mold for 24 hours. Once they were removed from the molds, the test specimens were placed in a moist-curing room at 70 ± 3 ^{o}F (21 ± 2 ^{o}C) for 7, 28, and 90 days, and then tested in compression for strength and modulus of elasticity. Prior to the curing, each cylinder was weighed to determine its unit weight upon demolding.

3.3 Optimum admixture dosage

The optimum admixture dosage was defined as the minimum amount of admixture required in achieving the target unconfined workability and dynamic stability. The optimized dosage requirements of HRWRA and VMA of the selected self-consolidating concretes are presented in Tables 3.1a through 3.1c. The comparisons of the test results are shown in Figures 3.4a through 3.4c. The discussion on the optimum admixture dosage, as influenced by the admixture source and slump flow, is presented below.

3.3.1 Influence of admixture source on optimum admixture dosage

The present section, devoted to the groups I and III, is intended to discuss the influence of the four selected admixture sources on the optimum admixture dosage in attaining the target slump flow of 20 inches (508 mm), 25 inches (635 mm), and 28 inches (711 mm) and a visual stability index (VSI) of 0 or 1. The test results indicate that there are differences in the dosage requirement of HRWRA and VMA in meeting the abovementioned fresh properties.

Irrespective of the SCC group, the required dosage amount of HRWRA was highest for the source A, followed by the sources C, B, and D in descending order. The optimum dosages of sources B, C, and D superplasticizers in making 20 inches (508 mm) slump flow for the group I were lower by 48, 21, and 48%, respectively, when compared to that of source A. The corresponding reductions in optimum HRWRA dosages were 36, 32, and 38%; and 41, 39, and 41 % for the 25 and 28 inches (635 and 711 mm) slump flow of the group I, respectively.

All 20 inches (508 mm) slump flow group I self-consolidating concretes exhibited acceptable dynamic stability and plastic viscosity without any use of VMA. However, the

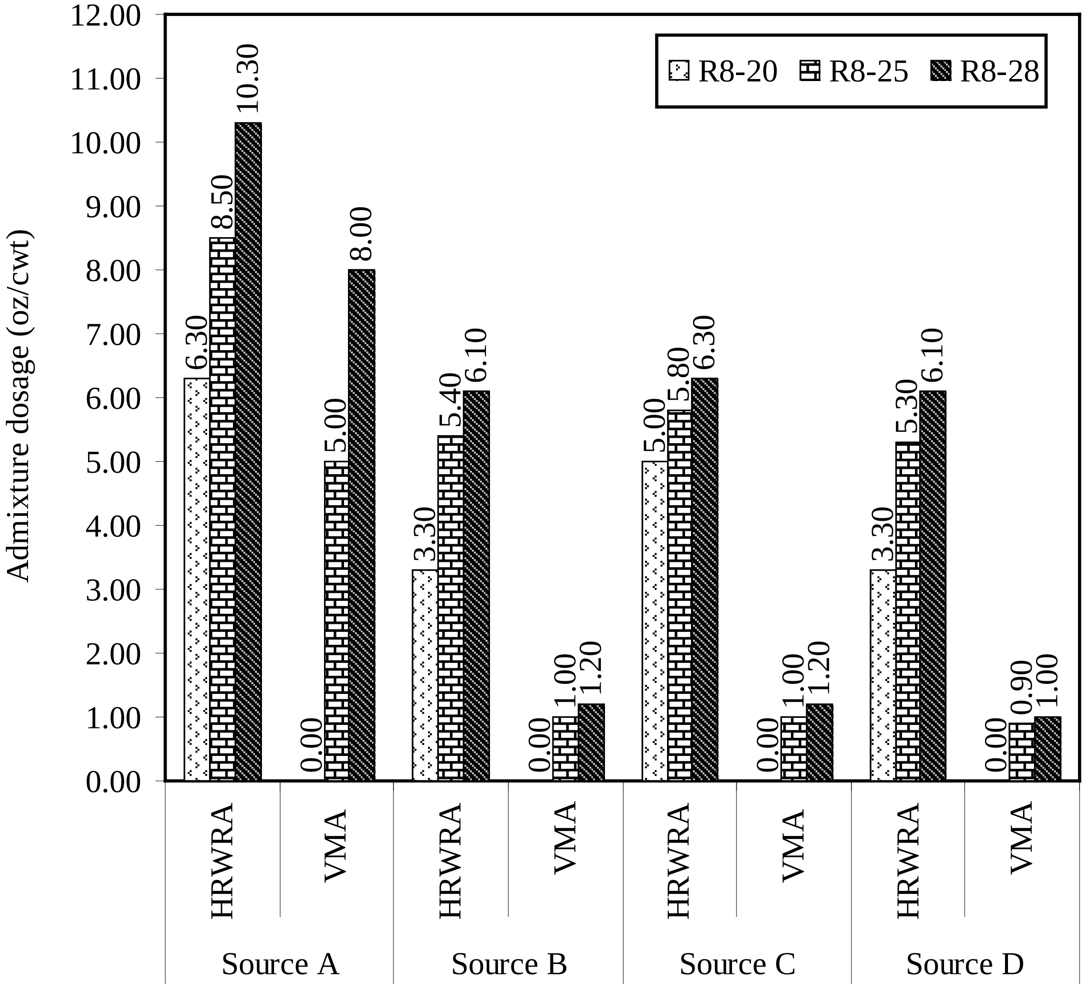


Figure 3.4a: Optimum admixture dosages for the group I self-consolidating concretes

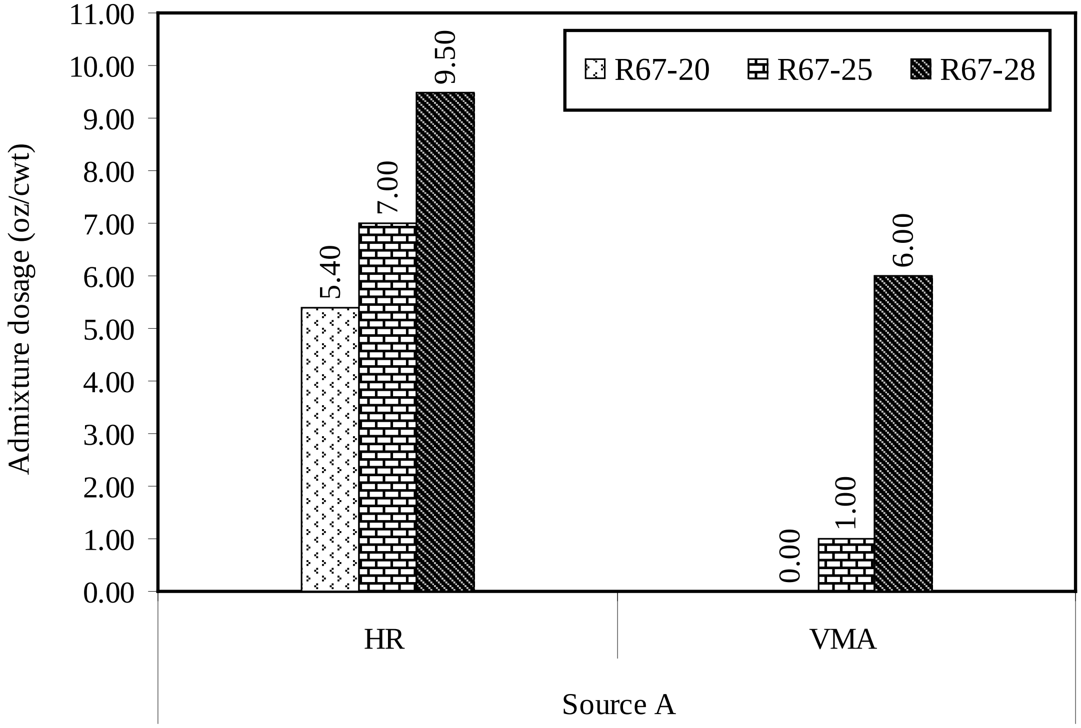


Figure 3.4b: Optimum admixture dosages for the group II self-consolidating concretes

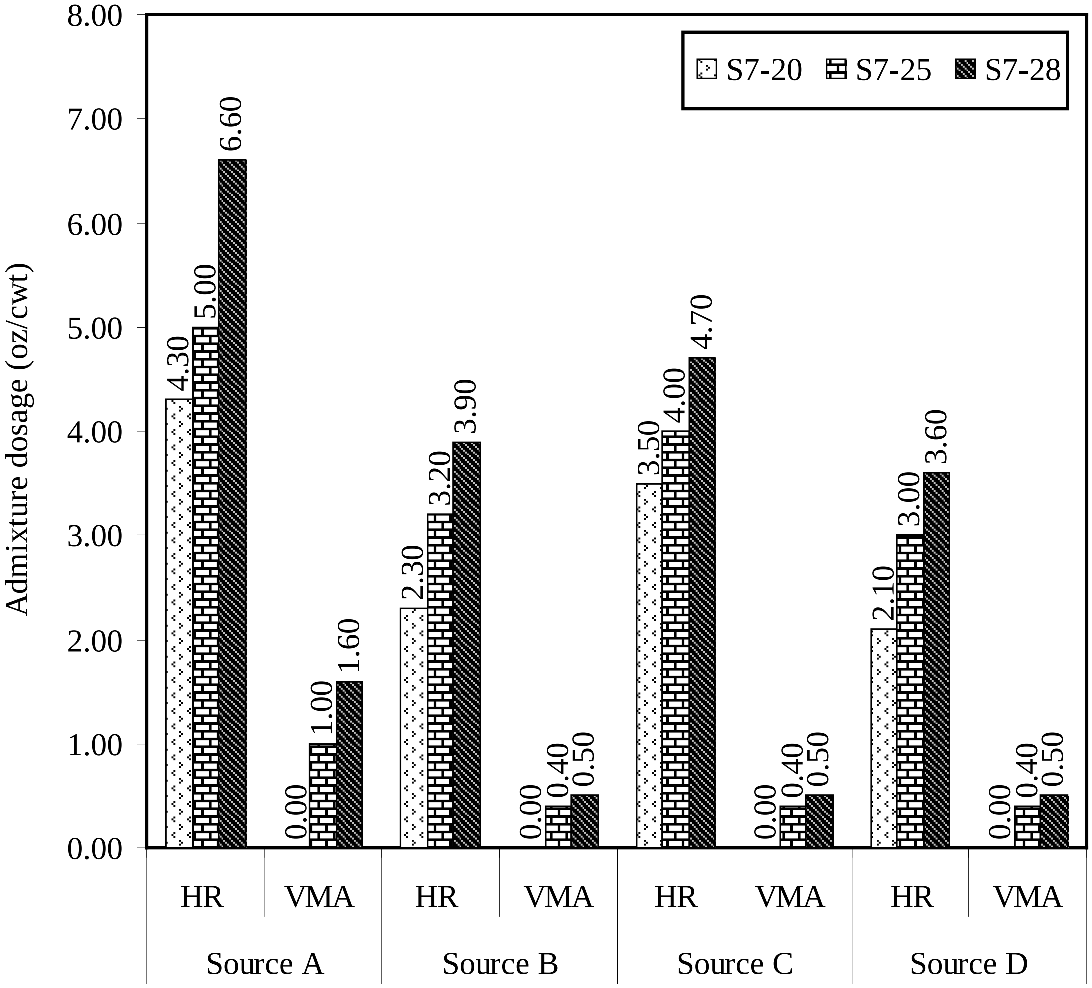


Figure 3.4c: Optimum admixture dosages for the group III self-consolidating concretes

SCCs with slump flow of 25 and 28 inches (635 and 711 mm) required a balanced amount of viscosity modifying admixture in order to obtain the required stability and viscosity. As shown in Tables 3.1a through 3.1c and Figures 3.4a through 3.4c, the optimum VMA dosage requirement was also highest for the source A but remained uniform for the sources B, C, and D. Indeed, for the self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flow, sources B, C, and D required less VMA than the source A by nearly 80, 80, and 82 %; and 85, 85, and 88%, respectively.

A similar trend in the variation of admixture dosage was also observed for the group III self-consolidating concretes. The admixtures sources B, C, and D required 47, 19, and 51 %; 36, 20, and 40 %; and 41, 29, and 45 % less amount of HRWRA than the admixture source A for the mixtures prepared with 20, 25, and 28 inches (508, 635 and 711 mm) slump flow, respectively.

When compared to the admixture source A, the reductions in VMA dosage for the sources B, C, and D were fairly uniform at about 60 and 69 % for the SCCs made with 25 and 28 inches (635 and 711 mm) slump flow, respectively. All 20 inches (508 mm) slump flow of group III self-consolidating concretes displayed acceptable dynamic stability and viscosity without the use of the plastic viscosity modifying admixture.

The information concerning the exact chemical structure and molecular weight of the HRWRA and VMA used in this investigation could not be obtained from the manufacturers. The explanation regarding the differences in optimum admixture dosages obtained during this investigation is based on the adsorption amount of HRWRA molecules in cement particles obtained from the ultraviolet-visible (UV/Vis) spectroscopy test, the information on the chemical type of the admixtures acquired from the Manufacturers Product Data (MPD) and Material Safety Data Sheet (MSDS) (see Tables 2.3 through 2.5), the related literature as summarized in Section 1.2.3, and the VMA-to-HRWRA ratios.

3.3.1.1 Adsorption of admixture on cement particles

This section is intended to explain and confirm the test results related to the trend of the optimum dosages requirement of the selected polycarboxylate-based HRWRAs (PC-HRWRA). As alluded to earlier in Task 1, the mechanism of action of superplasticizer in Portland cement solution involves adsorption, electrostatic repulsion, and steric hindrance repulsion. The PC-HRWRA carboxyl group (COO^-) has to be adsorbed first to the cement calcium ions (Ca^{2+}) before being able to play a dispersing role. The UV/Vis test was used to evaluate the concentration of free admixture in the cement-water-HRWRA solution before a correlation with admixture adsorption was made. The relationship between the increase in concentration of free admixture and the increase in adsorption amount was established through the effect of slump flow on admixture dosage. As can be seen in Section 3.3.2, the higher slump flow required a higher dosage of admixture (see Tables 3.1a through 3.1c).

The UV/Vis spectroscopy absorption is not a specific test for any given compound. The nature of the solvent, the pH of the solution, temperature, high electrolyte concentrations, and the presence of interfering substances can influence the absorption spectra of compounds, as can variations in effective bandwidth in the spectrophotometer[60]. However, the wavelengths of absorption peaks can be correlated with the types of bonds in a given molecule and are valuable in determining the functional groups within a molecule[60].

The UV/Vis experiment uses a test sample in the UV/Vis beam to determine the absorbance or transmittance at different wavelengths. Alternatively, samples are prepared in known concentrations and their absorbance determined by the UV/Vis spectrophotometer. Results are then graphed to make a calibration curve from which the unknown concentration can be determined by its absorbance.

In the present investigation, a uniform cement factor of 658 lb/yd^3 (390.38 kg/m^3) and a constant water-to-cementitious materials ratio of 0.4 were used for all trial matrices. The dosage of HRWRA was kept constant at 3.9 oz/cwt (255 ml/100 kg) for all four admixture sources, and distilled water was used throughout the study to avoid any contamination which could impair the test results. The test was performed as follows:

- First, the calibration curves for interpolation were generated. For that purpose, the selected polycarboxylate-based HRWRA were manually diluted in distilled water at different concentrations. After 10 minutes, the solutions were analyzed by the UV/Vis spectroscopy, and calibration curves of known HRWRA concentrations as a function of the recorded absorbance were plotted. Figures 3.5a through 3.5d present the calibration curves for the selected admixture sources. The test results indicated a very strong relationship between the concentration of HRWRA in water and the recorded absorbance, as indicated by the coefficient of multiple determinations (R^2).

- Second, the UV/Vis absorption curves for the cement-water-HRWRA solution were made. The cement and water were first mixed in a pan mixer at 14.5 rpm for 5 minutes before the pre-measured HRWRA was added and afterward the mixing continued for an additional 5 minutes. The blended paste was placed in sterilized tubes and centrifuged by ultracentrifugation for 5 minutes at 3500 rpm in order to suspend fine particles in solution. The liquid at the top of the sample was collected with a pipette and transferred into a syringe mounted on a 0.20 μm filter. The filtered liquid was then tested by the UV/Vis spectroscopy. Figure 3.6 shows typical ultraviolet absorption spectra and Figure 3.7 displays the UV/Vis absorption spectra of the four selected admixture sources.

The test results indicated that the recorded absorbance peaks varied from one admixture to another as they occurred at different wavelengths (from 230 to 265 nm), indicating their differences in chemical type. The test results were also used to determine the actual concentration of free admixture in the liquid phase of cement-water-HRWRA. The calculated concentrations of the selected admixture sources are summarized in Table 3.2. It can be seen that the solution concentration of free admixture was highest for the source D, followed by the sources B, C, and A in descending order. This test results also confirms the earlier findings for the optimum dosage requirement of the four selected admixture sources as reported in Section 3.3.1.

3.3.1.2 Chemical type of the selected HRWRA and VMA

The difference in the selected superplasticizers dosages requirement in attaining a uniform unconfined workability, flow rate/plastic viscosity, and dynamic stability can also be explained through their chemical types. In order to support this theory, a brief review on the chemical structure of the selected admixtures and their mode of functioning is necessary.

Figure 1.9, in Task 1, is a typical representation of the chemical structure of a copolymer of acrylic acid and acrylic ester. The characteristic of a PC-type superplasticizer can be modified by varying the acid-to-ester ratio (modules n and m). The higher the acid ratio is, the higher is the carboxylic group content, and the higher is the adsorption ability. On the other hand, when the ester ratio is predominant, the side

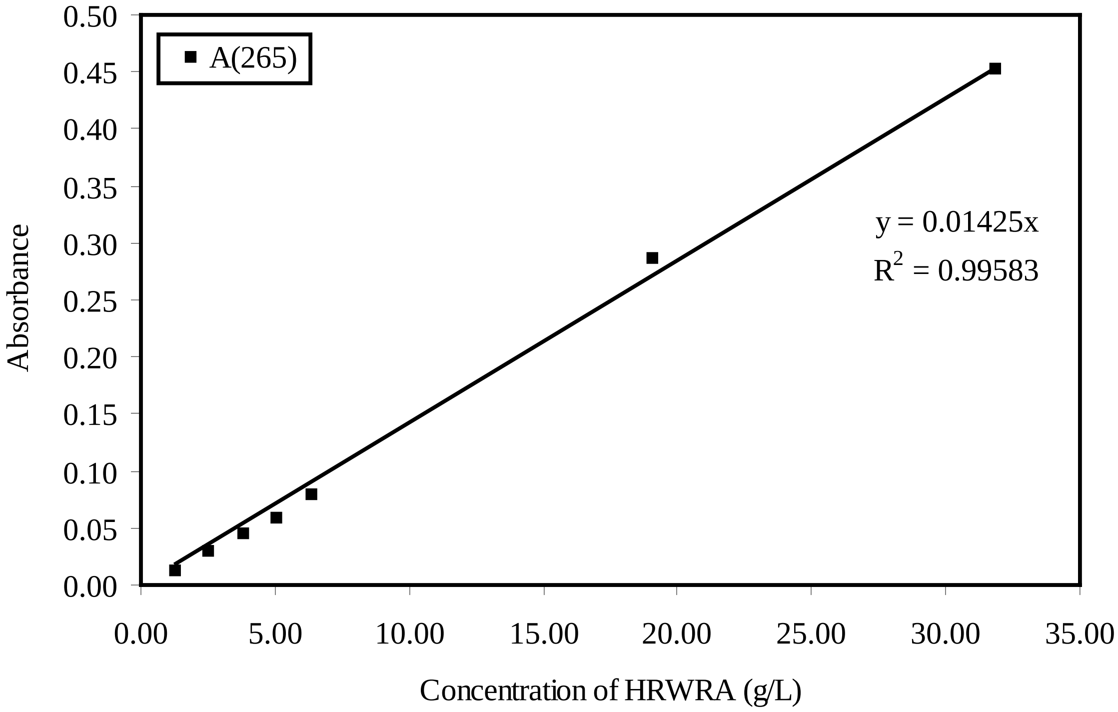


Figure 3.5a: Calibration curve of source A HRWRA at wavelength of 265 nm

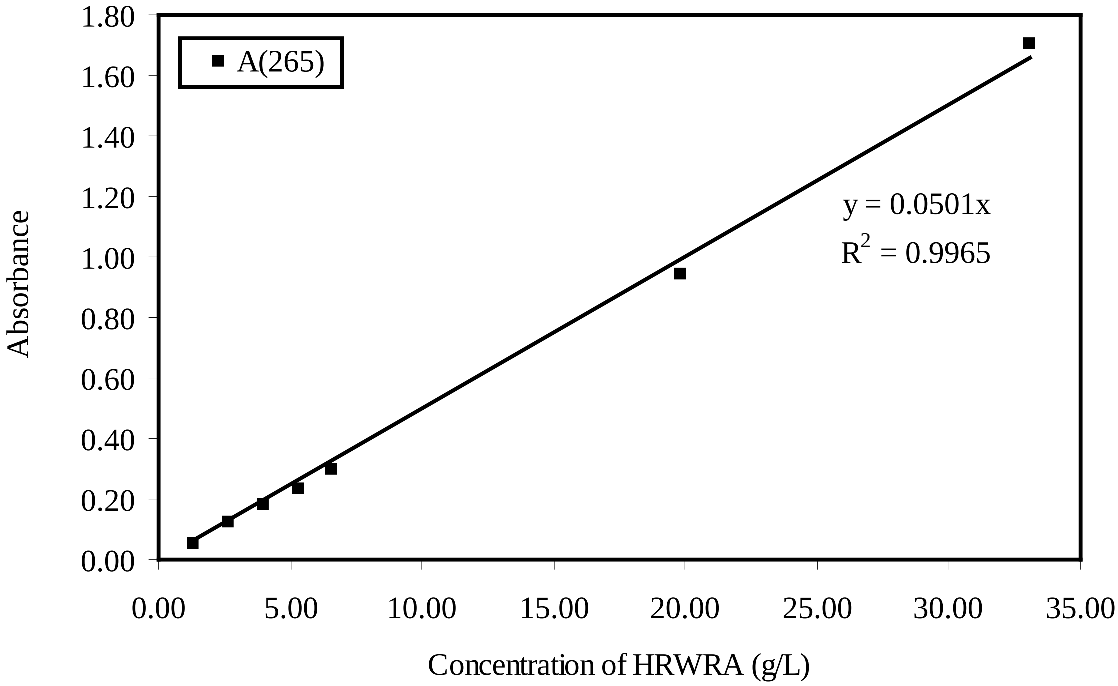


Figure 3.5b: Calibration curve of source B HRWRA at wavelength of 265 nm

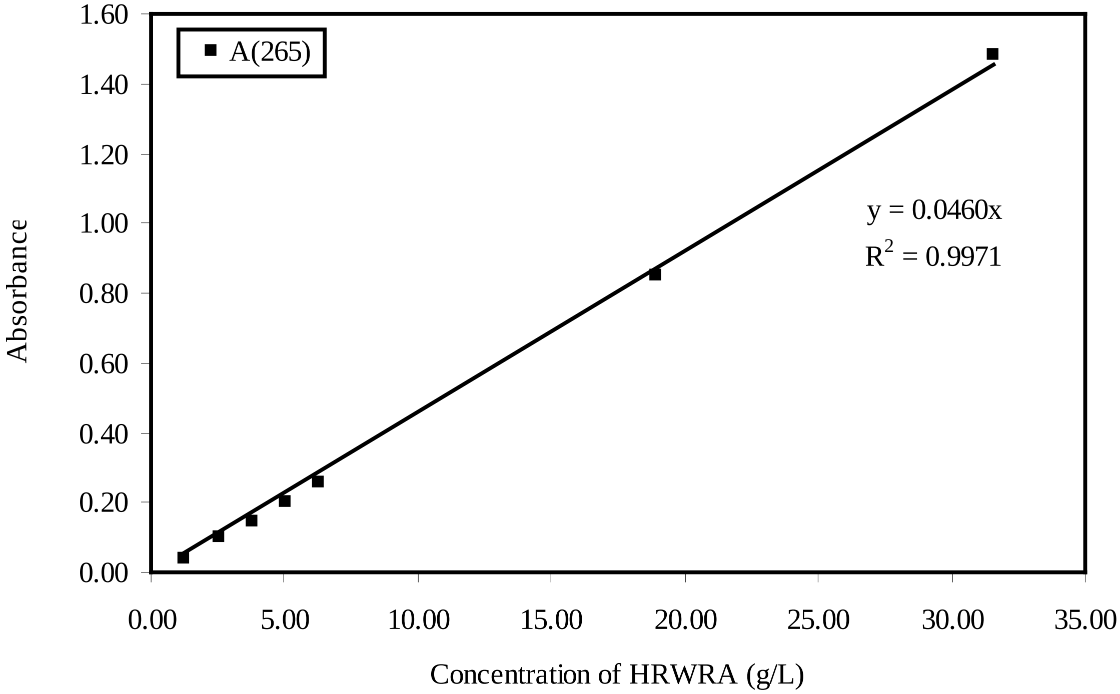


Figure 3.5c: Calibration curve of source C HRWRA at wavelength of 265 nm

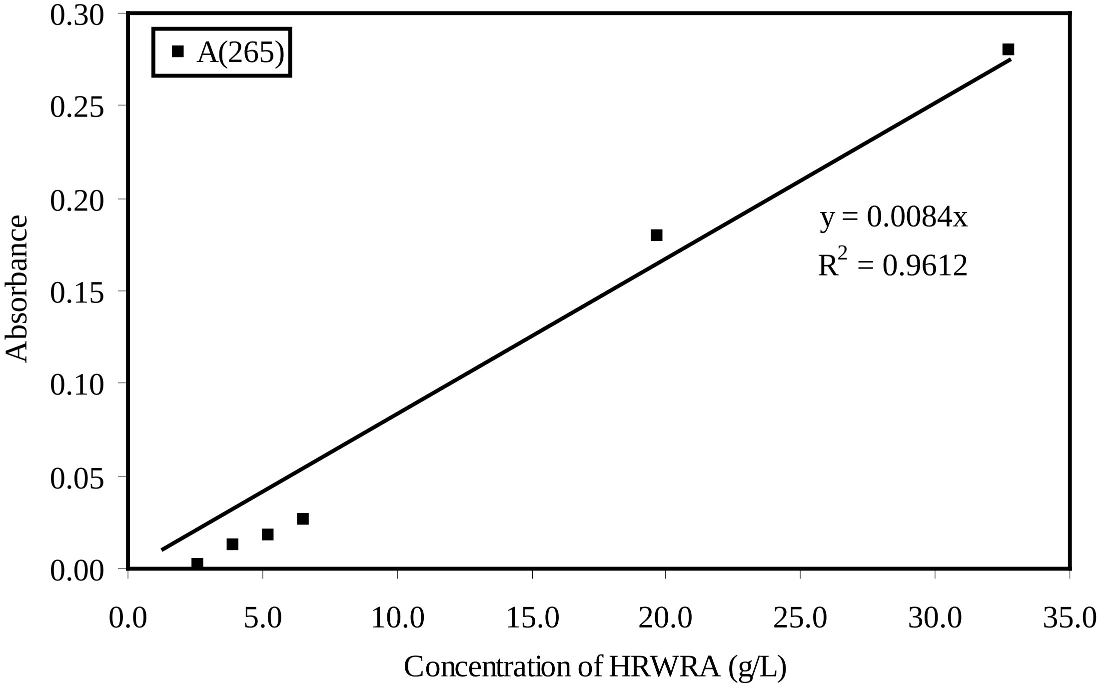


Figure 3.5d: Calibration curve of source D HRWRA at wavelength of 265 nm

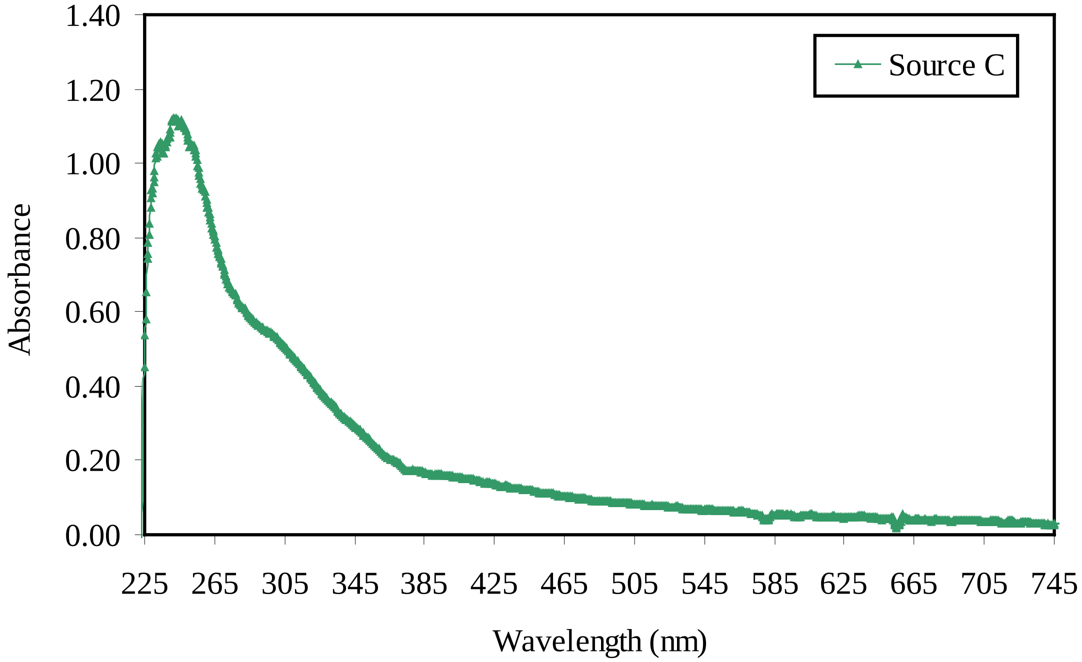


Figure 3.6: Typical ultraviolet-visible absorbance spectrum:
Case of source C HRWRA

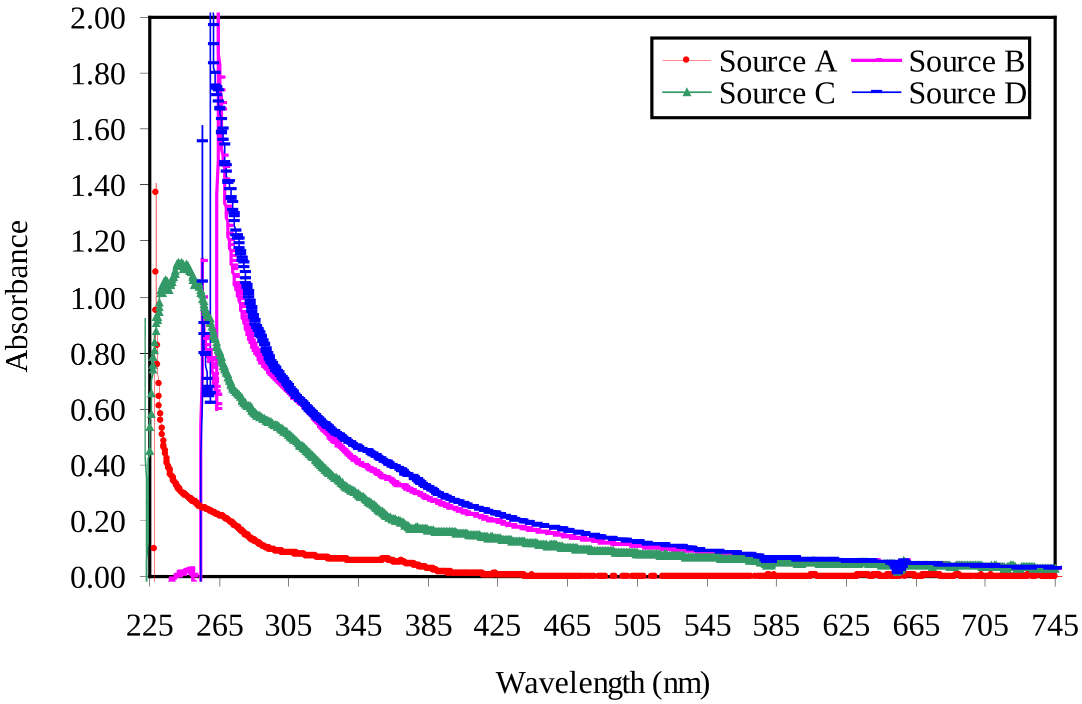


Figure 3.7: Comparison of ultraviolet-visible absorbance spectra
of sources A, B, C, and D HRWRAs

Table 3.2: Cement-water solution's concentration of free HRWRA

Designation	*Absorbance (λ, nm)			Increase in HRWRA concentration (g/L)
	A(265)	A(700)	A(265 corr)	
Source A	1.039	0.013	1.026	15.43
Source B	2.558	0.051	2.507	33.96
Source C	1.624	0.054	1.570	16.61
Source D	2.495	0.052	2.443	194.90

*Absorbance at wavelength λ, in nanometer

chains content increases and the carboxylic group content decreases, leading to a decrease in adsorption and dispersibility. Despite their relatively high dosage rate, the advantage of a high ester-to-acid ratio superplasticizer resides in its superior slump flow retention[31]. In fact, during the initial cement-polycarboxylate ester superplasticizer (PCE) interaction the polymers which could not react immediately are adsorbed gradually to cement particles as time elapsed, resulting in better flow retention.

All four superplasticizers were acrylic polymers-based and had the same mechanism of action, namely: adsorption, electrostatic repulsion, and steric repulsion. In general, the test results showed that the difference between the optimum HRWRA dosages requirement of the sources B, C, and D in attaining the required fresh performance was marginal; indicating that they might had a similar chemical structure. On the other hand, source A produced results that were different than those of the sources B, C, and D. The behavior of the sources B, C, and D superplasticizers was similar to that of a polycarboxylate-acid type (PCA), where the acid portion is predominant when compared to ester part. Source A had the highest ester-to-acid ratio and was polycarboxylate-ester type (PCE).

The difference in viscosity modifying admixture optimum dosage among the four sources can be attributed to the mechanism by which these admixtures function. Based on the reported results obtained during this study, the source A required a higher optimum VMA dosage than those of the sources B, C, and D. The source A viscosity modifying admixture functioned by thickening the concrete, making it very cohesive without significantly affecting the fluidity of the fresh matrix. The sources B, C, and D performed by binding the water within the concrete mixture resulting in an increase in viscosity while reducing or eliminating concrete bleeding. The present investigation revealed that a large amount of the source A VMA was always needed to modify the viscosity of the SCC, while a small amount of the VMA belonging to the sources B, C, and D generated a noticeable improvement in the fresh performance of the selected self-consolidating concretes.

3.3.1.3 VMA-to-HRWRA ratio

The minimum dosage required to achieve the stated fresh properties was obtained by trial and error combinations of HRWRA and VMA. The analysis of the test results obtained during this study indicated a trend for the VMA-to-HRWRA ratio, as it can be seen in Table 3.3. The similarity in the VMA-to-HRWRA ratios of the admixture sources B, C and D further affirms that these sources have a similar chemical composition. The higher ratio seen in the source A was due to its thickening mode of functioning which led to a higher amount of VMA required to make highly stable or stable matrices. It can also be noted that the VMA-to-HRWRA ratio decreased for the self-consolidating concrete made with a coarser aggregate due to its matrix incorporating a smaller volume of paste (see Tables 3.1a through 3.1c).

Table 3.3: VMA-to-HRWRA dosage ratios

Admixture sources	Group I SCC		Group III SCC	
	Slump flow 635 mm	Slump flow 711 mm	Slump flow 635 mm	Slump flow 711 mm
A	0.59	0.78	0.20	0.24
B	0.19	0.20	0.13	0.13
C	0.17	0.19	0.10	0.11
D	0.17	0.16	0.13	0.14

1 mm = 0.03937 inch

3.3.2 Influence of slump flow on optimum admixture dosage

As shown in Tables 3.1a through 3.1c and Figures 3.4a through 3.4c, the admixture dosages increased with an increase in slump flow, regardless of the admixture sources and the selected SCC groups.

For the group I self-consolidating concretes, as the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the optimum amount of HRWRA increased by 35 and 21%; 64 and 13%; 16 and 9%; and 61 and 15% for the admixture sources A, B, C, and D, respectively. When the slump flow increased from 25 to 28 inches (635 to 711 mm), the increases in the optimum VMA dosages became 60, 20, 20, and 11% for the admixture sources A, B, C, and D, respectively. The acceptable plastic viscosity and dynamic stability were achieved for the self-consolidating concretes prepared with 20 inches (508 mm) slump flow without the use of the viscosity modifier.

The group II self-consolidating concretes also showed an increase in the optimum admixture dosage when a higher slump flow was required. The HRWRA optimum dosage requirement for the group II self-consolidating concretes increased by 30 and 36% when the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), respectively. The VMA optimum dosage increased by nearly 500% when the slump flow changed from 25 to 28 inches (635 to 711 mm). Once again, the group II SCC prepared with 20 inches (508 mm) slump flow did not require any VMA to produce the target stability and plastic viscosity.

The trend in the optimum dosage requirement for the group III self-consolidating concretes was similar to that of the group I. For the slump flow increases from 20 to 25 to 28 inches (508 to 635 to 711 mm), the HRWRA optimum dosage for the admixture sources A, B, C, and D increased by 16 and 32 %; 39 and 22 %; 14 and 18 %; and 43 and 20 %; respectively. The increases in the VMA dosage remained at 60% for the admixture source A, and 25% for the admixture sources B, C, and D when the slump flow changed from 25 to 28 inches (635 to 711 mm). No VMA was needed for the group III self-consolidating concretes made with 20 inches (508 mm) slump flow.

The increase in optimum dosage requirement of HRWRA and VMA in obtaining a higher slump flow can be explained through the demand in the rheological performance of the concrete. During the deflocculation system, the bond between the finer cement particles was gradually broken by the mixing water until a uniform matrix (normal slump concrete) was generated. From that moment, a superplasticizer was needed to produce a flowable matrix. The need for a higher slump flow required an increase in the amount of HRWRA. In the presence of higher amount of HRWRA, the force needed to disperse the ingredients of the fresh matrix, i.e., the yield stress, was gradually reduced as the fresh concrete was allowed to spread further. In fact, when the amount of superplasticizer was increased, the adsorbed amount of polymer molecules in cement particles increased along with the induced zeta potential (the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed particle) leading to higher electrostatic repulsion forces. Additionally; the intensity of the steric repulsive forces (which were short-range repulsive forces caused by the overlapping of the adsorbed polymer) was also increased when a higher HRWRA dosage was used. It should be noted that the superplasticizer adsorption can show an adsorption plateau, which is also called the point of saturation. The adsorption plateau roughly corresponds to the amount of superplasticizer which allows for the optimum fluidity.

The increase in slump flow value or HRWRA dosage was usually accompanied by a decrease in plastic viscosity, and a viscosity modifying admixture was needed to overcome that problem. The addition of a VMA restored the plastic viscosity deteriorated by the increase in HRWRA.

3.3.3 Predictive statistical equations of the SCC admixture dosage

As it can be seen in Tables 3.1a through 3.1c, the selected 27 trial matrices have different proportions of paste volume ratio (P), mortar volume ratio (M) and coarse aggregate absolute volume (C_{Aggr}). The matrix factor $\beta = P \cdot M \cdot C_{Aggr}$ was used to characterize each trial matrix. The equations to predict the optimum admixture dosage requirement were determined using a statistical program[61]. Analyses were conducted at a 95% confidence level. The predictive equations were tested for accuracy using R^2 (the coefficient of multiple determination) and S (average standard deviation). Correlations between the data predicted from the regression equations and the actual test results were evaluated using F and T tests. Due to the difference in their mechanism of action, admixture source A in one hand, and admixture sources B, C, and D in other hand, were analyzed separately. The HRWRA and the VMA optimum dosages were related to the target slump flow (SF) and the matrix factor (β) through the following equations:

Admixture source A

$$HR_A = -39.43398 - \frac{1555.70460}{SF} + \frac{15975.14124}{SF^2} + 1082.324465\beta \qquad (3.1)$$

$$VMA_A = 13737.43542 + 0.34880SF - \frac{2096.88352}{\beta} + \frac{79.95360}{\beta^2} \qquad (3.2)$$

Admixture sources B, C, and D

$$HR_{B,C,D} = 1157230.04 + 4.77545x10^{-2}SF - \frac{264871.91}{\beta} + \frac{20206.77}{\beta^2} - \frac{513.81}{\beta^3} \qquad (3.3)$$

$$VMA_B = 1106.64427 + \frac{1176.27059}{SF} - 29782.34133\beta - \frac{2759.00576}{SF^2}$$

$$199803.43644\beta^2 - 13019.67234\frac{\beta}{SF} \qquad (3.4)$$

Where:

HR_A, $HR_{B,C,D}$ = optimum dosage requirement of high range water reducing admixture in attaining the target fresh performance, (oz/cwt)

VMA_A, $VMA_{B,C,D}$ = optimum dosage requirement of viscosity modifying admixture in attaining the target fresh performance, (oz/cwt)

SF = expected slump flow (inch), with 20 inches ≤ SF ≤ 28 inches

$\beta = P \cdot M \cdot C_{Aggr}$ *(%),*

Where:

P = Paste volume ratio

M = Mortar volume ratio

C_{Aggr} = Coarse aggregate absolute volume

N.B.: The paste and mortar used in β do not include the admixtures.

The regression variables R^2, S, Prob(t) and Prob(F) are given in Table 3.4. The calculated values are indicative of a strong relationship between the dependent variable (high range water reducing admixture (HR) or viscosity modifying admixture (VMA)) and the independent variables (slump flow value, paste volume ratio, mortar volume ratio, and coarse aggregate absolute volume).

3.4 Fresh characteristics

The results for the fresh characteristics of the selected self-consolidating concretes are shown in Tables 3.5a through 3.5c. The discussion on the fresh performance of the

Table 3.4: Statistical regression variables

Equations	Description	Coefficient of multiple determination R^2, %	Standard deviation S, oz/cwt	Prob (t)	Prob (F)
3.1	Optimum dosage of the source A HRWRA	98.10	0.4775	< 0.2148	0.0027
3.2	Optimum dosage of the source A VMA	99.60	0.3125	< 0.0112	0.0056
3.3	Optimum dosage of the sources B, C, and D HRWRA	92.70	0.4151	< 0.0028	0.0000
3.4	Optimum dosage of the sources B, C, and D VMA	98.90	0.0549	< 0.1796	0.0000

Table 3.5a: Fresh properties of group I self-consolidating concretes

Mix No.	Slump Flow (in.)	T_{50} (sec.)	VSI	J Ring Value (in.)	SI (%)	L box H_2/H_1			U-Box H_1-H_2 (in.)	V-Funnel (sec.)
						H_2/H_1	T_{20} (sec.)	T_{40} (sec.)		
R8.A.SF20	20.50	2.63	0	1.68	3.47	0.57	0.68	1.56	5.75	4.86
R8.B.SF20	20.25	2.97	0	1.63	2.90	0.60	0.71	1.60	6.00	5.55
R8.C.SF20	20.38	3.09	0	1.65	2.98	0.60	0.70	1.61	6.08	5.75
R8.D.SF20	20.63	2.67	0	1.63	3.55	0.63	0.67	1.65	5.78	4.75
R8.A.SF25	25.38	2.20	0	1.55	5.65	0.86	0.57	1.48	5.20	4.55
R8.B.SF25	25.25	2.47	0	1.50	4.52	0.84	0.70	1.46	5.60	5.15
R8.C.SF25	25.25	2.52	0	1.53	4.62	0.84	0.62	1.47	5.68	5.38
R8.D.SF25	25.25	2.28	0	1.50	5.75	0.85	0.64	1.47	5.25	4.50
R8.A.SF28	28.63	1.82	1	1.38	6.37	0.92	0.53	1.38	4.30	4.27
R8.B.SF28	28.88	2.14	1	1.30	4.95	0.90	0.68	1.35	4.71	4.63
R8.C.SF28	28.50	2.11	1	1.35	5.11	0.86	0.53	1.39	4.88	4.75
R8.D.SF28	28.50	1.92	1	1.35	6.49	0.87	0.58	1.37	4.38	4.25

1 in. = 25.4 mm

Table 3.5a: Fresh properties of group I self-consolidating concretes (continued)

Mix No.	Air content (%)	Bleeding (%)	Times of Setting (hrs.)		Adiabatic temperature				
			Initial	Final	Initial temp. of fresh SCC (^oF)	Temp. difference: Initial to dormant (^oF)	Temp. difference: Initial to peak (^oF)	Elapsed time to dormant (hrs.)	Elapsed time to peak (hrs.)
R8.A.SF20	1.20	4.34	5.50	7.00	70.16	-2.02	2.11	3.39	11.74
R8.B.SF20	2.10	3.76	5.33	6.75	70.97	-2.12	2.29	3.14	11.48
R8.C.SF20	1.25	3.96	5.28	6.70	71.51	-2.27	2.41	3.03	11.37
R8.D.SF20	1.75	4.09	5.75	7.03	70.65	-2.07	2.16	3.29	11.58
R8.A.SF25	0.80	4.31	5.85	7.53	71.15	-2.11	2.23	3.75	12.26
R8.B.SF25	2.00	3.84	5.50	7.17	72.23	-2.30	2.43	3.49	11.98
R8.C.SF25	1.10	4.05	5.42	7.07	73.02	-2.45	2.57	3.36	11.86
R8.D.SF25	1.50	4.19	5.92	7.53	72.05	-2.25	2.39	3.64	12.11
R8.A.SF28	0.80	4.59	6.45	8.03	71.87	-2.29	2.43	4.17	12.88
R8.B.SF28	1.20	3.96	5.75	7.73	72.95	-2.41	2.61	3.88	12.58
R8.C.SF28	0.80	4.17	5.63	7.75	73.74	-2.59	2.72	3.77	12.45
R8.D.SF28	1.20	4.24	6.13	8.17	72.77	-2.34	2.57	4.08	12.74

1 $^oF = 9/5\ ^oC + 32$

Table 3.5b: Fresh properties of group II self-consolidating concretes

Mix No.	Slump Flow (in.)	T_{50} (sec.)	VSI	J Ring Value (in.)	SI (%)	L box H_2/H_1			U-Box H_1-H_2 (in.)	V-Funnel (sec.)
						H_2/H_1	T_{20} (sec.)	T_{40} (sec.)		
R67.A.SF20	20.38	2.23	0	1.75	11.11	0.60	0.46	1.30	4.88	3.42
R67.A.SF25	25.25	1.87	0	1.58	11.66	0.84	0.42	1.09	2.25	3.18
R67.A.SF28	28.13	1.56	1	1.25	13.61	0.94	0.37	0.95	1.50	2.87

1 in. = 25.4 mm

Table 3.5b: Fresh properties of group II self-consolidating concretes (continued)

Mix No.	Air content (%)	Bleeding (%)	Times of Setting (hrs.)		Adiabatic temperature				
			Initial	Final	Initial temp. of fresh SCC (^oF)	Temp. difference: Initial to dormant (^oF)	Temp. difference: Initial to peak (^oF)	Elapsed time to dormant (hrs.)	Elapsed time to peak (hrs.)
R67.A.SF20	1.75	1.95	5.75	7.35	70.45	-2.32	2.43	2.96	11.32
R67.A.SF25	1.60	2.05	6.05	7.75	71.33	-2.41	2.65	3.25	11.98
R67.A.SF28	1.50	2.19	6.75	8.50	71.85	-2.52	2.70	3.53	12.64

1 $^oF = 9/5\ ^oC + 32$

Table 3.5c: Fresh properties of group III self-consolidating concretes

Mix No.	Slump Flow (in.)	T_{50} (sec.)	VSI	J Ring Value (in.)	SI (%)	L box H_2/H_1			U-Box H_1-H_2 (in.)	V-Funnel (sec.)
						H_2/H_1	T_{20} (sec.)	T_{40} (sec.)		
S7.A.SF20	20.75	2.69	0	1.73	6.37	0.65	0.55	1.62	8.88	4.82
S7.B.SF20	20.63	3.19	0	1.68	4.83	0.63	0.71	2.45	9.63	5.12
S7.C.SF20	20.63	3.15	0	1.80	5.07	0.65	0.67	1.82	9.75	5.17
S7.D.SF20	20.13	2.82	0	1.75	7.15	0.70	0.63	1.79	9.54	4.90
S7.A.SF25	25.63	2.48	0	1.45	8.12	0.84	0.52	1.61	8.50	4.35
S7.B.SF25	25.63	2.79	0	1.53	5.72	0.83	0.70	1.97	9.13	4.55
S7.C.SF25	25.63	2.69	0	1.48	5.64	0.83	0.59	1.74	9.12	4.65
S7.D.SF25	25.58	2.04	0	1.50	9.57	0.86	0.58	1.70	9.25	4.40
S7.A.SF28	28.63	1.85	1	1.25	9.11	0.88	0.48	1.48	7.25	4.07
S7.B.SF28	28.50	2.16	1	1.33	8.03	0.90	0.52	1.83	8.75	4.13
S7.C.SF28	28.38	2.15	1	1.28	8.17	0.86	0.56	1.64	8.88	4.22
S7.D.SF28	28.63	1.88	1	1.28	10.56	0.88	0.52	1.60	8.38	4.07

1 in. = 25.4 mm

Table 3.5c: Fresh properties of group III self-consolidating concretes (continued)

Mix No.	Air content (%)	Bleeding (%)	Times of Setting (hrs.)		Adiabatic temperature				
			Initial	Final	Initial temp. of fresh SCC (^{o}F)	Temp. difference: Initial to dormant (^{o}F)	Temp. difference: Initial to peak (^{o}F)	Elapsed time to dormant (hrs.)	Elapsed time to peak (hrs.)
S7.A.SF20	1.50	3.01	5.12	6.83	71.31	-2.02	2.25	3.17	11.17
S7.B.SF20	2.20	2.55	4.63	6.13	72.64	-2.27	2.50	2.97	10.85
S7.C.SF20	1.25	2.69	4.60	6.15	73.35	-2.54	2.66	2.85	10.73
S7.D.SF20	1.75	2.88	4.95	6.25	72.30	-2.21	2.27	3.02	11.01
S7.A.SF25	1.25	3.18	5.58	7.28	71.96	-2.07	2.41	3.45	11.70
S7.B.SF25	1.50	2.62	5.10	6.65	73.08	-2.34	2.75	3.23	11.37
S7.C.SF25	1.10	2.73	5.07	6.55	74.10	-2.59	2.81	3.10	11.20
S7.D.SF25	1.50	3.04	5.38	6.75	72.28	-2.32	2.52	3.30	11.57
S7.A.SF28	1.00	3.23	6.02	7.75	74.12	-2.18	2.61	3.66	12.49
S7.B.SF28	1.00	2.73	5.48	7.02	75.49	-2.47	2.92	3.45	12.17
S7.C.SF28	0.90	2.81	5.45	6.95	76.05	-2.66	3.08	3.33	12.00
S7.D.SF28	1.20	3.13	5.92	7.42	74.93	-2.43	2.79	3.50	12.34

1 ^{o}F = 9/5 ^{o}C + 32

selected self-consolidating concretes as related to their flow ability, viscosity, stability, passing ability, and filling ability is presented below.

3.4.1 Slump flow

The slump flow test as a measure of the unconfined workability was carried out using a traditional slump cone, by which the horizontal spread of the fresh concrete was measured. The test result is a mean value of the concrete spread determined from the measurements of diameters of the spread concrete at two perpendicular directions. It can be seen from the Tables 3.5a through 3.5c that all selected self-consolidating concretes were within the target uniform slump flow of 20 ± 1 inches (508 ± 25 mm), 25 ± 1 inches (635 ± 25 mm), or 28 ± 1 inches (711 ± 25 mm).

3.4.2 Flow ability/Viscosity

Slump flow values were used to describe the flow ability of the fresh concrete in an unconfined condition and the slump flow (SF) test is the preferred test method for flow ability. The flow ability of a given fresh SCC is related to its viscosity. The flow times of T_{20}, T_{40}, and T_{50} and V-funnel flow time (t_v) can be used to measure both the flow ability and the viscosity. The flow times reported in Tables 3.5a through 3.5c do not measure the viscosity of SCC, but they are related to it by describing the rate of flow. A T_{50} time of 2 seconds or less characterizes self-consolidating concrete with a low viscosity, and a T_{50} of 5 seconds and more is generally considered a high-viscosity SCC mixture[1]. A V-funnel time of 10 seconds is acceptable. Currently there is no agreement on the suitable values for the T_{20} and T_{40} times.

The tests results expressed in second are very small in nature and highly operator sensitive. A minimum of two operators are needed to perform these tests. The variations in test results can be caused by the admixture source or by one of the followings: moisture condition of the base plate, L-box or V-funnel apparatus; angle of slope of the base plate or L-box apparatus, the speed of lifting of the cone or the gates of L-box and V-funnel apparatus, the mixing action, the batching temperature, and the material preparation. Precautionary steps were taken in all phases of the experiments in order to minimize the potential influence due to the above-mentioned factors. Since there is no consensus on the acceptable T_{20} and T_{40} times, the discussion related to the flow ability (or viscosity per inference) is confined to the results obtained for the T_{50} and V-funnel tests.

3.4.2.1 Influence of admixture source on flowability/viscosity

The test results indicate that; for the slump flows of 20, 25, and 28 inches (508, 635, and 711 mm); the group I self-consolidating concretes made with sources B and C admixtures displayed similar T_{50} times which were on average 14, 11, and 14%, respectively, higher than those of the concretes prepared with the admixture sources A and D. The corresponding increases in T_{50} time were 15, 21, and 16%, respectively, for the group III SCCs. For the V-funnel test results, the pair sources B and C displayed on average 18, 16, and 9% reductions in t_v when compared to the pair sources A and D for the group I SCC prepared with slump flows of 20, 25, and 28 inches (508, 635, and 711 mm), respectively. For the group III SCCs, the corresponding viscosity gains (or flowability losses) as related to the V-funnel were 6, 5, and 3%, respectively.

In summary it can be concluded that the T_{50} time and V-funnel flow time varied among the selected self-consolidating concretes and were all within the acceptable values recommended by the ASTM committee C09.47[52]. Irrespective of the SCC groups, the admixture sources B and C displayed similar flowability which was lower than that of the sources A and D; or by inference, sources B and C showed higher viscosity when compared to sources A and D.

3.4.2.2 Influence of slump flow on flowability/viscosity

The increase in the flow ability of the selected self-consolidating concretes led to reductions in the T_{50} and V-funnel flow times. For the group I SCCs, when the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the T_{50} and V-funnel flow times decreased on average by 17 and 6 %, and 16 and 8 %, respectively. The corresponding decreases were 19 and 8 %, and 20 and 11 % for the groups II SCCs; and 16 and 10 %, and 19 and 8 % for the group III SCCs. This, by no means, is a statistically rigorous comparison, but it gives a good idea of the trend in flow ability/viscosity as related to the increase in slump flow values. The loss in viscosity (or gain in flowability) induced by an increase in slump flow can be attributed to increases in adsorption of admixture leading to an increase in dispersion of cement flocs and the break down of the bond between the cement particles due to increases in the amount of superplasticizer. The incorporation of VMA helped to partially restore the loss in viscosity by elevating the T_{50} and V-funnel flow times to the acceptable values.

3.4.3 Stability

The stability of the self-consolidating concrete is defined as its ability to maintain homogeneous distribution of its ingredients during its flow and setting. Dynamic and static stabilities are the two most common stability characteristics of self-consolidating concretes. The section below presents the test results obtained for the dynamic and static stabilities of the trial self-consolidating concretes.

3.4.3.1 Dynamic segregation resistance

Dynamic segregation resistance refers to the resistance of the SCC to separation of its constituents during placement into formwork[1]. It was evaluated by visual examination of the fresh concrete and reported as visual stability index (VSI). A visual assessment for any indication of mortar/paste separation at the circumference of the flow and any aggregate separation in the central area gives an indication of dynamic segregation resistance.

3.4.3.1.1 Influence of admixture source on dynamic segregation resistance

All selected self-consolidating concretes were designed to attain a visual stability index of 0 (highly stable concrete) or 1 (stable concrete) by balanced proportioning of HRWRA and VMA once sufficient cementitious materials content and an appropriate coarse-to-fine aggregate ratio were determined. As reported in Tables 3.5a through 3.5c, irrespective of the admixture source and aggregate type and size, the target VSI of 0 or 1 was obtained for all trials matrices. No evidence of segregation or bleeding in slump flow was observed in any of the selected self-consolidating concretes, indicating that stable matrices were attained with all four admixture sources.

3.4.3.1.2 Influence of slump flow on dynamic segregation resistance

Highly stable mixtures (VSI = 0) were achieved for the selected self-consolidating concretes made with 20 and 25 inches (508 and 635 mm) slump flows. When the slump flow was increased from 25 to 28 inches (635 to 711 mm), the attainment of a highly stable matrix was not possible without the utilization of excessive and impractical amount of admixtures. Consequently, in order to maintain a practical design in searching for the optimum dosage and proportioning of the admixtures, the ranking of stable dynamic segregation resistance (VSI = 1) was adopted for the 28-inch (711 mm) slump flow self-consolidating concretes. HRWRA and VMA were used in the selected concretes to decrease their yield stress and increase their plastic viscosity, respectively. The reduction in dynamic stability for the 28-inch (711 mm) slump flow self-consolidating concretes was primarily due to the increase in the amount of HRWRA leading to a gain in dispersibility and a reduction in the homogeneity of the matrix. For all three SCC groups, and irrespective of admixture source, the selected self-consolidating concretes made with 25 and 28 inches (508 and 635 mm) slump flows required the use of VMA to obtain an acceptable visual stability index.

3.4.3.2 Static segregation resistance

Static stability or static segregation resistance refers to the resistance of self-consolidating concrete to bleeding, accumulation of paste at the top, and settling of aggregates on the bottom after casting while the concrete is still in a plastic state[1]. Such heterogeneity can result in considerable variations in the hardened properties across the concrete. Self-consolidating concrete which experiences a dynamic segregation (segregation during placement) also sees static segregation, but lack of dynamic segregation does not necessary imply that the mixture is definitely stable[2]. In this investigation, the static segregation resistance of self-consolidating concrete was determined using column segregation test. The top-to-bottom retained #4 sieve coarse aggregate mass (weight) ratio was measured to find the segregation resistance of the SCC. The detail testing procedure is summarized in the Appendix A. This section discusses the static stability of the 27 designed self-consolidating concretes as related to admixture sources and slump flow.

3.4.3.2.1 Influence of admixture source on static segregation resistance

The segregation indices (SI) of the 27 trial matrices, as reported in Tables 3.5a through 3.5c, were lower than the maximum recommended value of 15%. Irrespective of the SCC group, the admixture sources A and D exhibited similar segregation indices which were higher than those of the admixture sources B and C. This is indicative of a better static segregation resistance of SCCs made with the admixture sources B and C as compared to those made with the admixture sources A and D. On average, groups I and III self-consolidating concretes incorporating the admixture sources A and D experienced reduction in static stability of 20 and 26 %, respectively, when compared to those obtained when admixture sources B and C were used. The increase in static segregation resistance due to admixture sources B and C may be attributed to their relative higher viscosity (by inference) as can be seen from the results of the T_{20}, T_{40}, T_{50}, and V-funnel times reported in Tables 3.5a through 3.5c.

3.4.3.2.2 Influence of slump flow on static segregation resistance

The segregation indices of the selected self-consolidating concretes increased as the slump flow increased irrespective of admixture source and SCC group. When the slump flows increased from 20 to 25 to 28 inches (508, 635, and 711 mm), the static stability decreased on average by 59 and 11 %, 5 and 14 %, 24 and 27 %; for groups I, II, and III, respectively. This is mainly due to the reduction in the viscosity (by inference) of the higher slump flow concrete.

The static stability mechanism of action can be explained through aggregate sedimentation which is related to the viscosity and the density of the mixture, the size and the density of the aggregate, and the flow velocity of the mixture. Bonen and Shah[2] reported that the sedimentation velocity of aggregate is proportional to the radius square of the aggregate, the differences in the specific densities of the aggregate and the matrix, and inversely related to the viscosity of the mixture. The explanation is presented through equations 3.5a, 3.5b, and 3.5c; and Figure 3.8. Laminar flow was assumed. Considering the gravitational force (F_g), the buoyancy force (F_a) and the frictional force (F_r) acting on aggregate particles as shown in Figure 3.8; and the specific gravity of common aggregate being greater than that of the concrete paste, the velocity of the aggregate will increase until there is equilibrium of forces. At this point the net forces acting on the aggregate become zero.

This is translated in equations 3.5a and 3.5b (note that aggregate are assumed to have spherical shape).

$$F_r = 6\pi\eta r v_e \tag{3.5a}$$

$$F_r = F_g - F_a \tag{3.5b}$$

Substituting F_g and F_a for F_r

$$v_e = \frac{2gr^2\left(\rho_{agg} - \rho_m\right)}{9\eta} \tag{3.5c}$$

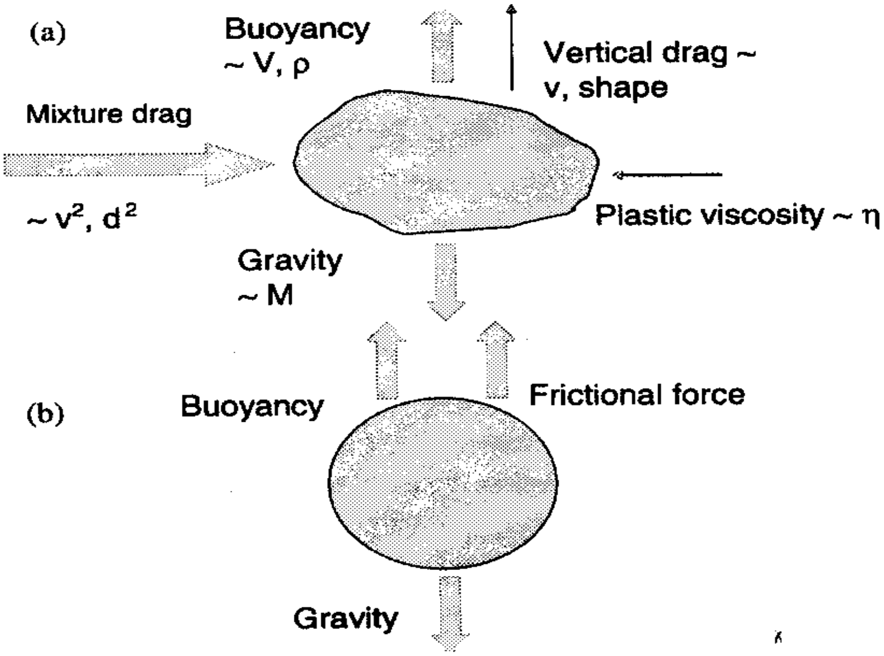


Figure 3.8: Force acting on particles: (a) horizontal flow; (b) sedimentation[2]

Where: v_e = equilibrium sedimentation velocity,

g = gravitational force,

r = sphere radius of coarse aggregate,

ρ_{agg} and ρ_m = specific densities of the aggregate and the matrix, respectively,

η = plastic viscosity.

While comparison of the segregation resistance among the three SCC groups was not critical to the objective of this investigation, a few observations can be noted. It is shown in Tables 3.5a through 3.5c that irrespective of admixture source, the group I trial matrices displayed the highest resistance to static segregation (lowest segregation index (SI) value), followed by the group III and then the group II in descending order. This can be mainly attributed to the combination of the following three factors:

- The differences in the size of the coarse aggregate: The lowest static segregation resistance of the group II matrices stems mainly from the larger size of the coarse aggregate used in their composition (see section 2.2.1 for the selected aggregates nominal maximum sizes).
- The specific densities of the fine and coarse aggregates: The group III self-

consolidating concretes were manufactured with heavier type of fine and coarse aggregates (about 8% more) when compared to those of the groups I and II (see Table 2.1 for the selected aggregates specific density).

- The matrix's paste viscosity: The viscosity of the paste is influenced by its water-to-cementitious materials ratio and cementitious materials content. The group III self-consolidating concretes were manufactured with less amount of fly ash (about 20% less) when compared to that of the groups I and II (see Table 3.1a through 3.1c for the selected matrices design and proportion).

The abovementioned observations confirmed that the sedimentation theory, as alluded to earlier, can validate the variation in static segregation resistance of the selected self-consolidating concretes.

3.4.4 Passing ability

The passing ability or the capacity of the fresh matrix to flow through confined spaces and narrow opening without blocking was measured by the J-ring, L-box and U-box tests. The blocking develops more easily when the size of aggregate is large relative to the size of the opening; the total content of the aggregate is high; and when the shape of the particles deviates from spherical. It is also likely that the friction between the flowing concrete and the surface of the obstacle/confinement, e.g. the reinforcement and formwork, as well as the type of the material used in the J-ring and L-box, will influence the blocking and thus the passing ability of a fresh self-consolidating concrete[35]. In the present study, standard J-ring, L-box and U-box testing apparatus as described in Appendix A were used.

The passing ability as related to the J-ring test was conducted to assess the blocking of fresh self-consolidating concretes. The passing ability as related to the L-box was determined by the flow height ratio H_2/H_1, where H_1 is the height of the concrete flow at the sliding gate and H_2 at the end of the horizontal portion of the L box. The passing ability as related to the U-box was evaluated by the filling height H_1-H_2, the difference in height between the left and right compartments of the U-box. For an acceptable SCC, a J-ring value between 0 and 2 inches (0 and 51 mm), an L-box flow height ratio H_2/H_1 of 0.8 to 1, and a U-box filling height H_1-H_2 lower than 12 inches (305 mm) are recommended. The current section is intended to discuss the influence of the four selected admixture sources and the three slump flow values on the passing ability of the designed self-consolidating concretes.

3.4.4.1 Influence of admixture source on passing ability

As shown in Tables 3.5a and 3.5c it can be seen that for both groups I and III SCCs, the measured J-ring values of the four admixture sources were between 1 and 2 inches (25 and 51 mm), indicating a moderate passing ability (passing ability rate of 1) or minimal to noticeable blocking of the selected self-consolidating concretes.

The test results as related to the L-box and U-box are also presented in Tables 3.5a through 3.5c. The flow height ratios H_2/H_1 of the 20 inches (508 mm) slump flow self-consolidating concretes were less than the minimum recommended value of 0.8, indicating their extreme blocking ability. However, regardless of the admixture source and SCC group, for concretes made with slump flow of 25 and 28 inches (635 and 711 mm), the flow height ratios remained near the bottom third-point of the recommended limits, indicating their moderate passing ability.

The results pertaining to the U-box test were also indicative of a moderate passing ability for the 27 selected SCC mixtures. The U-box filling height H_1-H_2 values of the group I SCCs were near the middle point of the allowable 12 inches (305 mm) value. The corresponding results for the group III SCCs were also less than the maximum recommended value, but remained near its upper limit of 12 inches (305 mm).

Overall, with proper proportioning, self-consolidating concrete with acceptable passing ability can be achieved with any of the four selected admixture sources.

While it is not intended to compare the three SCCs groups, since their aggregate type and size were different, a few observations are worth mentioning. All four admixture sources exhibited similar flow height ratio H_2/H_1 independently of the selected SCC groups. The flow height ratio of the groups I, II and III self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows represented on average 87, 89 and 86%, respectively, of the recommended upper limit of passing ability for the L-box test (the 20 inches (508 mm) slump flow matrices were excluded in this comparison because they failed to pass the L-box test). On the other hand, there was a noticeable difference in the U-box filling height H_1-H_2 values among the three trial self-consolidating concretes groups. The average U-box filling height H_1-H_2 values of the groups I, II and III 25 and 28 inches (635 and 711 mm) slump flow SCCs were 42, 16 and 72%, respectively, of maximum recommended value of 12 inches (305 mm) for the passing ability of the U-box test. The findings of the two passing ability test methods (L-box and U-box) highlighted the difference in the test mechanism that exists between them.

3.4.4.2 Influence of slump flow on passing ability

Irrespective of the admixture source and SCC group, the passing ability of the selected matrices improved with an increase in slump flow. When the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the J-ring passing ability improved by an average of 8 and 12%, 11 and 21%, and 14 and 14% for the groups I, II, and III, respectively. Similar gains in passing ability were observed when the assessment included the L-box or U-box tests. The corresponding improvements in L-box passing ability were 41 and 5%, 29 and 11%, and 28 and 5% for the groups I, II, and III, respectively; and 8 and 16%, 117 and 50%, and 5 and 8% for the same groups respectively, when the U-box test was used. This behavior can be attributed to a decrease in the yield point and an increase in the viscosity of the higher slump flow self-consolidating concretes, allowing an ease of movement around blocking rebars.

3.4.5 Filling ability

V-funnel and U-box tests were also utilized to assess the filling ability of the selected concretes. As reported above, the test results for all four admixture sources as related to the V-funnel times and U-box filling heights were indicative of their good filling ability, for the groups I and II, and moderate filling ability for the group III SCCs.

3.4.6 Air content

The air content of the non-air self-consolidating concretes was evaluated using ASTM C 173[53] “Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method”. The results pertaining to the air content of the selected self-consolidating concretes are shown in Tables 3.5a through 3.5c. Although no air-entraining admixture was used, the test results indicated that the admixture sources B and D were able to produce more air than the sources A and C. In fact, for the groups I and III SCCs, admixture sources B and D entrained on average, approximately 0.60 % and 0.35 %, respectively, more air than the admixture sources A and C.

Additionally, irrespective of admixture source and SCC group, the air content decreased as the slump flow increased. When the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the average air content of groups I, II, III SCCs decreased by 14 and 22%, 9 and 7%, and 19 and 23%, respectively.

The use of AEA to make air-entrained self-consolidating concrete was not part of the present investigation. However, a companion investigation made by Ghafoori N., and Barfield M.,[62] revealed that the source of air entrainment admixture (AEA) dictates the dosage requirement to produce similar air content and air void characteristics. They found that: (1) The smallest and closely spaced air voids were produced by the synthetic detergent type AEA of source A; (2) the AEA containing tall oil (source B) produced the best air void characteristics, followed by the saponified wood rosin/resin-acid combination (source C), and the natural wood rosin (source D); and (3) the increase in the matrix fluidity engendered a deterioration of the self-consolidating concrete's air void characteristics because of the increased ability of the air voids to move in the cement paste, causing bubble coalescence.

3.4.7 Bleeding

The bleeding was assessed using ASTM C 232[54] "Standard Test Method for Bleeding of Concrete." Tables 3.5a through 3.5c present the test results pertaining to the bleeding of the selected self-consolidating concretes. The four admixture sources produced self-consolidating concretes with a relatively similar bleedings values which were about 4, 2, and 3% for groups I, II, and III, respectively; indicating that the four admixture sources had marginal influence on the bleeding of the self-consolidating concretes.

Irrespective of the admixture source, when the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the group I SCCs exhibited increases in bleeding by nearly 2 and 3%, respectively. For the groups II and III SCCs, the corresponding increases were 5 and 6 %, and 4 and 3 %, respectively. The marginal variation between the bleeding of different slump flows was due to the high cementitious material content and low water-to-cementitious materials ratio used for the trials matrices.

3.4.8 Setting time

The ASTM C 403[55], "Standard Test Method for Time of Setting of Concrete

Mixture by Penetration Resistance," was used to evaluate the times of setting of the trial mixtures. The test results pertaining to the setting times of the selected self-consolidating concretes are shown in Tables 3.5a through 3.5c. The admixture sources A and D displayed similar initial setting times which were, on average, higher than those of the admixture sources B and C by about 6.8 and 7.5% for the groups I and III SCCs, respectively. The corresponding increases in the final setting times were 4.9 and 7.2 %, respectively. On the whole, the differences in setting times between the pair sources A and D in one side, and the pair sources B and C in the other side, were less than 30 minutes, indicating that the source of polycarboxylate-based admixture used had little impact on the setting times of the selected self-consolidating concretes.

In general, independently of the admixture source and the matrix group, the selected self-consolidating concretes produced higher setting times when the slump flow increased. On average, as the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), groups I, II, and III SCCs displayed rises in the initial setting time of 3.8 and 5.6 %, 5.2 and 11.6 %, and 9.5 and 8.6 %, respectively. The corresponding increases in the final setting times were 6.6 and 8.1 %, 5.4 and 9.7 %, and 7.4 and 7.0 %, respectively. These delays in setting times can be attributed to the increase in the bleeding water generated by the increase in the dosages requirement of HRWRA in attaining a higher slump flow.

3.4.9 Adiabatic temperature

ASTM C 1064[56], "Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete," was used to evaluate the adiabatic temperature of the trial mixtures. A data acquisition apparatus "DI-1000 TC"[63] with 8 channels and compatible software "WinDaq"[64] was used to record the temperature of the freshly-mixed self-consolidating concretes. Tables 3.5a through 3.5c display the adiabatic test results of the selected self-consolidating concretes. A typical sample of temperature evolution of trial matrices over the period of 24 hours is presented in Figure 3.9. The figure documents the occurrence of the four different stages involved in Portland cement hydration process, namely: initial hydration (from 0 to 1), induction or dormant period (from 1 to 2), acceleration and setting period (from 2 to 3) and deceleration period (from 3 to 4).

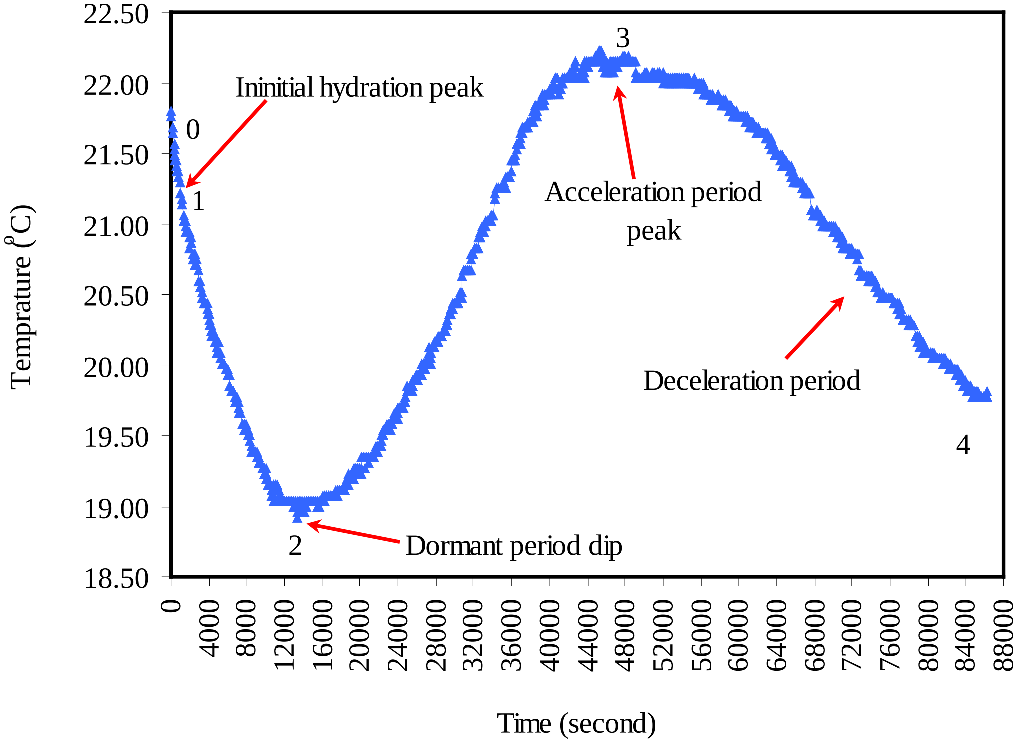


Figure 3.9: Temperature evolution over 24-hour of group I and admixture source A-SCC

3.4.9.1 Influence of admixture source on adiabatic temperature

Irrespective of the admixture source; groups I, II, and III self-consolidating concretes displayed induction periods lasting about 3.4, 3.0, and 3.0 hours, respectively. The corresponding periods for the acceleration and setting stage were 8.3, 8.5, and 8.1 hours. These hydration characteristics indicated that both the induction and the acceleration stages displayed durations close to the upper end of the recommended ranges (15 minutes to 4 hours for the induction stage, and 4 to 8 hours for the acceleration stage) for conventional concrete. Moreover, the tests results indicated a relatively insignificant influence of admixture source on the temperature evolution of the self-consolidating concretes.

Irrespective of the SCC group and slump flow, the selected polycarboxylate-based superplasticizers produced similar temperature evolution trend in which an analogous temperature drop of about 2.3 ^{o}F (1.1 ^{o}C) during the initial and dormant hydration (from point 1 to 2) and an increase of roughly 4.7 ^{o}F (2.3 ^{o}C) in the acceleration and setting phase (from point 2 to 3) were observed. Marginal differences, less than 1 ^{o}F (0.5 ^{o}C), among dormant or peak temperatures of the four admixture sources were also recorded.

In comparing the four selected admixture sources, there were slight differences in elapsed times from the beginning of the hydration to the end of induction or acceleration stages. When admixture sources changed from A to B, C, and D, the elapsed times to the dormant stage of groups I and III SCCs decreased by 16, 23, and 6 minutes; and 13, 20, and 9 minutes, respectively. The corresponding reductions for the acceleration and setting phase became 17, 24, and 9 minutes; and 19, 29, and 9 minutes, respectively. These results indicate a delay in hydration time of the admixture sources A and D when compared to the admixture sources B and C, pointing out that admixture sources A and D generated similar hydration time which was longer than that of the admixture sources B and C.

3.4.9.2 Influence of slump flow on adiabatic temperature

As shown in Tables 3.5a through 3.5c, regardless of the admixture source, all the trial self-consolidating concrete groups displayed negligible increases in the dormant and peak temperatures when the slump flow increased. On average, as the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), all three SCC groups experienced less than 1 ^{o}F (0.5 ^{o}C) increase in the dormant and peak temperatures. This relative conservation of temperature may be due to the chemical type of the HRWRA and VMA which does not induce any temperature increase when a higher dosage is used. However, the increase in slump flow led to increases in elapsed times to the dormant and peak point. Irrespective of the admixture sources, when the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), the delay in reaching the dormant temperature of groups I, II and SCCs were on average 21 and 25 minutes, 17 and 17 minutes, and 16 and 13 minutes, respectively. The corresponding delay for reaching the peak temperature became 31 and 37 minutes, 40 and 40 minutes, and 31 and 47 minutes, respectively. As was the case for the setting time, the delays in adiabatic temperature are the consequences of the increase in the bleeding water caused by the increase in HRWRA dosages requirement in attaining the higher slump flow.

3.5 Bulk characteristics

Tables 3.6a through 3.6c present the mean demolded unit weight, compressive strength and modulus of elasticity of the trial matrices. In the following sections, the

Table 3.6a: Bulk characteristics of group I self-consolidating concretes

Mix No.	Demolded unit weight (pcf)	Modulus of elasticity (psi)		Compressive strength (psi)		
		28-day	90-day	7-day	28-day	90-day
R8.A.SF20	142.74	3798858	4134621	5185	7068	9032
R8.B.SF20	142.74	3874895	4217345	5305	7241	9237
R8.C.SF20	142.74	3919273	4262175	5350	7311	9326
R8.D.SF20	142.74	3838314	4180257	5267	7156	9182
R8.A.SF25	142.74	3816669	4181074	5331	7196	9146
R8.B.SF25	142.74	3897125	4267396	5456	7355	9380
R8.C.SF25	142.74	3937169	4312521	5498	7400	9465
R8.D.SF25	142.74	3867528	4228583	5413	7279	9300
R8.A.SF28	142.74	3855085	4254142	5428	7288	9454
R8.B.SF28	142.74	3938145	4343362	5557	7484	9686
R8.C.SF28	142.74	3975115	4387523	5610	7538	9786
R8.D.SF28	142.74	3901346	4302294	5506	7391	9588

1 pcf = 16.02 kg/m^3, 1 psi = 0.006895 MPa

Table 3.6b: Bulk characteristics of group II self-consolidating concretes

Mix No.	Demolded unit weight (pcf)	Modulus of elasticity (psi)		Compressive strength (psi)		
		28-day	90-day	7-day	28-day	90-day
R67.A.SF20	142.74	3720998	4193158	5363	6889	8535
R67.A.SF25	142.74	3791756	4291608	5377	7032	8810
R67.A.SF28	142.74	3834358	4332590	5525	7098	8855

1 pcf = 16.02 kg/m^3, 1 psi = 0.006895 MPa

Table 3.6c: Bulk characteristics of group III self-consolidating concretes

Mix No.	Demolded unit weight (pcf)	Modulus of elasticity (psi)		Compressive strength (psi)		
		28-day	90-day	7-day	28-day	90-day
S7.A.SF20	153.06	5655119	6738052	6410	8048	10040
S7.B.SF20	153.06	5770136	6890686	6544	8219	10273
S7.C.SF20	153.06	5837961	6961832	6622	8326	10385
S7.D.SF20	153.06	5724291	6829384	6495	8152	10173
S7.A.SF25	153.06	5880279	6854848	6485	8166	10170
S7.B.SF25	153.06	6003658	7002305	6609	8325	10387
S7.C.SF25	153.06	6062696	7069152	6689	8399	10509
S7.D.SF25	153.06	5959698	6944377	6581	8263	10301
S7.A.SF28	153.06	6019987	6903018	6605	8277	10212
S7.B.SF28	153.06	6152139	7061509	6730	8453	10437
S7.C.SF28	153.06	6207253	7115570	6818	8559	10566
S7.D.SF28	153.06	6089913	7004440	6698	8390	10339

1 pcf = 16.02 kg/m^3, 1 psi = 0.006895 MPa

results of the bulk characteristics as influenced by different admixture sources and slump flows are discussed.

3.5.1 Demolded unit weight

The unit weight of conventional normal-weight concrete used in pavements, buildings, and other structures ranges between 140 to 150 pcf (2240 to 2400 kg/m^3). The amounts of air, water and cementitious materials, which in turn are influenced by the maximum size and the density of the aggregates, have a direct impact on the unit weight of concrete. The ASTM C 138[57], “Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete,” was used to evaluate the unit weight of the trial mixtures. The one-day unit weights of the selected matrices, immediately after demolding, are shown in Tables 3.6a through 3.6c. These values represent the average of four samples. Both the groups I and II self-consolidating concretes exhibited demolded unit weights within the 140 - 150 pcf (2240 - 2400 kg/m^3) range of normal-weight concrete. On the other hand, the group III self-consolidating concretes displayed demolded unit weights slightly above the upper limit of that reported for normal-weight concrete due to the relatively high specific gravity of its coarse and fine aggregates (2.79 and 2.78, respectively), when compared to that of most natural aggregates (2.4 to 2.9)[9,16].

In general, irrespective of the self-consolidating concrete's constituent and proportions, the unit weight of all selected trial matrices remained at the level equal to (groups I and II) or above (group III) that is required to produce normal- weight concrete. The recorded demolded unit weights were affected neither by the selected admixture sources nor by the slump flow value.

3.5.2 Compressive strength

The ASTM C 39[58], "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," was used to evaluate the compressive strength of the designed self-consolidating concretes. The compressive strength test results of the selected trial mixtures at different curing ages are shown in Tables 3.6a through 3.6c. Each of these values is the average of four tested cylinders.

3.5.2.1 Influence of admixture source on compressive strength

Typical representations of compressive strength as a function of admixture source and curing age are displayed in Figures 3.10a and 3.10b, respectively. In comparison to the admixture source C, both groups I and III self-consolidating concretes incorporating admixture sources A, B, and D showed reductions in compressive strength of 3, 1, and 2%, respectively, regardless of the slump flow and curing age. These relatively small variations indicate that the four selected polycarboxylate-based HRWRA and their corresponding VMA had the type of chemical composition that did not interfere with hydration reaction and did not alter the compressive strength development of concrete. The increase in strength at 28 and 90 days is attributed to the availability of more calcium silicate hydrate (C-S-H) binder, due to the pozzolanic reaction of fly ash with lime, and the continued hydration of the cement paste.

3.5.2.2 Influence of slump flow on compressive strength

Figure 3.10c is a typical representation of the compressive strength as a function of slump flow. On the whole, when the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), irrespective of admixture source and curing age, all three SCC groups displayed similar compressive strength improvement of less than 3% variation. This marginal difference in compressive strength indicated the insignificant influence of increased in fluidity of self-consolidating concrete due to increases in slump flow through additional dosage of admixtures.

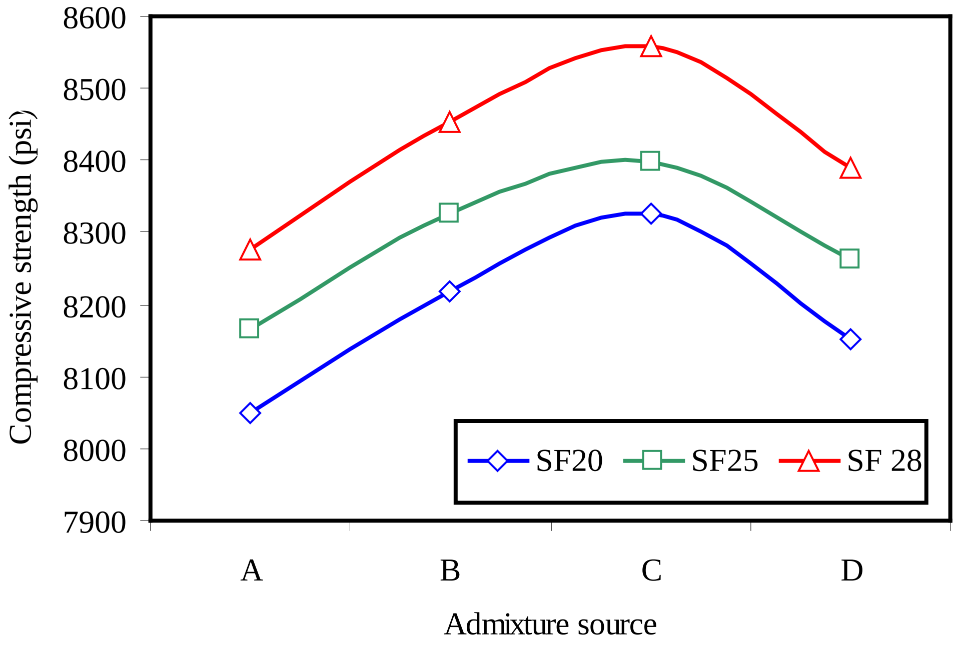


Figure 3.10a: Influence of admixture source on the 28-day compressive strength of group III self-consolidating concretes

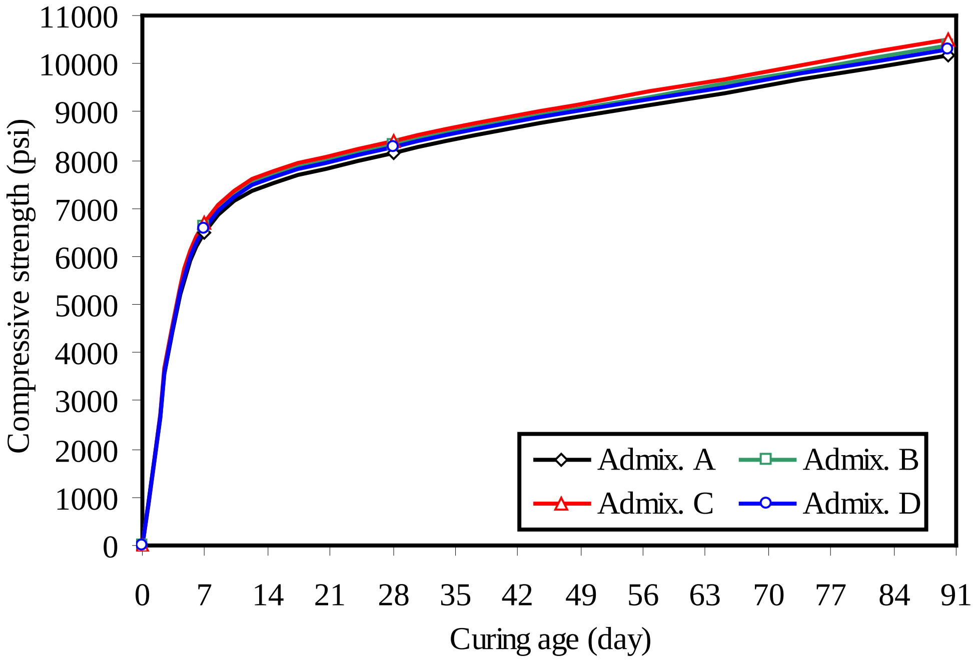


Figure 3.10b: Influence of admixture source and curing age on the compressive strength of group III-25 inches (635 mm) slump flow self-consolidating concretes

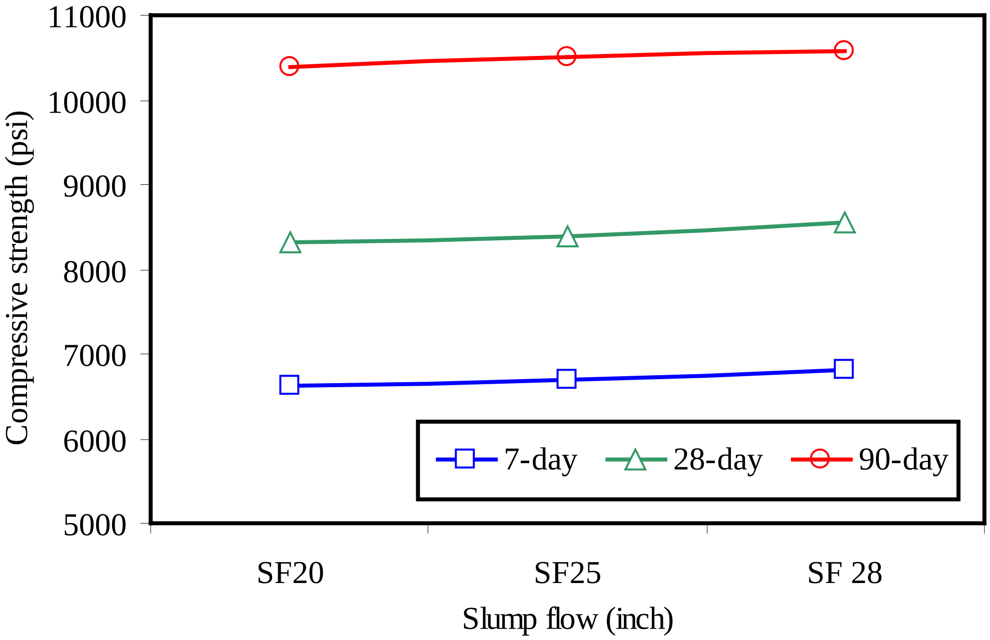


Figure 3.10c: Influence of slump flow value on the compressive strength of group III self-consolidating concretes made with admixture source C

3.5.2.3 Strength and aggregate correlation

It can be seen from Tables 3.6a through 3.6c, that irrespective of admixture source and curing age, the group III SCCs exhibited a higher compressive strength than group I, which in turn yielded stronger concrete than group II. Using the group III SCC as reference, the groups I and II SCCs experienced reductions in their 28-day compressive strength of about 12 and 16%, respectively. The corresponding losses in strength were 9 and 12% at 90 days of curing. The three SCC groups were totally independent from each other. The groups I and II SCCs were made of the aggregate source R which had different size, shape, surface texture, grading and mineralogy than the source S used to produce group III self-consolidating concretes. While both groups I and II had richer paste than that of group III concretes, the increase in paste quality was not sufficient enough to overcome the higher quality aggregates used to produce group III self-consolidating concretes.

3.5.2.4 Predictive statistical equations of the compressive strength of the selected self-consolidating concretes

A statistical program[61] was used to determine the best-fit predictive equations for compressive strength of the groups I and III SCCs at different curing ages. Analyses were conducted at 95% confidence level. The predictive equations were tested for accuracy using R² (the coefficient of multiple determination) and S (average standard deviation). Correlations between the data predicted from the regression equations and the actual results obtained from the compressive strength test results of the selected trial matrices at various curing ages were evaluated using F and T tests. The compressive strength can be related to the slump flow and the curing age in the form of $CS = a\left(SF^{b}\right)\left(CA^{c}\right)$ as follow:

Group I self-consolidating concrete

$$CS_{I} = 3149.52617\left(1.00505^{SF}\right)\left(CA^{0.21539}\right) \qquad (3.6)$$

Group III self-consolidating concrete

$$CS_{III} = 4353.56838\left(1.00281^{SF}\right)\left(CA^{0.17579}\right) \qquad (3.7)$$

Where:

CS_I *and* CS_{III} = *Compressive strength of the groups I and III SCCs, (psi)*

SF = *Slump flow (inch), with* $20 \text{ inches} \le SF \le 28 \text{ inches}$

CA = *Curing age (day), with* $7 \text{ days} \le CA \le 90 \text{ days}$

The regression equations 3.6 and 3.7 produced R² and S values of 99.6% and 106 psi; and 99.6% and 124 psi, respectively, indicating a strong relationship between the dependent variable (compressive strength) and the independent variables (slump flow and curing age). F and T tests were performed to confirm the significance of coefficients a, b, and c in the regression model. Both equations 3.6 and 3.7 displayed Prob(t) = 0.00 for all the coefficients, and Prob(F) = 0, indicating that the slump flow and curing age had a similar influence on the predicted compressive strength.

3.5.3 Static modulus of elasticity

The elastic characteristics of a material are a measure of its stiffness. The term pure elasticity is used when the strains appear and disappear immediately. Four main categories of stress-strain response exist: (a) linear and elastic, such as in steel; (b) non-linear and elastic, such as in timber and some plastics; (c) linear and non-elastic, such as in brittle materials like glass and most rocks; and (d) non-linear and non-elastic, in which a permanent deformation remain after removal of load. This behavior is typical of concrete in compression or tension loaded to moderate and high stresses but is not very pronounced at very low stresses. The nonlinearity of concrete stems from its composite nature. While both hydrated cement paste and aggregates show linear elastic properties, their combined material, namely concrete, does not[12]. The slope of the relation between stress and strain of concrete under uniaxial loading gives the static modulus of elasticity, but the term Young's modulus can be applied strictly only to linear categories[9]. Since the curve for concrete is nonlinear, the following three methods for computing the modulus of elasticity are used: (a) the tangent modulus, given by the slope of a line drawn tangent to the stress-strain curve at any point on the curve; (b) the secant modulus, given by the slope of a line drawn from the origin to a point on the curve corresponding to a 40 percent stress of the failure load; and (c) the chord modulus, given by the slope of a line drawn between two points on the stress-strain curve. To further modify the secant modulus, the origin of the line is drawn from a point representing a longitudinal strain of 50 μin/in. to the point that corresponds to 40 percent of the ultimate load. Shifting the base line by 50 micro strains is recommended to correct for the slight concavity that is often observed at the beginning of the stress-strain-curve. Figure 3.11 represents a typical stress-strain curve of concrete along with the tangent and secant moduli.

The elastic modulus is defined as the ratio between the applied stress and instantaneous strain within an assumed proportional limit. In spite of the nonlinear behavior of concrete, an estimate of the elastic modulus is necessary for determining the stress induced by strains associated with environmental effects. It is also needed for computing the design stress under load in simple element, and moments and deflections in complicated structures. It is usually estimated from empirical expressions that assume direct dependence of the elastic modulus on the strength and density of concrete. According to the ACI Building Code 318[66], the secant modulus of elasticity can be determined from:

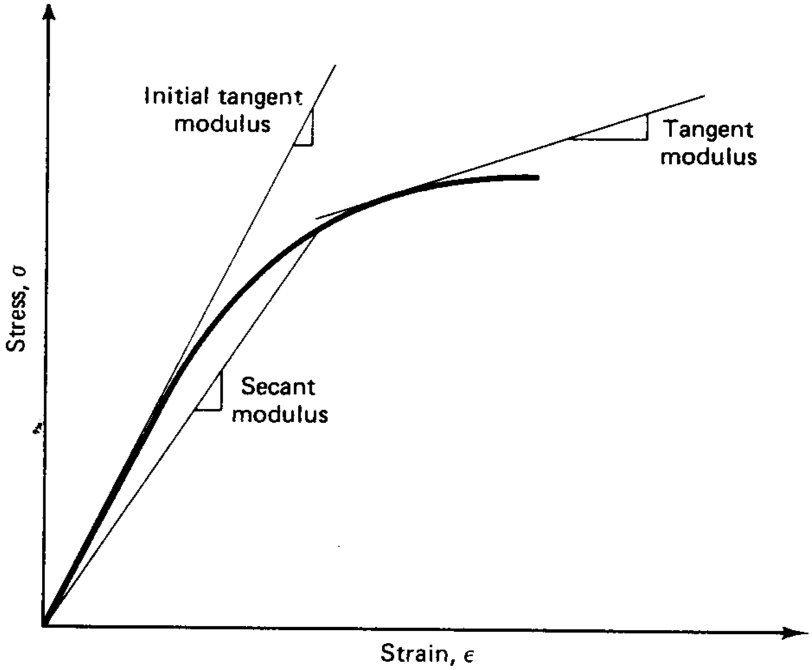


Figure 3.11: Tangent and secant moduli of concrete[65]

$$E_c = 33 w_c^{1.5} \sqrt{f_c^{'}} \text{, in psi} \qquad (3.8)$$

$$E_c = 0.0143 w_c^{1.5} \sqrt{f_c^{'}} \text{, in MPa} \qquad (3.9)$$

for concrete with a unit weight between 90 and 155 lb/ft^3 (1442 and 2432 kg/m^3)

or $E_c = 57000\sqrt{f^{'}}$, in psi (3.10)

or $E_c = 4730\sqrt{f^{'}}$, in N/mm^2 (3.11)

for normal-weight concrete

Where E_c is the static modulus of elasticity, w_c the unit weight, and $f_c^{'}$ the 28-day compressive strength of standard cylinder. Equations (3.8) through (3.11) are valid only for normal-strength concretes with characteristic strengths up to 6000 psi (41 MPa).

High strength concrete (with $f_c^{'}$ from 6000 to about 12000 psi (41 to 82 MPa)) behaves in fundamentally different ways from normal strength concrete, more like a homogeneous material. Its stress-strain curves are steeper and more linear to a higher stress-strength ratio than in normal-strength concretes. When using high strength concrete ACI proposed a modified version of equation (3.8) or (3.9) for computing the static modulus of elastic normal weight concrete of strength up to 12000 psi (83 MPa) and lightweight concrete up to 9000 psi (62 MPa), based on expression due to Carrasquillo et al.[67] as follow:

$$E_c = \left(40000\sqrt{f_c^{'}} + 1x10^6\right)\left(\frac{w_c}{145}\right)^{1.5}, \text{ in psi} \tag{3.12}$$

$$E_c = \left(3.2\sqrt{f_c^{'}} + 6895\right)\left(\frac{w_c}{2320}\right)^{1.5}, \text{ in MPa} \tag{3.13}$$

The ASTM C 469[59], “Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression,” was used to evaluate the modulus of elasticity of the selected self-consolidating concretes. In the present study, the static modulus of elasticity E_c as the slope of the line drawn from the stress of zero to the compressive strength of $0.45f_c$’ was adopted. The test results of the E_c for the selected trial mixtures at 28 and 90 days curing ages are shown in Tables 3.6a through 3.6c. Each of these values is the average of four tested samples.

3.5.3.1 Influence of admixture source on static modulus of elasticity

Figures 3.12a and 3.12b are the typical representations of static modulus of elasticity of the trial matrices as function of admixture sources and curing ages, respectively. A similar trend and behavior to that of the compressive strength was observed for the static modulus of elasticity of the selected self-consolidating concretes. In comparison to the admixture source C, admixture sources A, B, and D displayed the overall percentage reduction of about 3, 1, and 2%, respectively, for the groups I and III self-consolidating concretes. This similarity is normal because the modulus of elasticity is simply the ratio between the resistance of the compressive stress and the strain within the assumed stress limit. Like the compressive strength, the change in the admixtures source did not affect the static modulus of elasticity of the selected self-consolidating concretes. The increase in static modulus of elasticity at 28 and 90 days is due to the improvement in compressive strength during the same period.

3.5.3.2 Influence of slump flow on static modulus of elasticity

The influence of slump flow value on static modulus of elasticity can be seen in Tables 3.6a through 3.6c. When the slump flow increased from 20 to 25 to 28 inches (508 to 635 to 711 mm), irrespective of the admixture source and curing age, marginal

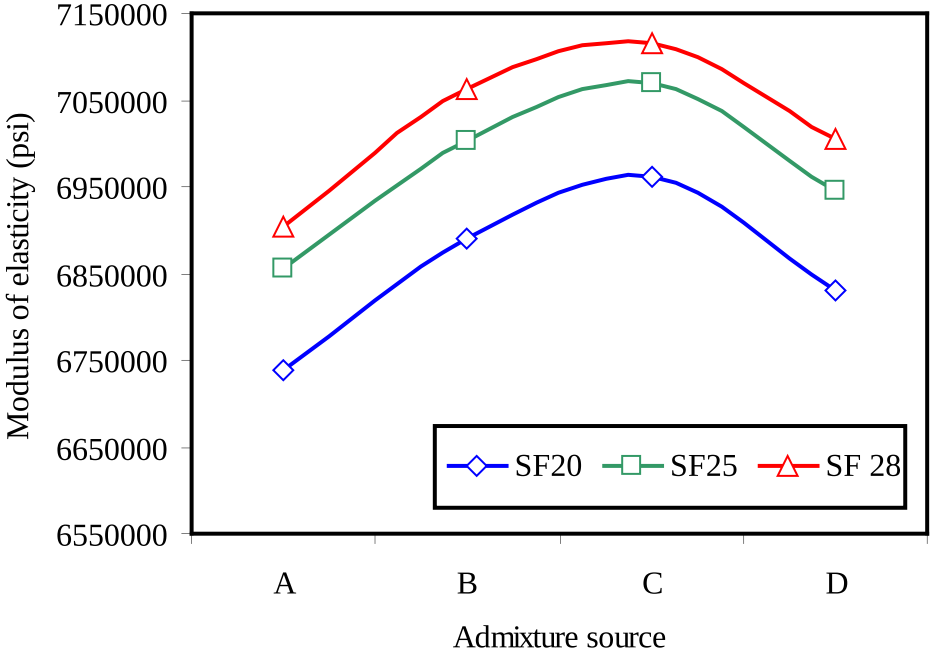


Figure 3.12a: Influence of admixture source on the 28-day modulus of elasticity of the group III self-consolidating concretes

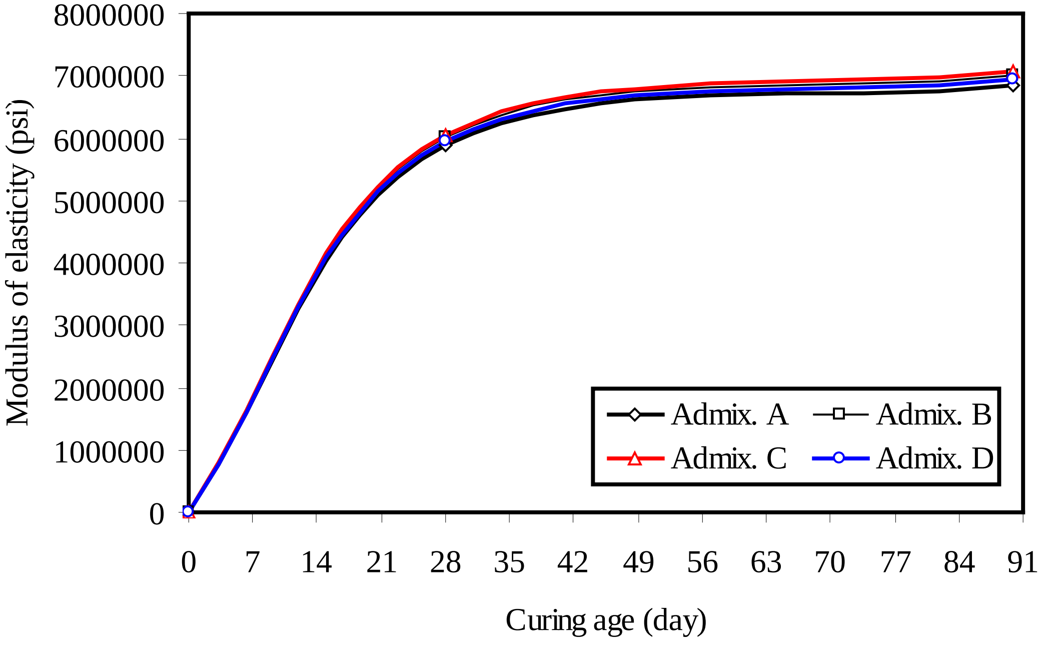


Figure 3.12b: Influence of admixture source and curing age on the group III-25 inches slump flow SCCs modulus of elasticity

improvements in static moduli of elasticity of less than 3% were recorded for all three SCC groups, indicating that the increases in slump flow had virtually no influence on the modulus of elasticity of the trial self- consolidating concretes.

3.5.3.3 Measured versus specified modulus of elasticity

The modulus of elasticity is usually estimated from empirical expressions that assume direct dependence of the elastic modulus on the strength and density of concrete. Since all the three SCC groups are normal weight concretes which exhibited compressive strength at 28 and 90 days between 6000 and 12000 psi (62 to 83 MPa), equation 3.10 or 3.11 was used to determine the ACI specified modulus of elasticity where f'_c is the 28-day compressive strength of the selected matrix. For the groups I and II SCCs, the experimental static moduli of elasticity were on average 11% lower than that obtained from equation (3.12) or (3.13). The group III SCCs displayed an opposite trend and produced moduli of elasticity which on average were higher than that obtained from equation (3.10) or (3.11) by 15 %. On whole, all selected trial SCCs exhibited moduli of elasticity within the typical range of 120 to 80% recommended by the ACI 318[66].

In addition to the compressive strength and the unit weight reflected in equations (3.8) and (3.12), the modulus of elasticity of concrete is very sensitive to the modulus of the aggregate. Considering that the group I matrices had 4% more cementitious materials content than group III matrices, and both groups I and III had identical water-to-cementitious materials and coarse-to-fine aggregate ratios, it can be concluded that the aggregate S used in the group III had a higher modulus of elasticity than the aggregate R used in the group I matrices.

3.6 Conclusions

For the test results of this study the following conclusions can be drawn:

a) Irrespective of the self-consolidating concrete groups, the optimum dosages requirement in obtaining a uniform slump flow and visual stability index varied among the four selected admixture sources. As shown in Table 3.7, the required dosage amount of HRWRA was highest for the source A, followed by the sources C, B, and D in descending order. On the other hand, the required VMA dosage was highest for the source A and remained uniform for the sources B, C, and D. For all four admixture sources, the self-consolidating concretes made with slump flow of 20 ± 1 inches (508 ±

25 mm) did not require VMA to yield a satisfactory unconfined workability and dynamic stability. An increase in the slump flow generated a higher dosage demand for all admixture sources.

Table 3.7: Influence of admixture sources on optimum dosage requirement

Optimum dosage of HRWRA	Low			High
	←			→
	D	B	C	A
Optimum dosage of VMA	Low			High
	←			→
	B, C, D			A

The differences among admixture sources can be explained through the ultraviolet-visible (UV/Vis) spectroscopy test, the chemistry of admixture, and the calculated VMA-to-HRWRA ratios.

- The relationship between the cement-water-superplasticizer solution concentration of free admixture and the fluidity of the matrix was studied. The increase in the solution concentration of free admixture produced higher adsorption of the PC-HRWRA carboxyl group (COO^-) on the cement calcium ions (Ca^{2+}), generating more electrostatic and steric hindrance repulsions which favored greater dispersibility of the mixture. The UV/Vis test results indicated that the concentration of the PC-HRWRA was highest for the source D, followed by the sources B, C, and A in descending order, supporting the results obtained for the optimum dosage requirement of the four admixture sources.
- The difference in the admixture sources can also be attributed to their chemical type. The behavior of the sources B, C, and D superplasticizers was similar to that of a polycarboxylate-acid type (PCA), where the acid portion was predominant when compared to the ester part (PCE). The higher acid ratio increased the adsorption of the polymer to cement particles resulting in further dispersion of the fresh matrix. On the other hand, source A was polycarboxylate-ester type and for the same dosage, it was unable to disperse cement grains at a rate similar to that of polycarboxylate acid type. The gradual adsorption of the polycarboxylate-ester type superplasticizer increased the slump flow retention of freshly-mixed self-consolidating concrete.

- The test results also indicated a trend for the VMA-to-HRWRA ratio. The similarity of the VMA-to-HRWRA ratios of the admixture sources B, C, and D led to the conclusion that these sources had to have a similar chemical composition. The higher VMA-to-HRWRA ratio of the source A admixture was due to its thickening mode of functioning which led to a higher demand for the source A VMA to produce a highly stable or stable fresh matrix.

b) With proper proportioning, self-consolidating concrete with acceptable flow ability, plastic viscosity, dynamic and static stabilities, passing ability, and filling ability can be achieved with any of the four selected admixture sources. However, the performance of the selected admixtures in attaining a uniform fresh property varied among the admixture sources. The ranking of the four admixture sources as related to their influence on the fresh performance of the trial self-consolidating concrete is presented in Table 3.8.

Table 3.8: Influence of admixture sources on the fresh properties of SCC

Flowability/viscosiy	Low/High			High/Low
	⟵			⟶
	B, C			A,D
Dynamic stability	Similar			
	⟵			⟶
	A	B	C	D
Static stability	Best			Worst
	⟵			⟶
	B,C			A,D
Passing ability	Similar			
	⟵			⟶
	A	B	C	D
Filling ability	Similar			
	⟵			⟶
	A	B	C	D

c) The 20 ± 1 inches (508 ± 25 mm) slump flow SCCs exhibited very low plastic viscosity, very high dynamic stability, moderate filling ability, low passing ability, and high static stability. As a result, the 20 ± 1 inches (508 ± 25 mm) slump flow was found unsuitable for congested reinforced structures. All 25 ± 1 inches (635 ± 25 mm) and 28 ± 1 inches (711 ± 25 mm) slump flow self-consolidating concretes displayed high flow ability (or low plastic viscosity by inference), high dynamic stability, moderate static stability, moderate passing ability, and moderate to high filling ability, indicating their suitability for most civil engineering applications. The formwork for the 28 ± 1 inches (711 ± 25 mm) slump flow SCCs may be subjected to a higher than expected pressure due to the flow ability that remained near the lower bond of the acceptable limit.

d) The data pertaining to the air content, bleeding, time of setting, adiabatic temperature, demolded unit weight, compressive strength and modulus of elasticity revealed marginal differences among the selected self-consolidating concretes made with different sources of admixtures and various slump flows.

e) Predictive equations to correlate HRWRA or VMA dosages or compressive strength with concrete paste content, aggregate sizes, and target slump flow showed significant statistical relationships between the dependant variables and independent variables.

TASK 4

INFLUENCE OF HAULING TIME ON FRESH PERFORMANCE OF SELF CONSOLIDATING CONCRETE

The present chapter is intended to evaluate the influence of hauling time on the fresh performance of selected self-consolidating concretes. Nine different hauling times, namely: 10, 20, 30, 40, 50, 60, 70, 80, and 90 minutes, were used to evaluate the change in unconfined workability, flow ability rate, and dynamic segregation resistance of freshly-mixed self-consolidating concretes. Additionally, the overdosing approach (sufficient initial optimum admixture dosage) was selected to revert the adverse influence of hauling time on the fresh characteristics of the selected matrices.

4.1 Background on mixing and hauling concrete

Immediately after or during its mixing, concrete is transported from its mixing location to the final destination. During its transportation, concrete should remain cohesive and workable within acceptable tolerances. Transportation methods which promote segregation should be avoided. Since hauling generally includes mixing, a presentation detailing the method and equipments involved in mixing concrete is necessary.

4.1.1 Concrete mixers

To produce concrete with consistent quality, an appropriate mixer should be used. The concrete mixers are classified into two main categories: batch mixers and continuous mixers.

4.1.1.1 Batch mixers

The batch mixers can be divided into two categories depending on the orientation of the axis of rotation: horizontal or inclined (drum mixer) and vertical (pan mixer)[9,12,68].

a. Drum mixers: Drum mixers are composed of blades attached to the inside of the movable drum. The role of the blades is to lift the materials as the drum rotates. Depending on the speed of rotation of the drum and the angle of inclination of the rotation axis, the drum mixers can be classified in three main categories, namely: non-tilting drum, tilting drum, and reversing drum.

- Non-tilting drum mixer: For this type of mixer, the orientation of the drum is fixed. The materials are added at one end and discharged at the other.
- Tilting drum mixer: For this type of mixer the inclination can be varied. A horizontal inclination provides more energy for mixing concrete, because more concrete is lifted to the full diameter of the drum before dropping. If the axis of rotation is almost vertical the

blades cannot lift the concrete and the concrete is not well mixed. Axis at an angle of 15 degrees generally provides efficient mixing[68]. The tilting drum is the most common type of drum mixer for small batches (less than 18 ft^3 (0.5 m^3)) both in the laboratory and in the field.

- Reversing drum mixer: This type of mixer is similar to the non-tilting drum mixer except that the same opening is used to add the constituents and discharge the concrete. The drum rotates in one direction for mixing and in the opposite direction for discharging concrete. The blades have a spiral arrangement to obtain the desired effect for discharge and mixing. The truck mixers belong to the reversing category of drum mixers. In the United States, most ready-mixed concretes are mixed in trucks and not premixed in plant. When a truck mixer is used, 70 to 100 revolutions of the drum or blades at the rate of rotation designated by the manufacturer as mixing speed are usually required to produce the specified uniformity of concrete. The mixing speed is generally 6 to 18 rpm. Any additional revolutions beyond the 100 are classified as agitating speed, which are usually about 2 to 6 rpm[9,10,69].

b. Pan mixers: Pan mixers are forced-action mixers. They consist essentially of a cylindrical pan (fixed or rotating) which contains the concrete to be mixed, one or two sets of blades which rotate inside the pan to mix the materials, and a blade which scrapes the wall of the pan. The concrete in every part of the pan is generally thoroughly mixed, and scraper blades ensure that the mortar does not stick to the sides of the pan. To discharge the mixer, the pan is usually emptied through a trap on the bottom. For small mixers (less than 1 ft^3 (28 liters or 0.028 m^3)), the blades are lifted and the pan can be removed to empty the mixer. Pan mixers are particularly efficient with stiff and cohesive mixes and often preferred for mixing small quantities of concrete or mortar in the laboratory[12].

4.1.1.2 Continuous mixers

For continuous mixers, the materials are continuously fed into the mixer at the same rate as the concrete is discharged. They are usually no-tilting drums with screw-type blades rotating in the middle of the drum. These mixers are used for applications that require a short working time, long unloading time, remote sites (not suitable for ready-mix) and small deliveries[68]. A major use of these types of mixers is for zero or low slump (i.e. roller compacted cement concrete pavements).

4.1.2 Batching concrete

Batching is the process of measuring concrete mix ingredients by either mass or volume and introducing them into the mixer[9]. Concrete batching can be characterized by the order of loading the constituents into the mixer and the duration of the loading period. The loading period is extended from the time when the first constituent is introduced in the mixer to when all the constituents are in the mixer. ASTM C 94[70] and AASHTO M 157[71] require batching to be done by mass rather than by volume. Volumetric method (ASTM C 685[72] or ASASHTO M 241[73]) is used for batching concrete in a continuous mixer[9].

RILEM[74] (Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions) divides the loading period into two parts: dry mixing and wet mixing. Dry mixing is the mixing that occurs during loading but before water is introduced. Wet mixing is the mixing after or while water is being introduced, but still during mixing. The loading period is important because some of the concrete properties will depend on the order in which the constituents are introduced in the mixer. It is well known that the delayed addition of high range water-reducing admixture leads to a better dispersion of cement[25,27].

Specifications generally require the following batching delivery tolerances: cementitious material ± 1% by weight, aggregates ± 2% by weight, water ± 1% by weight (or volume at central mix plants only), and admixtures ± 3% by weight (or volume ± 1 ounce (30 milliliters), whichever is greater)[9,75].

4.1.3 Mixing concrete

Mixing concrete consists of blending its constituents until it is uniform in appearance with all ingredients evenly distributed. In many countries the mixing is performed in the truck where water and then dry materials are dosed into the truck. The truck mixing is not as efficient as the plant mixing, where much longer times, up to 20 minutes, are needed[9]. The required mixing time varies depending on the equipment, materials used, gradations of aggregates, amount and types of admixtures, temperature, etc. However, if factors such as segregation, bleeding, finishing and others are of concern, the first and easiest solution is to adjust the mixing time or speed. The mixing time requirements are recommended by the manufacturer of the mixer. Each mixer has attached in a prominent place a manufacturer's plate showing the capacity of the drum in terms of volume of mixed concrete and the speed of rotation of mixing drum or blades.

Generally, the mixing time is defined as the elapsed time between the loadings of the first constituent to the final discharge of the concrete[9,12]. RILEM[74] defines mixing time as the time between the loading of all constituents and the beginning of concrete discharge. In any case, it is important to fully describe the mixing process for each batch of concrete. *In the current study, the mixing time is defined as the elapsed time between the loading of the first ingredient to the beginning of concrete discharge, and during the mixing time the mixer is operated at the mixing speed.*

4.1.4 Ready-mixed concrete

In a ready-mixed plant, concrete is generally mixed using one or a combination of the following operations: (1) central mixing: the batched (weighed or metered) ingredients are added into a stationary mixer, completely mixed, and then delivered either in a truck agitator, a truck mixer operating at agitating speed, or a nonagitating truck for transporting to the point of discharge. (2) shrink mixing: concrete is partially mixed in a stationary mixer and the mixing is complete en route in a truck mixer; and (3) truck mixing: concrete is mixed entirely in the truck mixer[9]. Nowadays, ready-mixed plants are largely used in concrete industry due to the numerous related advantages, such as: close quality control, use in congested sites, use of agitator trucks to prevent segregation and maintain workability[10], etc. The cost of ready-mixed concrete may be higher than that of site-mixed concrete, but the in-place concrete cost can be cheaper by saving in construction time, organization, labor and cement content.

4.1.5 Hauling concrete

Several methods for transporting and handling concrete exist and the most important are: wheelbarrows or handcarts, dumpers, lorries, buckets, chutes, belts conveyors, pneumatic placers with pipeline, concrete pumps with pipelines, and truck mixers[9,12,69]. The choice of the transportation method depends on economic consideration and the quantity of concrete to be transported. In most cases truck mixers are used for mixing and hauling concrete, and truck agitators are used for hauling central-mixed concrete. In some cases nonagitating (e.g., flatbed) trucks can be also used for delivering concrete (e.g., pavement). *The hauling time, which can be defined as the elapsed time between the first contact of water and cement to the beginning of concrete discharge*, ranges usually between 30 minutes (when the concrete is hauled in nonagitating trucks) to 90 minutes (when the concrete is hauled in truck mixers or truck agitators). In the case of hot weather or under other conditions contributing to quick stiffening of concrete, the maximum allowable time may be reduced[75]. Short mixing periods will reduce the amount of entrained air and will likely lead to a non-uniform mixture. During the hauling time the mixer is operated at the agitating speed.

4.1.6 Mixing and hauling of self-consolidating concrete

Self-consolidating concrete requires special attention in the mixing and delivery method due to its low water content relative to the high cementitious materials content. Shrink mixing or truck mixing can be used. Several researchers have reported that the length of mixing and the time of addition of superplasticizers to SCC can influence both its fresh and hardened properties. Due to its high fluidity, the volume of SCC placed into a truck should not exceed 80% of the drum capacity. This type of monitoring will prevent the SCC from spilling out of the drum during hauling. Concrete truck operators should keep the drum revolving in a mixing rotational direction while in transport. Self-consolidating concrete can also be made from conventional concrete by adding admixtures at the discharge site to bring the mixture to the desired consistency[1].

In general, slump flow loss occurs when the free concrete’s mixing water is absorbed by the hydration reactions, adsorbed on the surfaces of cement hydrated products, or by evaporation[9,10]. It can be defined as the loss of consistency in fresh concrete with elapsed time. It is a normal phenomenon which is related to the intrinsic nature of concrete. Mixing at a high speed or for a long period of time (about one or more hours); and high temperature due to excessive heat of hydration in mass concreting, and/or the use of hot materials can result in slump loss[9,10,12,69]. The slump flow loss can lead to an unusual rate of stiffening in fresh concrete and cause loss of entrained air, strength and durability; difficulty in pumping and placing; and excessive effort in placement and finishing operation[9,12].

To overcome the slump flow loss, two main remediation methods are generally practiced. They consist of starting with a higher initial slump than needed (overdosing), or adding extra water or admixtures just before placement which is referred to as retempering. The progressive increase use of chemical admixture in concrete industry has facilitated the control of slump loss. Superplasticizers or high range water-reducing admixtures were developed in order to improve the dispersibility and the slump retention of melamine and naphthalene type admixtures. Their extended life can impart up to 2 hours longer working life of concrete[30]. Overdosing the admixture amount in attaining the target slump flow at job site or retempering with admixture instead of water are the preferred methods in remediation of the slump flow loss. The use of extra water in retempering or in making a higher initial slump can induce side effects on the properties and serviceability of the hardened concrete (i.e. decrease in strength and durability, increase in permeability and drying shrinkage, etc.)[9,10,12].

4.2 Experimental programs

The self-consolidating concretes S7.B.SF20, S7.B.SF25, and S7.B.SF28 were used. Their mixture constituents and proportions are presented in Table 3.1c. The detail of design proportioning procedure is shown in Task 3. Laboratory trial mixtures were used to produce all SCCs. An electric counter-current pan mixer with a capacity of 1 ft^3 (0.028 m^3) was used to blend concrete components. A pan mixer was preferred because it is particularly efficient for mixing small quantities of concrete in a laboratory. In simulating the influence of hauling time on the fresh SCCs, a realistic concrete mixing tool with changeable velocity was needed. Therefore, a speed control box was designed and mounted on the mixer to control its rotational velocity during hauling. Figure 4.1 documents the actual mixing apparatus used in this study. The aggregates, cement, fly ash, water and chemical admixtures were prepared as reported in Task 2; and stored in the laboratory prior to their use. The laboratory room condition was always maintained at 25±5% relative humidity and 70 ± 3 ^oF (21 ± 2 ^oC) temperature. The concrete mixtures at the end of hauling time were used to determine the unconfined workability, flow rate or plastic viscosity per inference, segregation resistance, and J-ring passing ability in accordance with the ASTM C 1611[49] and C 1621[50]. The test results were measured immediately after the hauling time to avoid any variation in the concrete properties over time.

The workability of concrete is influenced by the mixing tool, velocity and time.

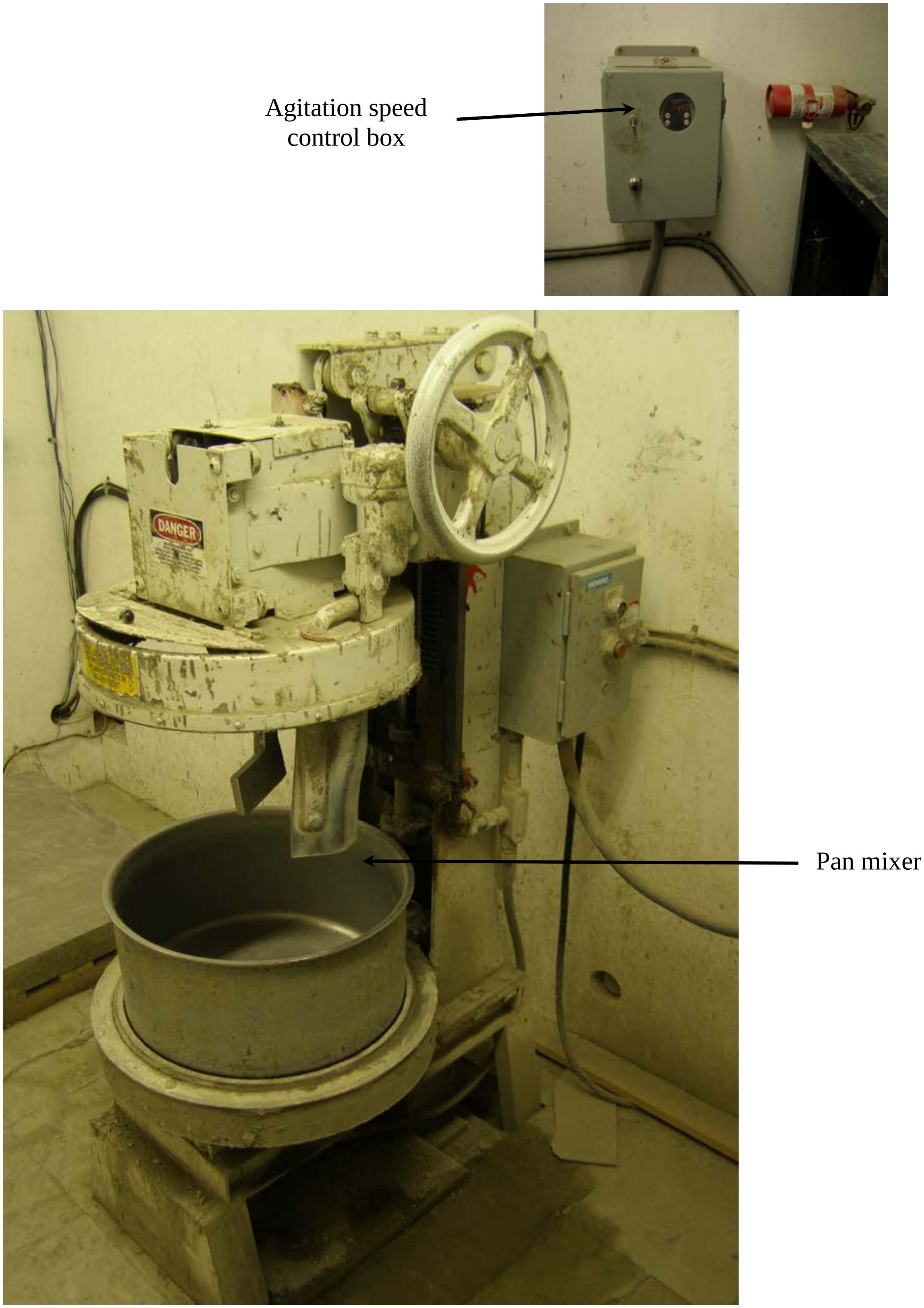


Figure 4.1: Mixing tool and agitation speed control box

Because of its low water content relative to the amount of cementitious materials, self-consolidating concrete requires a higher mixing energy than conventional concrete to thoroughly distribute the ingredients. In fact, when water is added to dry matrix, the inter-particle forces are increased due to the water surface tension and the capillarity pressure inside the fluid bond. In the presence of superplasticizer, the fluidity of the matrix further increases, resulting in a lower required mixing energy. The need for transporting concrete to its final place of deposit requires additional mixing time. In order to reflect the high energy level followed by a lower energy needed in the production and transport of SCC, a mixing and hauling procedure as shown in Figure 4.2 was adopted. *As it can be seen, the hauling time was defined as the elapsed time between the first contact of water and cementitious materials to the beginning of concrete discharge.*

4.3 Discussion of results

4.3.1 Influence of hauling time on fresh performance of SCC

During the present study, the effect of hauling time on the unconfined workability (measured by the slump flow), the flow rate (evaluated by the T_{50} time), and the dynamic segregation resistance (assessed by the VSI) was investigated. Tables 4.1, 4.2, and 4.3 document the test results.

4.3.1.1 Unconfined workability

The measured slump flows at the end of 20, 30, 40, 50, 60, 70, 80, and 90 minutes of hauling time were compared to that of the reference (control) hauling time of 10 minutes. Figure 4.3 represents the slump flow losses of the selected trials matrices as a function of hauling times. It can be seen from the abovementioned tables and figure that all three selected self-consolidating concretes lost slump flow as early as 20 minutes hauling time. In comparing to 10 minutes hauling time, mixtures made with 20 inches (508 mm) slump flow displayed slump flow losses of 16, 21, 23, 26, 30, 35, 36, and 38% at 20, 30, 40, 50, 60, 70, 80, and 90 minutes hauling time, respectively. The corresponding slump flow losses were 14, 17, 20, 24, 29, 34, 36, and 38%; and 7, 12, 17, 21, 25, 31, 35, and 37% for the mixtures prepared for 25 and 28 inches (635 and 711 mm) slump flows, respectively. The decrease in slump flow can be translated to the loss in ability of self-consolidating concrete to flow through unconfined areas or formwork.

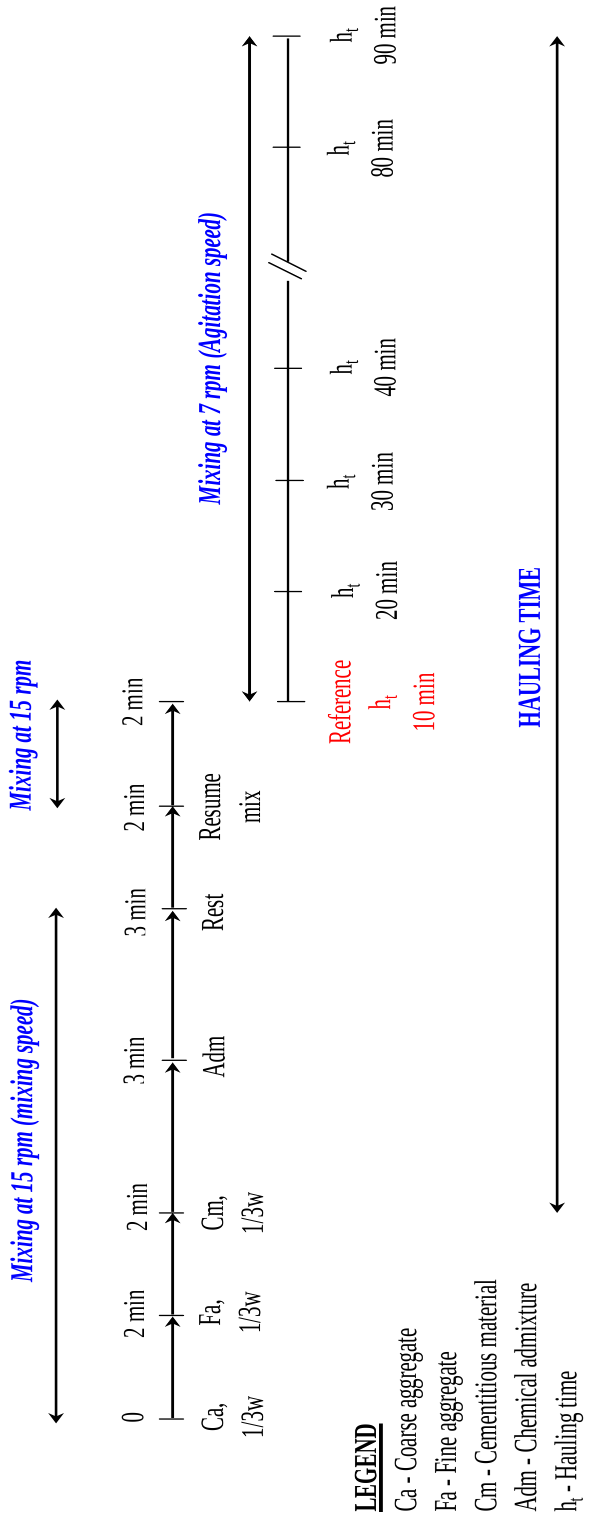


Figure 4.2: Mixing and hauling sequences

Table 4.1: Slump flow loss of SCC with an initial slump fow of 20 inches

Hauling time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump flow (in.)	T_{50} (sec.)	VSI	Slump flow loss (in.)
10	2.30	0.00	20.63	3.19	0	0.00
20	2.30	0.00	17.25	-	0	-3.38
30	2.30	0.00	16.25	-	0	-4.38
40	2.30	0.00	15.82	-	0	-4.82
50	2.30	0.00	15.25	-	0	-5.38
60	2.30	0.00	14.50	-	0	-6.13
70	2.30	0.00	13.50	-	0	-7.13
80	2.30	0.00	13.25	-	0	-7.38
90	2.30	0.00	12.75	-	0	-7.88

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

Table 4.2: Slump flow loss of SCC with an initial slump fow of 25 inches

Hauling time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump flow (in.)	T_{50} (sec.)	VSI	Slump flow loss (in.)
10	3.20	0.40	25.63	2.79	0	0.00
20	3.20	0.40	22.00	2.92	0	-3.63
30	3.20	0.40	21.25	3.10	0	-4.38
40	3.20	0.40	20.50	3.28	0	-5.13
50	3.20	0.40	19.50	-	0	-6.13
60	3.20	0.40	18.25	-	0	-7.38
70	3.20	0.40	17.00	-	0	-8.63
80	3.20	0.40	16.50	-	0	-9.13
90	3.20	0.40	16.00	-	0	-9.63

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

Table 4.3: Slump flow loss of SCC with an initial slump fow of 28 inches

Hauling Time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump flow (in.)	T_{50} (sec.)	VSI	Slump flow loss (in.)
10	3.90	0.50	28.50	1.85	1	0.00
20	3.90	0.50	26.50	2.20	0	-2.00
30	3.90	0.50	25.00	2.55	0	-3.50
40	3.90	0.50	23.75	2.67	0	-4.75
50	3.90	0.50	22.50	2.80	0	-6.00
60	3.90	0.50	21.50	3.00	0	-7.00
70	3.90	0.50	19.75	-	0	-8.75
80	3.90	0.50	18.50	-	0	-10.00
90	3.90	0.50	18.00	-	0	-10.50

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

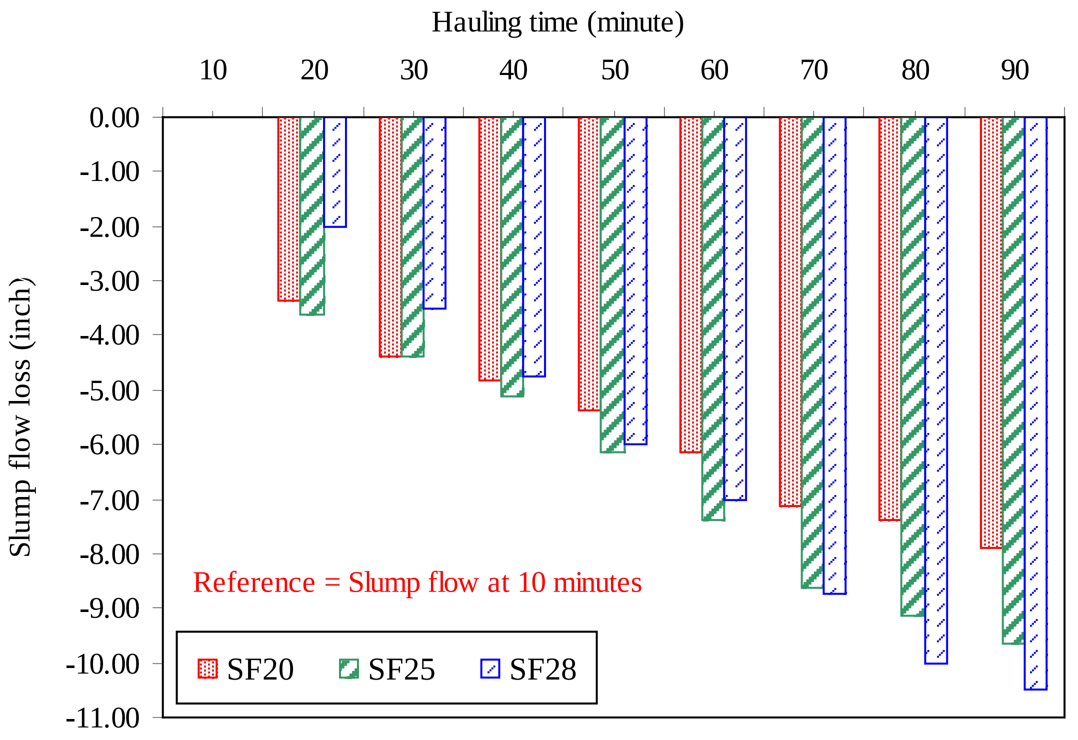


Figure 4.3: Slump flow loss of self-consolidating concretes as a function of hauling time

4.3.1.2 Flow rate or viscosity per inference

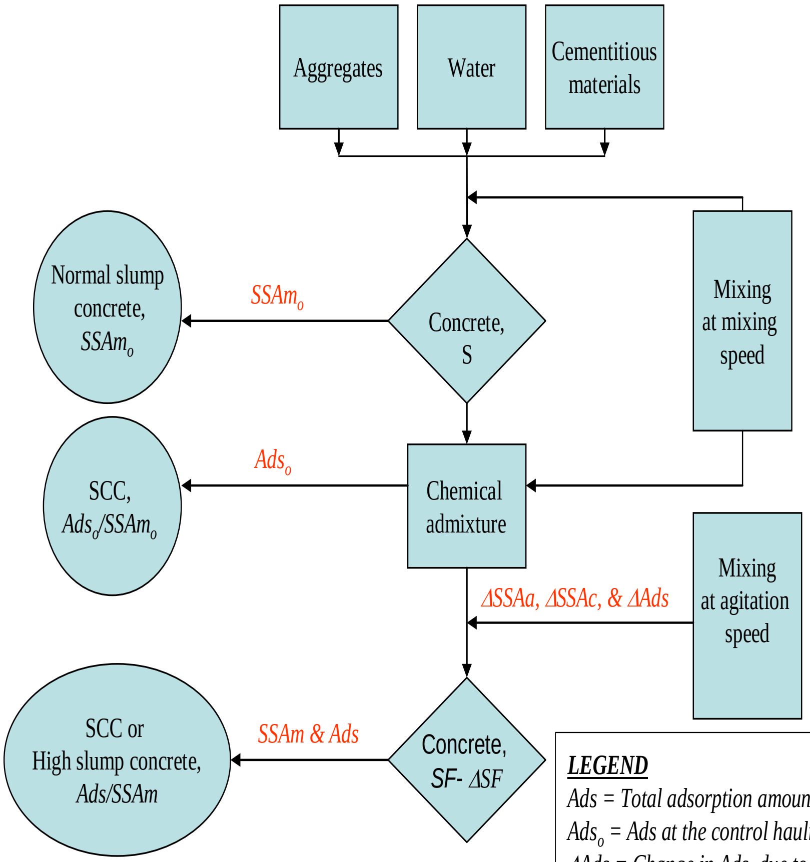
As an index of viscosity, the T_{50} times of the selected self-consolidating concretes were also recorded and compared to that of the reference hauling time. Irrespective of the slump flow value, the T_{50} always increased with an increase in hauling time. At hauling time of 20 minutes and more, the T_{50} of the mixtures made for 20 inches (508 mm) slump flow could not be measured since the concrete spread was less than the 20 inches (508 mm) recommended value. In comparison with the 10-minute reference hauling time, the T_{50} time of the mixture made for 25 inches (635 mm) slump flow increased by 0.13, 0.31, and 0.49 second after 20, 30, and 40 minutes hauling times, respectively. Beyond that time, the T_{50} could not be measured due to the severe loss in slump flow. For the mixture made with 28 inches (711 mm) slump flow, the increases in T_{50} time were 0.35, 0.70, 0.82, 0.95, and 1.15 seconds after 20, 30, 40, 50, and 60 minutes hauling time, respectively; after which the mixture displayed a significant loss in slump flow. An increase in T_{50} time is indicative of enhanced viscosity. It is to note that the T_{50} times of the selected self-consolidating concretes were all within the recommended value of 2 to 5 seconds.

4.3.1.3 Dynamic segregation resistance

The influence of hauling time on dynamic segregation resistance of the selected matrices was also evaluated through the visual stability index (VSI). Irrespective of slump flow value, all selected self-consolidating concretes displayed high stability (VSI = 0) for the selected hauling times.

4.3.2 Mechanism of slump flow loss due to hauling time

The fundamental mechanism of slump loss of concrete during the hauling process has been established and reported by several, studies. It mainly involves the additional fines brought to the concrete mortar by the grinding of aggregates and cement particles, the growth of the cement hydrated products, and the adsorption of the superplasticizer on the cement hydrates throughout the hauling time[9,29,76,77,78,79]. The flow chart of Figure 4.4 presents the phases and actions involved in aggregate-cement-admixture mechanical interaction during mixing and hauling.



$$\frac{Ads}{SSAm} = \frac{Ads_o + \Delta Ads_{ht}}{SSAm_o + \Delta SSAa + \Delta SSAc}$$

LEGEND

Ads = Total adsorption amount of admixture
Ads_o = Ads at the control hauling time
ΔAds = Change in Ads_o due to haling time ht
SSAm = Total specific surface area of concrete mortar
$SSAm_o$ = SSAm at the control hauling time
$\Delta SSAa$ = Increase in SSAm due to aggregates grinding
$\Delta SSAc$ = Increase in SSAm due to friction between cement particles and growth of cement hydrated products
S = Concrete slump
SF = SCC Slump flow
ΔSF = Change in SF

Figure 4.4: Self-consolidating concrete production and slump flow loss mechanism during hauling

Since the fluidity of concrete is mostly controlled by the fluidity of the mortar portion[1,78,80], the slump flow losses recorded during the present investigation can be explained through the specific surface area of concrete mortar (*SSAm*) and adsorption amount of chemical admixtures (*Ads*). The ratio *Ads/SSAm* will be used to characterize the fresh performance of self-consolidating concrete.

4.3.2.1 Specific surface area of concrete mortar (*SSAm*)

The specific surface area (SSA) can be defined as a material property which measures the total surface area per unit of mass (with units of m^2/kg), solid or bulk volume (units of m^2/m^3 or m^{-1}). It has a particular importance in the case of adsorption and reactions on surfaces. The value of the specific surface area depends critically upon the method of measurement. The SSA can be calculated from a particle size distribution, making some assumption about the particle shape. This method, however, fails to account for surface associated with the surface texture of the particles.

The increase in the specific surface area of SCC mortar due to hauling can be attributed to the combined effect of three factors, namely: aggregate grinding, cement particles' grinding, and growth of cement hydrated products.

- *Aggregate grinding*

During the hauling process of concrete further collisions between aggregate particles; as well as between them and the wall and blades of the mixing pan took place. This phenomenon resulted in additional fine particles from the abraded aggregates; and led to an increase in specific surface area of the concrete mortar (*ΔSSAa)*. The resulting matrix contributed to an increase in the SCC slump flow loss.

- *Cement particles' grinding*

Similarly to the aggregates, abrasion of the cement particles during the hauling also contributed to the increase in specific surface area of concrete mortar (*ΔSSAc)*. The friction between the cement particles as well as between the cement particles and mixing tool disaggregated cement clinker into finer cement particles with higher specific surface areas. During the flocculation system, the finer cement particles bond thicker and stickier necessitating higher repulsive forces (through additional admixture dosages) for their dispersion.

- *Growth of cement hydrated products*

Cements are reactive multimineral powders whose particle's surface grows with time mainly in the presence of water where the surface area of ordinary Portland cement can increase by 2 to 2.5 times[81]. The growth of the cement hydrated product can be attributed to the tricalcium aluminate's (C_3A) final hydrated product and the formation of ettringite compound (calcium aluminate trisulfate, $C_3A \cdot 3Cs \cdot H_{32}$)[18,25,78]. In fact, in the presence of mixing water, the C_3A compound hydrates very rapidly (during the initial hydration) as it first converts into unstable phases and then into stable calcium aluminate hydrate phase (C_3AH_6) which has a larger surface area than the original C_3A (see equation 1.3). Additionally, in the presence of the dissolved Ca^{2+} and $H_2SiO_4^{2-}$, the C_3A is converted into ettringite which has also larger specific surface area than other cement hydrated phases such as: gypsum ($CaSO_4$), portlandine (CH), calcium silicate hydrate (CSH), and calcite (stable polymorph of $CaCO_3$)[76]. These progressive growths of cement hydrated products throughout the hauling process (*ΔSSAc)* contributed to the slump flow loss by affecting the overall specific surface area of the concrete mortar.

4.3.2..2 Adsorption of HRWRA during the hauling of SCC

The mechanism of action of Portland cement-superplasticizer involves adsorption first, and then electrostatic and steric hindrance repulsions. In concrete, the most important parameter in cement-admixture interaction is not the adsorption amount per mass of clinker minerals, but it is the adsorption amount per surface area of hydrated cement paste[69]. Due to the repulsive electrostatic and steric hindrance forces created between cement particles by the adsorbed polycarboxylate molecules on cement particles, the fluidity of the system significantly increases in the presence of the admixture. The amount of admixture molecules adsorbed in cement particles (*Ads*) characterizes the intensity of that fluidity. In the presence of a uniform SSAm, the higher *Ads* is, the higher fluidity becomes.

The direct measure of adsorption is beyond the scope of this investigation. However, in Task 3, it was found that the production of higher slump flow matrices required increases in the amount of polycarboxylate-based high range water-reducing admixture (PC-HRWRA) dosages. In another word, the higher amount of the superplasticizer resulted in a higher rate of adsorption on cement grains, which in turn, provided a more fluid fresh matrix.

The ultraviolet-visible (UV/Vis) spectroscopy can be used to determine the cement-water-superplasticizer solution concentration of free admixture, from which correlation between hauling time and the amount of adsorption can be made. A companion investigation made by Ghafoori N., and Diawara H.,[82] revealed that the concentration of free admixture in cement-water solution increased as hauling time increased up to 80 minutes. Beyond that time, gradual decreases were recorded as longer hauling times of 100, 140, and 180 minutes were used. The increase or decrease in admixture concentration led to an increase or decrease in admixture adsorption on cement particle. This finding is in line with the theory of Ads variation with hauling time used to characterize the fresh performance of self-consolidating concrete through the expression Ads/SSAm in the flow chart of Figure 4.4.

From the beginning of the mixing up to the end of the hauling, not only do the hydrating minerals evolve, but the chemical composition of the solution also changes. During the hydration of Portland cement, the dissolved Ca^{2+} and $H_2SiO_4^{2-}$ ions are hydrolyzed from C_3A and C_3S. These Ca^{2+} ions produce positive charged surface-adsorbed layer around the cement particles. In the presence of a superplasticizer, the hydrophilic end of the molecule chain (i.e. COO^-) is adsorbed to the cement particles, and the admixture adsorption rate is higher during the first few minutes of the hydration reaction. Beyond the rapid initial adsorption (to saturate the most reactive phases), the admixture uptake by the hydrating cement continues at a reduced rate. Continuing adsorption occurs, mainly due to the growth and abraded product of new hydrated particles. During the induction period of cement hydration, the solution concentration of free admixture decreases, and simultaneously the sulfate ion (SO_4^{2-}) concentration increases with elapsed time. The increase in sulfate ion concentration is due to the solubility product of gypsum. The adsorption of polycarboxylate-based superplasticizer on cement particles by the carboxylic group may be prevented by the competitive adsorption between the sulfate ions and the dissociated carboxylic group on cement particles. The reduction in the adsorption amount of admixture contributed to the loss in fluidity of the trial matrices[18,25,78].

In summary it can be concluded that the fresh performance of SCC, such as: flow ability, flow rate, and dynamic stability can be characterized by *Ads/SSAm*. While both Ads and SSAm increased with hauling time (up to 80 min for the Ads), the contribution of SSAm on the slump flow loss was greater than that of Ads. In fact, the ratio Ads/SSAm decreases with increase in hauling time and can be expressed as follows:

$$\frac{Ads}{SSAm} = \frac{Ads_o + \Delta Ads_{ht}}{SSAm_o + \Delta SSAa + \Delta SSAc} \tag{4.1}$$

The terms Ads, Ads_o, ΔAds_{ht}, $SSAm$, $SSAm_o$, $\Delta SSAa$, and $\Delta SSAc$ are defined in Figure 4.5.

4.3.3 Predictive statistical equation of hauling time's slump flow loss

Predictive statistical analysis at a 95% confidence level was conducted to determine the slump flow loss due to hauling time. The predictive equation was tested for accuracy using R² (the coefficient of multiple determination) and S (average standard deviation). The slump flow loss can be related to the initial slump flow and the hauling time as follows:

$$SF_{loss} = 0.027379\left(SF^{0.581965}\right)\left(h_t^{0.891310}\right) \tag{4.2}$$

Or $SF_{loss} = a\left(SF^{b}\right)\left(h_t^{c}\right)$, Where:

SF_{loss} = Slump flow loss at the end of the hauling time (inch)

SF = Initial SCC slump flow (inch), with 20 inches ≤ SF ≤ 28 inches

h_t = Target hauling time (minute), with 10 minutes ≤ h_t ≤ 90 minutes

The regression equation (4.2) produced a R² and S values of 94.2% and 0.75 inch, respectively, indicating a strong relationship between the dependent variable (slump flow loss) and the independent variables (initial slump flow and hauling time). F and T tests were performed to confirm the significance of coefficients a, b and c, in the regression model. The following results were found: Prob(t) = 0.1236, 0.0000, 0.0029 for a, b and c, respectively, and Prob(F) = 0, indicating that both the slump flow value and the hauling time have similar influence on the predictive slump flow loss induced by the hauling process.

4.3.4 Remediation of slump flow loss

A remediation method based on admixture overdosing was adopted to attain the target fresh properties at the completion of each selected hauling time. Tables 4.4, 4.5, and 4.6 present the required optimum dosages of admixtures along with the recorded slump flows, T_{50} times, VSI ratings, and J-ring values at different hauling times.

4.3.4.1 HRWRA dosage requirement for the remediation of slump flow loss

Figure 4.5 presents the optimum dosages requirement of HRWRA for the remediation of slump flow loss due to hauling time. Irrespective of the SCC mixtures, the optimum dosage of HRWRA in attaining the required workability increased as the hauling time increased. In comparing to the optimum dosage at the control 10 minutes hauling time, the mixture made for 20 inches (508 mm) of slump flow required 13, 22, 30, 39, 48, 52, 65, and 74% more HRWRA at 20, 30, 40, 50, 60, 70, 80, and 90 minutes hauling times, respectively. The corresponding increases in HRWRA optimum dosages. were 16, 22, 25, 31, 38, 44, 50, and 56 %; and 8, 13, 21, 28, 33, 38, 46, and 51 % for the SCCs prepared for 25 and 28 inches (635 and 711 mm) of slump flow, respectively.

The higher demand for the superplasticizer in contesting the slump flow loss of the selected SCCs, induced by the hauling process, can be explained through Figure 4.4 and equation (4.1). The idea behind the adopted remediation technique was to find by trial and error an initial admixture dosage in which $(Ads/SSAm)_{ht}$ at the end of hauling time became identical or nearly identical to $(Ads/SSAm)_{10}$ at the control 10 minutes hauling time. The term h_t refers to the hauling at time (t = 20 to 90 minutes). This was achieved by admixture overdosing and is explained through the equations (4.30 and (4.4).

- *At 10 minutes hauling time:*

$$\left(\frac{Ads}{SSAm}\right)_{10} = \frac{Ads_o}{SSAm_o} \tag{4.3}$$

- *During the remediation, at hauling time h_t:*

$$\left(\frac{Ads}{SSAm}\right)_{ht} = \underbrace{\frac{Ads_o + \Delta Ads_{ht1}}{SSAm_o + \Delta SSAa + \Delta SSAc}}_{\textcircled{A}} + \underbrace{\frac{\Delta Ads_{ht2}}{SSAm_o + \Delta SSAa + \Delta SSAc}}_{\textcircled{B}} \approx \left(\frac{Ads}{SSAm}\right)_{10} \tag{4.4}$$

Table 4.4: Admixtures dosages and fresh properties of remediated SCC mixture S7.B.SF20

Time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump flow (in.)	T_{50} (sec.)	VSI	J-ring value (in.)
10	2.30	0.00	20.50	3.19	0	1.38
20	2.60	0.00	20.50	3.25	0	1.13
30	2.80	0.00	20.38	3.48	0	1.49
40	3.00	0.00	20.50	3.10	0	0.88
50	3.20	0.00	20.44	3.69	0	0.82
60	3.40	0.00	20.45	3.79	0	0.82
70	3.50	0.00	20.38	3.08	0	1.13
80	3.80	0.00	20.25	3.11	0	1.13
90	4.00	0.00	20.38	3.00	0	0.75

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

Table 4.5: Admixtures dosages and fresh properties of remediated SCC mixture S7.B.SF25

Time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump flow (in.)	T_{50} (sec.)	VSI	J-ring value (in.)
10	3.20	0.40	25.63	2.79	0	1.13
20	3.70	0.40	25.31	2.29	0	1.31
30	3.90	0.40	25.25	2.22	0	1.25
40	4.00	0.40	25.13	2.33	0	1.13
50	4.20	0.40	25.38	2.24	0	0.75
60	4.40	0.40	25.13	2.34	0	1.38
70	4.60	0.40	25.38	2.30	0	1.38
80	4.80	0.40	25.38	2.33	0	1.38
90	5.00	0.40	25.25	2.30	0	1.13

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

Table 4.6: Admixtures dosages and fresh properties of remediated SCC mixture S7.B.SF28

Time (min)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump Flow (in.)	T_{50} (sec.)	VSI	J-ring value (in.)
10	3.90	0.50	28.50	1.85	1	1.00
20	4.20	0.50	28.25	1.97	1	0.63
30	4.40	0.50	28.00	2.03	1	0.75
40	4.70	0.50	28.13	2.13	1	0.56
50	5.00	0.60	28.25	1.98	1	0.50
60	5.20	0.60	28.50	2.02	1	0.63
70	5.40	0.70	28.30	1.94	1	0.32
80	5.70	0.80	28.25	2.02	1	0.63
90	5.90	0.90	28.13	2.13	1	0.56

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm

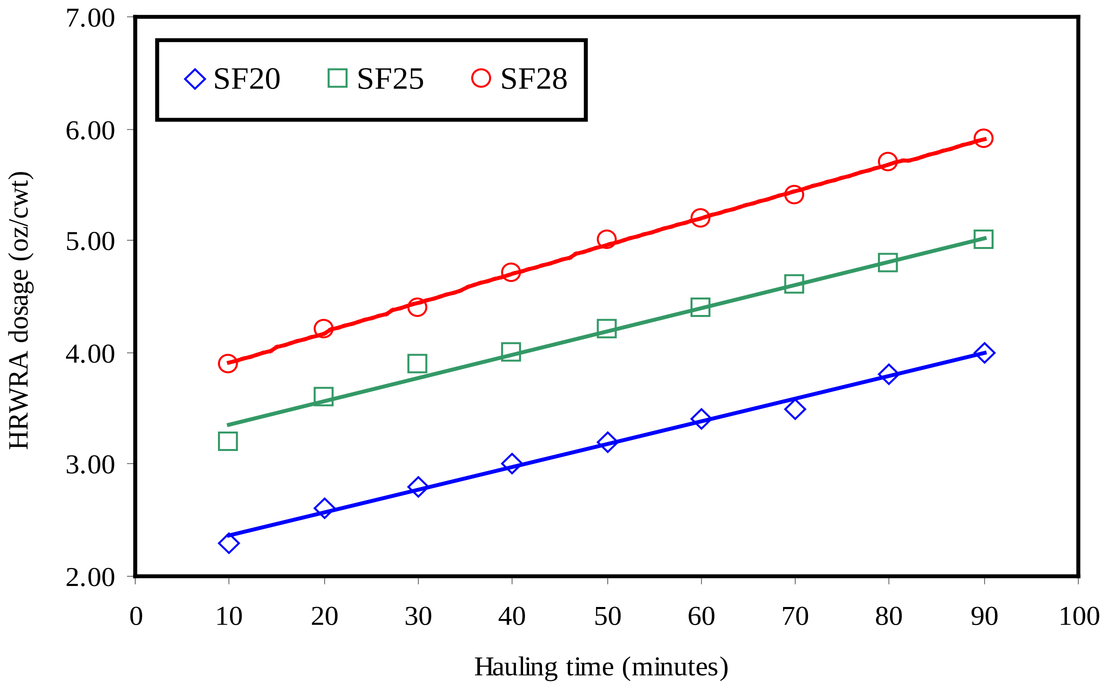


Figure 4.5: Optimum dosage of HRWRA for remediation of slump flow loss due to hauling time

Ⓐ Characterizes the slump flow loss

Ⓑ Characterizes the slump flow restoration

ΔAds_{ht1} and ΔAds_{ht2} in Equation 4.4 correspond to the increases in adsorption amount of admixture during the hauling time and brought by the additional superplasticizer used for the remediation purpose, respectively. The term "ΔSSAa + ΔSSAc" reflects the increase in specific surface area of concrete mortar due to the additional fines brought by the grinding of aggregates and cement particles, and the growth of the cement hydrated products. While Ads and SSAm increased with hauling time (up to 80 min for the Ads), the contribution of SSAm on the slump flow loss was greater than that of Ads.

In remediating the slump flow loss, the designed optimum dosages of HRWRA at h_t were sufficient to maintain the solution concentration of free admixture and sulfate ion at the level that produced adequate amount of adsorption to meet the target fluidity at the end of the hauling time h_t. ΔAds_{ht2} generated additional repulsive electrostatic and steric hindrance forces between the cement particles to further disperse the cement agglomerations provoked by the grinding and hydration of cement particles in the course of hauling time.

The rate of HRWRA dosage increment was higher at 20 minutes hauling time (0.3, 0.5 and 0.3 oz/cwt (20, 33, 20 ml/100 kg) for 20, 25, and 28 inches (508, 635, and 711 mm)) slump flows, respectively, and became constant thereafter at about 0.2 oz/cwt (13 ml/100 kg) per 10 minutes hauling time increment, irrespective of the slump flow target. In remediating the slump flow loss, the higher demand of HRWRA during the first 20 minutes hauling time may be attributed to the rapid ettringite formation (during the first 15 minutes of cement hydration). The hydrated phase of ettringite is formed around the C_3A grains and protects them from further rapid hydration during the dormant period. The larger specific surface area of ettringite required higher superplasticizer dosages to restore the SCC fluidity back to its initial level. The decrease in the rate of superplasticizer dosage can be attributed to the availability of a lower amount of C_3A found in Type V Portland cement in producing ettringite compounds at the higher hauling times.

4.3.4.2 VMA dosage requirement for the remediation of workability loss

Figure 4.6 shows the optimum dosages of VMA used to remediate the slump flow loss for different hauling times. Irrespective of the hauling time, self-consolidating concretes prepared with slump flows of 20 and 25 inches (508 and 635 mm) did not require any adjustments in their initial VMA dosage in reaching the target fresh properties. However, the matrices made with 28 inches (711 mm) slump flow required 0, 0, 0, 20, 20, 40, 60, and 80% augmentation at 20, 30, 40, 50, 60, 70, 80, and 90 minutes of hauling times, respectively, when compared to the required optimum dosage of VMA needed for the control hauling time. The results for the mixtures produced with 20 and 25 inches (508 and 635 mm) of slump flows can be explained through the increase in specific surface area of the concrete mortar (*SSAm*) induced by the hauling process as noted earlier. The viscosity modifying admixture is mainly used in SCC to increase its viscosity and stability. Despite a higher demand for HRWRA, the increase in *SSAm* during hauling may have been sufficiently effective in enriching and thickening the cement paste, resulting in a higher viscosity (T_{50} time between 2 and 5 seconds) and a higher VSI (0 or 1) of the trial self-consolidating concretes. On the other hand, after 40 minutes of hauling time, the increase in *SSAm* of the mixtures made of 28 inches (711 mm) slump flow may not have been enough to repair the destabilized viscosity and reduced stability generated by a higher dosage requirement of HRWRA. The additional VMA used in these mixtures helped the viscosity and stability by reverting them to their acceptable levels.

4.3.4.3 Fresh properties of remediated self-consolidating concretes

As reported in Tables 4.4, 4.5, and 4.6, the test results showed that independently of hauling time, all trial self-consolidating concretes were within the target slump flows ± 1.0 inch (25 mm), VSI of 0 (highly stable) or 1 (stable), T_{50} time of 2 to 5 seconds, and J-ring value of 1 to 2 inches (25 to 50 mm).

In comparing the slump flow values at different hauling times to that measured at the 10 minutes hauling time, the remediated fresh SCCs displayed an insignificant difference of less than 2%. All T_{50} times decreased as the slump flow increased, and within the same group of concrete remained similar to that of the reference hauling time. No evidence of segregation or bleeding in slump flow was observed in any of the selected

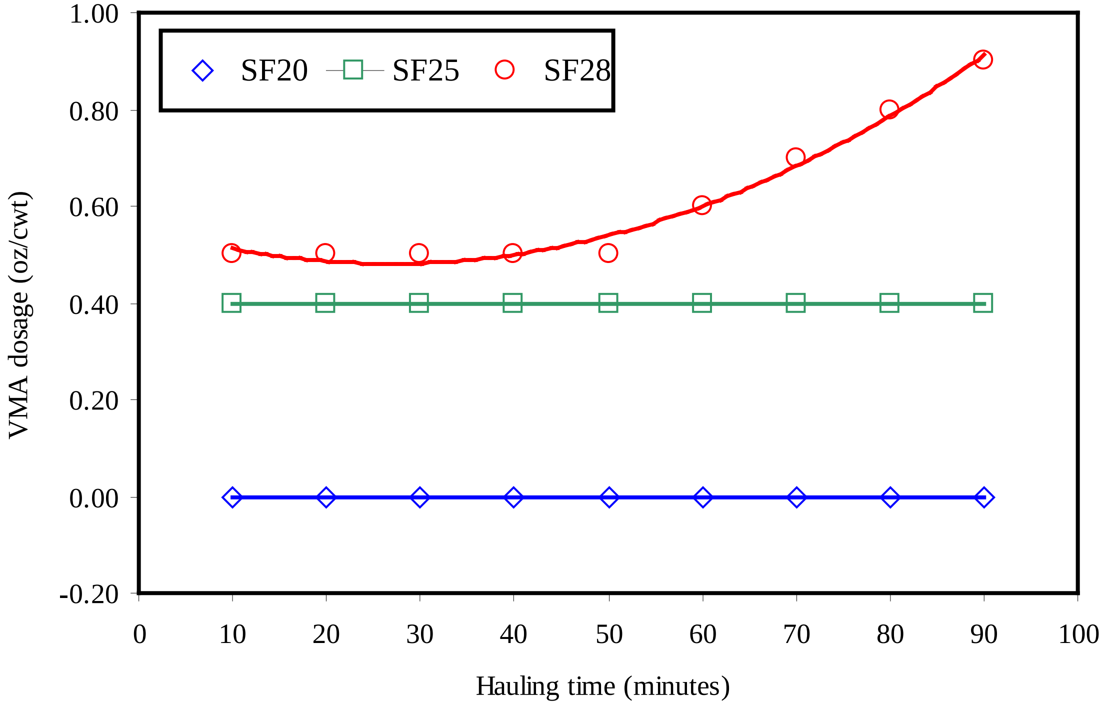


Figure 4.6: Optimum dosage of VMA for remediation
of slump loss due to hauling time

self-consolidating concretes, indicating that a stable matrix condition was achieved through the adopted overdosing remediation method.

Irrespective of the hauling time, the measured J-ring values of all trial matrices were within the allowable limit of 1 to 2 inches (25 to 50 mm) indicating a moderate passing ability or minimal to noticeable blocking of the selected self-consolidating concretes. As was the case for the unconfined workability and resistance to dynamic segregation, the overdosing method of remediation was effective in obtaining a passing ability which was similar to that of the control hauling time (10 minutes).

4.3.4.4 Predictive statistical equations of HRWRA and VMA optimum dosages for remediation of slump flow loss due to hauling time

The most suitable predictive relationships between the HRWRA or VMA optimum dosage, and the slump flow and hauling time of the remediated self-consolidating concretes were determined at 95% confidence level. The predictive equations were tested for accuracy using R^2 (regression value) and S (standard deviation). The relationships are as follows:

$$HR = 0.024479\left(SF^{1.342666}\right)\left(h_t^{\,0.215874}\right)$$

$$\text{Or } HR = a\left(SF^{b}\right)\left(h_t^{\,c}\right) \tag{4.5}$$

$$VMA = 14.00584 - \frac{734.59516}{SF} + 0.04465h_t + \frac{9939.24945}{SF^{2}} + 4.88721x10^{-5}\,h_t^{\,2} - 1.25636\frac{h_t}{SF}$$

$$\text{Or } VMA = a + \frac{b}{SF} + ch_t + \frac{d}{SF^{2}} + eh_t^{\,2} + f\,\frac{h_t}{SF} \tag{4.6}$$

Where:

HR = High Range Water Reducing Admixture initial optimum dosage (oz/cwt)

VMA = Viscosity Modifying Admixture initial optimum dosage (oz/cwt)

SF = Target SCC slump flow at the end of the hauling time (in.)

Equation 4.5 is valid for 20 inches ≤ SF ≤ 28 inches only

Equation 4.6 is valid for 25 inches ≤ SF ≤ 28 inches only

h_t = Target hauling time (min), with 10 minutes ≤ h_t ≤ 90 minutes

The regression variables R², S, Prob(t) and Prob(F) are given in Table 4.7. The calculated values are indicative of a good relationship between the dependent variable (HRWRA or VMA dosage) and the independent variables (slump flow and hauling time). However, the Prob(t) of 0.39 of coefficients b and d in equation (4.6) indicate that the slump flow value has less impact than the hauling time in predicting the VMA optimum dosage.

Table 4.7: Regression variables

	R^2	S	Prob (F)	Prob(t)					
	(%)	(oz/cwt)		a	b	c	d	e	f
For Equation (4.5)	98.00	0.14	0.00	0.00	0.00	0.00	-	-	-
For Equation (4.6)	95.60	0.04	0.00	0.38	0.39	0.00	0.39	0.01	0.00

4.4 Conclusions

The results of this section of the investigation revealed the following conclusions:

a) The fresh performance of self-consolidating concrete was affected by hauling time. The effects were manifested in the form of loss in flow ability, and gain in plastic viscosity and dynamic stability.

b) The change in fresh properties can be characterized by the adsorption amount of admixture per specific surface area of concrete mortar Ads/SSAm. The increase in hauling time increased both Ads and SSAm. The contribution of SSAm on the slump flow loss was greater than that of Ads.

c) Regardless of the slump flow value, the losses in slump flow due to hauling time were observed as early as 20 minutes, and increased with increasing hauling time. For the selected self-consolidating concretes made with slump flow of 20, 25, and 28 inches (508, 635 and 711 mm), the T_{50} could not be measured after 20, 40, and 60 minutes of hauling time, respectively, due to the severe loss in slump flow.

d) A remediation technique consisting of admixture overdosing was able to produce SCCs with a similar flow ability, plastic viscosity, dynamic stability, and passing ability to those obtained at the control hauling time. The rate of HRWRA dosage increment was higher at 20 minutes hauling time (0.3, 0.5, and 0.3 oz/cwt (20, 33, and 20 ml/100 kg) for 20, 25, and 28 inches (508, 635, and 711 mm) slump flows, respectively) and became constant thereafter at about 0.2 oz/cwt (13 ml/100 kg) per 10 minutes hauling time increment, independently of the slump flow. The additional amount of admixtures increased admixture adsorption and generated supplementary repulsive electrostatic and steric hindrance forces between cement particles. These forces further dispersed cement agglomerations provoked by the grinding and hydration of the cement constituents during hauling time.

e) The predictive equations to correlate: (1) the slump flow loss with the initial slump flow value and hauling time, and (2) the required amount of overdosed admixtures (HRWRA and VMA) with the target slump flow and hauling time, showed significant statistical relationships between the dependent and independent variables.

TASK 5

INFLUENCE OF TEMPERATURE ON FRESH PERFORMANCE OF SELF CONSOLIDATING CONCRETE

The goal of the Chapter 5 is to study the influence of extreme temperatures on the fresh performance of self-consolidating concrete. Seven different temperatures, namely: 109, 96, 83, 70, 57, 44, and 31 ^{o}F (43, 36, 28, 21, 14, 7, and -0.5 ^{o}C) to simulate hot and cold temperatures were used to evaluate the unconfined workability, the rate of flow ability or viscosity per inference, and the dynamic stability of the trial matrices. Additionally, the overdosing approach (sufficient initial optimum admixture dosage) was used to remediate the adverse influence of hot and cold temperatures on the fresh performance of the selected self-consolidating concretes.

5.1 Background on concrete in extreme temperatures

During the last half of the twenty century, the world climate has been unusual and unnatural due to a phenomenon called global warming. Warmer, colder, drier and wetter climate than the climatic average have been recorded all over the world. Scientific literatures and popular media have extensively reported the cause and consequence of the global warming.

The operation of the concrete industry is not immune from the adverse effect of extreme climatic conditions. Particularly, mixture proportioning, mixing, transporting, placing, and curing are all negatively impacted. The hot or cold weather can adversely affect the fresh and hardened properties of concrete by accelerating or retarding the rate of moisture loss and the rate of cement hydration.

5.1.1 Hot concrete temperature

Hot concrete temperature is mainly caused by hot weather or mass concreting. ACI Committee 305[83] defines hot weather as any combination of high air temperature, low relative humidity, and high wind velocity tending to impair the quality of fresh and hardened concrete or otherwise resulting in abnormal properties. The Standard Specification for Ready Mixed Concrete, ASTM C 94[70], reports that some difficulties may be encountered when concrete temperatures approach 90 ^{o}F (32 ^{o}C). Admissible hot concrete should have a temperature between 85 ^{o}F to 90 ^{o}F (29 ^{o}C to 32 ^{o}C) in the time of its placement[9].

The hot weather condition is transferred to the concrete through the concrete ingredients. High temperature of fresh concrete than normal results in a fast hydration of cement leading to an accelerated rate of setting and a lower long term strength and hardened properties. If the high temperature is accompanied by a low relative humidity, rapid evaporation of some mixing water takes place, causing loss of workability[9,10,69]. Other problems which can be induced by high concrete temperature are the tendency to plastic shrinkage, the potential for thermal cracking, and difficulty in controlling entrained-air. High temperature is also detrimental when placing large volume concrete[9,10,69]. During mass concreting, for instance in gravity dam, the hot concrete temperature is associated with possible cracking due to restraint to contraction on cooling from temperature rise provoked by the heat of hydration of cement[69].

Precaution can be taken in remediation to hot weather concreting. Starting with a higher initial slump than needed, or retempering the fresh concrete by adding water at the job site is frequently used to restore the loss of workability induced by the hot temperature. However, the extra water in concrete mixture may cause adverse effects in its hardened properties. The development and increase use of plasticizers and superplasticizers admixtures can make them a best overdosing or retempering material in hot weather condition at job site instead of water. Supplementary cementitious materials such as fly ash and ground granulated blast furnace slag are often used in hot concreting to slow down the rate of setting as well as the rate of slump loss[9]. Injection of liquid nitrogen into the mixer is performed if a greater temperature reduction is required. Liquid nitrogen can be added directly into a central mixer drum or the drum of a truck mixer to lower concrete temperature. It does not in itself influence the amount of mix water requirement[9]. Lowering the temperature of the concrete ingredients is also used to combat the undesirable effects of hot concreting[9,10,69]. The contribution of each ingredient in the freshly matrix temperature is related to the temperature, specific heat, and quantity of each material. Among all concrete material, water is the easiest to cool. Cooling the mix water temperature by 3.5 to 4 ^{o}F will usually lower the concrete temperature by about 1 ^{o}F (0.5 ^{o}C). Mixing water can be cooled by refrigeration, liquid nitrogen, or ice. Aggregates temperatures have more pronounced effect on the concrete temperature since they represent 70 to 85% of the total mass of concrete. In order to lower the temperature of concrete by 1 ^{o}F (0.5 ^{o}C), it is necessary to reduce the aggregate temperature by only 1.5 ^{o}F to 2 ^{o}F (0.8 ^{o}C to 1.1 ^{o}C). Aggregates can be cooled by shading the stockpile or keeping them moist by sprinkling. Refrigeration, circulation of cooled air through the storage bin can also be used to lower the aggregate temperature. Cement temperature has only a minor effect on the temperature of the freshly mixed concrete because of cement's low specific heat and the relatively small amount of cement in a concrete mixture. A cement temperature change of 9 ^{o}F (5 ^{o}C) generally will change the fresh concrete temperature by only 1 ^{o}F (0.5 ^{o}C)[9]. Retarding admixtures may also be beneficial in delaying the setting time.

5.1.2 Cold concrete temperature

Cold concrete temperature is usually caused by cold weather. ACI Committee 306[84] defines cold weather as a period when for more than 3 successive days the average daily air temperature drops below 40 ^{o}F (5 ^{o}C) and stays below 50 ^{o}F (10 ^{o}C) for more than one-half of any 24-hour period. Cold temperature affects the rate of cement hydration by retarding the setting, hardening and strength gain of concrete. As the temperature of concrete decreases, the rate of setting and hardening, and the development of strength decrease progressively until the freezing point is reached[9,10,69]. If concrete is frozen and remains frozen at 14 ^{o}F (-10 ^{o}C) it will gain strength slowly. Below that point the cement hydration and concrete setting and hardening process cease[9]. When the temperature rises again, thawing takes place and the setting and hardening resume. Ultimate compressive strength reduction of up to 50% can occur if concrete is frozen within a few hours after placement or before it attains a compressive strength of 500 psi (3.5 MPa)[9].

In order to alleviate or eliminate the adverse effect of cold temperature on concrete, the water and the aggregates can be heated or a heater can be applied in the mixer. The simplest and cheapest method consists of heating water, and water can hold five times the amount of heat held by aggregate or cement[10]. Water heated to 122 ^{o}F (50 ^{o}C) can produce a temperature of 61 ^{o}F (16 ^{o}C) in the resulting concretes even when the cement and aggregates have an initial temperature of only 4 ^{o}F (-15 ^{o}C). The approximate temperature of concrete can be calculated from the following equation[9]:

$$T = \frac{0.22\left(T_a M_a + T_c M_c\right) + T_w M_w + T_{wa} M_{wa}}{0.22\left(M_a + M_c\right) + M_w + M_{wa}} \tag{5.1}$$

Where,

T = temperature of the freshly mixed concrete, ^{o}F (^{o}C)

T_a, T_c, T_w, and T_{wa} = temperature in ^oF (^oC) of aggregates, cements, added mixing water, and free water on aggregates, respectively.

M_a, M_c, M_w, and M_{wa}= mass, lb (kg), of aggregates, cementing material, added mixing water, and free water on aggregates, respectively.

The use of ASTM C 150[13] Type III cement (high-early strength cement), additional cement content and chemical accelerators constitute also an alternative to increase the rate of initial hydration and, consequently produce high early-strength concrete. The increase in cost induced by high early-strength concrete can be tolerated in high-value added applications, especially when cost savings can be realized from the earlier reuse of forms and shore, earlier setting times that allows the finishing, and earlier use of structure[9].

The use of air entrainment admixture is strongly recommended in cold temperature concreting. The incorporation of suitable entrained air will help prevent strength loss and internal as well as surface damage resulting from the concrete freezing and thawing.

5.2 Experimental programs

Similarly to the Task 4, the self-consolidating concrete mixtures S7.B.SF20, S7.B.SF25, and S7.B.SF28 were used in the study of Task 5. Their mixture constituents and proportions are presented in Task 3, Table 3.1.c. Laboratory trial mixtures were used to produce the required self-consolidating concretes. An electric counter-current pan mixer with a capacity of 1 ft^3 (0.028 m^3) was used to blend concrete components. An environmental chamber to simulate hot or cold temperature conditions was built around the mixing apparatus. The walls, roof and floor of the room were made with plywood and insulated with polystyrene foam to maintain a uniform temperature throughout the experiments. The hot temperatures were generated by a heater while a cooling unit was used to produce the cold temperatures. A temperature regulator, which was connected to the heating and cooling units and assisted by multiple probes, maintained the target temperature within ± 3 ^oF (2 ^oC) margin. A separate control unit also monitored and recorded the relative humidity of the environmental chamber. Figure 5.1 shows the actual environmental chamber.

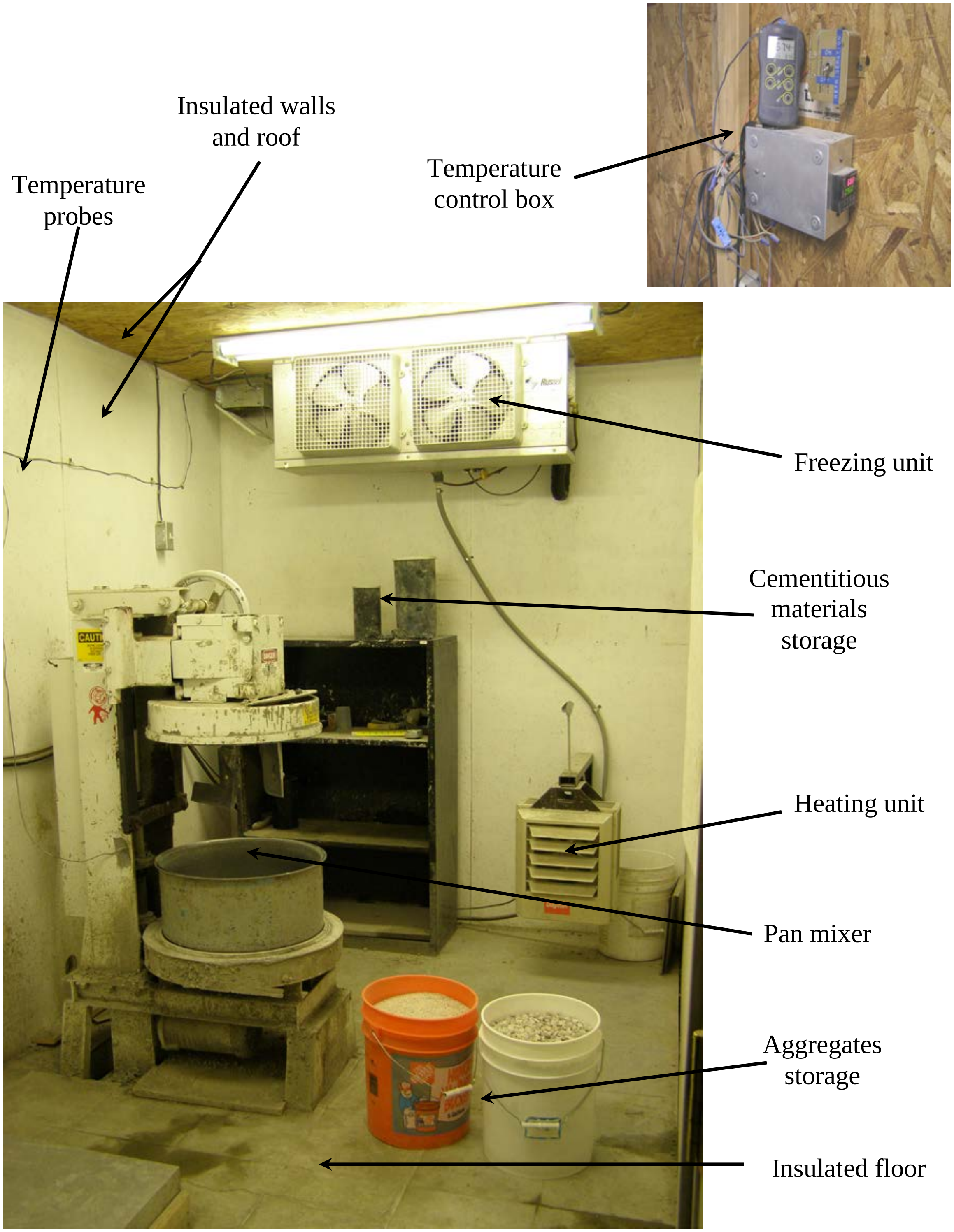


Figure 5.1: Environmental room and equipments

The concrete's dry ingredients (i.e., aggregate, cement and fly ash) were prepared as reported in Task 2, Section 2.2. Prior to the actual mixing, they were stored in the environmental chamber, as shown in Figure 5.1, for 24 hours or until they reached the target temperature. The effect of the mixing water temperature on the fresh performance of the selected matrices was not part of this study. Thus, the mixing water was kept at a constant temperature of 70 ± 3 ^{o}F (21 ± 2 ^{o}C) to avoid any interference with the rate of cement hydration. The HRWRA and the VMA were also kept at the normal laboratory conditions as recommended by the manufacturer. Table 5.1 presents the materials' temperatures and the chamber's environmental conditions at the time of mixing.

The mixing sequence was identical to that reported in Task 3, Section 3.2. Immediately upon completion of the mixing, the fresh self-consolidating concretes were evaluated for the unconfined workability (measured by the slump flow), the flow rate or viscosity by inference (evaluated by T_{50} time), the dynamic segregation resistance (evaluated by VSI), and J-ring passing ability in accordance with the ASTM C 1611[49], and C 1621[50].

In the present study, laboratory conditions characterized by a temperature of 70 ± 3 ^{o}F (21 ± 2 ^{o}C) and a relative humidity of 25 ± 5%, was used as the control condition. The selected hot temperatures were 109, 96, and 83 ^{o}F (43, 36, and 28 ^{o}C) while the cold temperatures were characterized by 57, 44, and 31 ^{o}F (14, 7, and -0.5 ^{o}C). The relative humidity reported in Table 5.1 were generated by heating or cooling of the environmental chamber. The impact of hot and cold temperatures on the performance of the selected self-consolidating concretes as related to the unconfined workability, flow rate, and dynamic stability is discussed below.

5.3 Discussion of results

5.3.1 Influence of hot temperature on fresh performance of SCC

Table 5.2 presents the fresh properties; namely: slump flows, T_{50}, and VSI of the trial self-consolidating concretes at the selected hot temperatures. Figure 5.2 displays the slump flow losses caused by the elevated temperature. In general, the hot temperature adversely affected the unconfined workability in the form of slump flow loss. In comparing to the control slump flow, the selected self-consolidating concretes displayed average slump flow losses of about 25, 12, and 5% at 109, 96, and 83 ^{o}F (43, 36, and

Table 5.1: Materials and mixing room environmental conditions

Mix No.	Target temp. (^{o}F)	Coarse aggr. (^{o}F)	Fine aggr. (^{o}F)	Cement & fly ash (^{o}F)	Water (^{o}F)	Admixtures (^{o}F)	Air temp. (^{o}F)	Relative humidity (%)
S7.B.SF20	109	111.45	107.80	112.40	69.60	71.50	110.95	16.75
S7.B.SF25		110.00	108.30	111.50	70.20	71.38	110.90	18.15
S7.B.SF28		110.30	107.60	112.40	69.80	72.90	110.70	17.70
S7.B.SF20	96	95.60	96.00	99.00	70.20	70.05	98.60	19.50
S7.B.SF25		96.10	96.50	98.40	70.20	70.30	98.10	19.50
S7.B.SF28		97.65	96.70	98.80	70.30	70.20	98.05	19.75
S7.B.SF20	83	84.40	83.60	85.00	70.20	69.00	86.00	20.20
S7.B.SF25		84.75	85.40	85.30	70.10	69.90	84.80	19.35
S7.B.SF28		82.95	84.85	85.30	70.20	70.20	85.50	19.50
S7.B.SF20	70	71.40	71.30	70.40	70.00	71.20	70.40	26.50
S7.B.SF25		80.80	71.00	70.60	69.80	71.00	70.60	25.30
S7.B.SF28		71.20	70.80	71.00	69.50	71.20	70.50	26.80
S7.B.SF20	57	58.50	58.50	58.60	69.90	70.00	57.60	45.50
S7.B.SF25		57.60	57.80	57.10	70.10	70.00	56.80	46.00
S7.B.SF28		57.40	57.80	56.80	70.20	69.00	56.70	44.75
S7.B.SF20	44	45.00	44.70	44.10	70.00	68.00	44.80	54.50
S7.B.SF25		45.50	45.40	44.30	70.20	69.00	45.20	53.50
S7.B.SF28		45.00	45.00	44.40	69.60	68.50	44.70	54.60
S7.B.SF20	31	31.60	30.85	31.15	70.20	69.00	31.10	70.00
S7.B.SF25		32.60	32.00	31.20	70.00	68.50	30.40	70.60
S7.B.SF28		32.30	32.35	31.95	70.1.	68.00	30.60	70.00

1 ^{o}F = 9/5 ^{o}C + 32

Table 5.2: Slump flow change induced by hot or cold temperatures

Mix No.	Target temp. (^{o}F)	Matrix temp. (^{o}F)	HRWR (oz/cwt)	VMA (oz/cwt)	Slump Flow (in.)	T_{50} (sec.)	VSI	Slump Flow loss (in.)
S7.B.SF20	109	106.20	2.30	0.00	15.38	-	0	-5.25
S7.B.SF25		106.15	3.20	0.40	18.88	-	0	-6.75
S7.B.SF28		106.30	3.90	0.50	21.25	2.82	0	-7.25
S7.B.SF20	96	94.50	2.30	0.00	18.00	-	0	-2.63
S7.B.SF25		94.20	3.20	0.40	22.50	2.98	0	-3.13
S7.B.SF28		94.20	3.90	0.50	25.00	2.74	0	-3.50
S7.B.SF20	83	79.90	2.30	0.00	19.50	-	0	-1.13
S7.B.SF25		80.20	3.20	0.40	24.25	2.83	0	-1.38
S7.B.SF28		80.60	3.90	0.50	26.83	2.59	0	-1.67
S7.B.SF20	70	71.40	2.30	0.00	20.63	3.19	0	0.00
S7.B.SF25		71.60	3.20	0.40	25.63	2.79	0	0.00
S7.B.SF28		71.90	3.90	0.50	28.50	1.85	1	0.00
S7.B.SF20	57	65.40	2.30	0.00	21.59	2.95	0	0.96
S7.B.SF25		66.40	3.20	0.40	26.50	2.51	0	0.87
S7.B.SF28		65.30	3.90	0.50	29.38	1.80	1	0.88
S7.B.SF20	44	56.00	2.30	0.00	21.50	2.90	0	0.87
S7.B.SF25		56.20	3.20	0.40	26.38	2.49	0	0.75
S7.B.SF28		56.00	3.90	0.50	29.25	1.81	1	0.75
S7.B.SF20	31	46.00	2.30	0.00	21.38	3.00	0	0.75
S7.B.SF25		45.50	3.20	0.40	26.50	2.50	0	0.87
S7.B.SF28		46.20	3.90	0.50	29.25	1.80	1	0.75

1 ^{o}F = 9/5 ^{o}C + 32, 1oz/cwt = 65 ml/100 kg, 1 in. = 25.4 mm

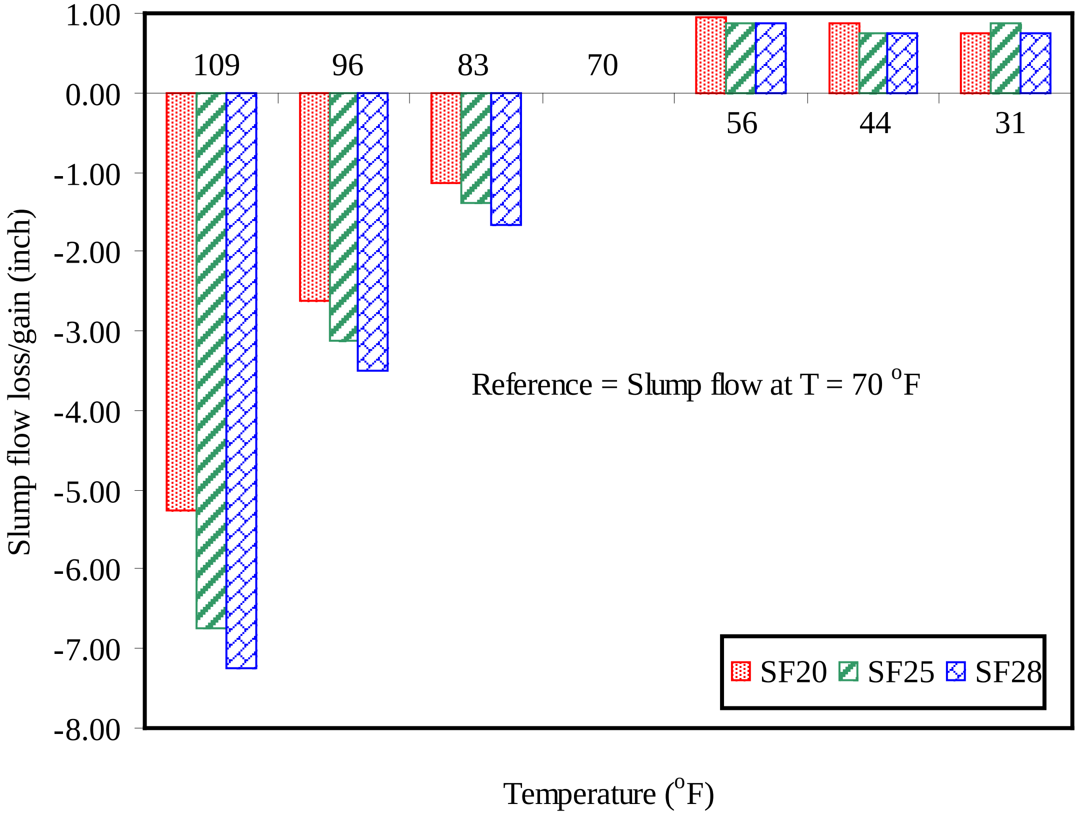


Figure 5.2: Influence of hot and cold temperatures on slump flow of SCC

28 ^{o}C), respectively. As it can be seen from Figure 5.2, the losses were small at the lower hot temperatures and increased progressively as the temperature moved toward the elevated ones.

The T_{50} time was used to determine the flow rate or plastic viscosity per inference of the self-consolidating concretes. Overall, regardless of the slump flow, all selected hot temperatures adversely influenced the flow rate of the trial matrices by increasing the T_{50} times. The increases in T_{50} times were indicative of gains in plastic viscosity (by inference), or decrease in flow rate. The flow rate further increased as the temperature increased. The T_{50} times of the mixtures made for 20 inches (508 mm) slump flow could not be measured in any of the selected hot temperatures since their flow spreads were below the established limit of 20 inches (508 mm). At the temperatures of 96 and 83 ^{o}F (36 and 28 ^{o}C), the mixtures made for 25 inches (635 mm) slump flow displayed relatively small increases in T_{50} time of about 1 and 1%, respectively, when compared to that of the control temperature. The same concrete ceased to be self-consolidating at 109 ^{o}F (43 ^{o}C) and its T_{50} could not be measured. For the mixture prepared for the slump flow of 28 inches (711 mm), significant increases in flow rate were induced by hot temperatures. In comparing to the control temperature, the augmentations in flow rate were 52, 48 and 40% at 109, 96, and 83 ^{o}F (43, 36, and 28 ^{o}C), respectively.

The influence of elevated temperatures on dynamic stability of the selected self-consolidating concretes was also evaluated. As shown in Table 5.2, the effect of hot temperatures on the dynamic stability of the selected SCCs was manifested by an improvement in the visual stability index (VSI), from 1 (stable matrix) to 0 (highly stable matrix) for the mixtures made with 28 inches (711 mm) slump flow. The others two SCC types (slump flows of 20 and 25 inches (508 and 635 mm)) remained highly stable at the selected elevated temperatures.

5.3.2 Influence of cold temperature on fresh performance of SCC

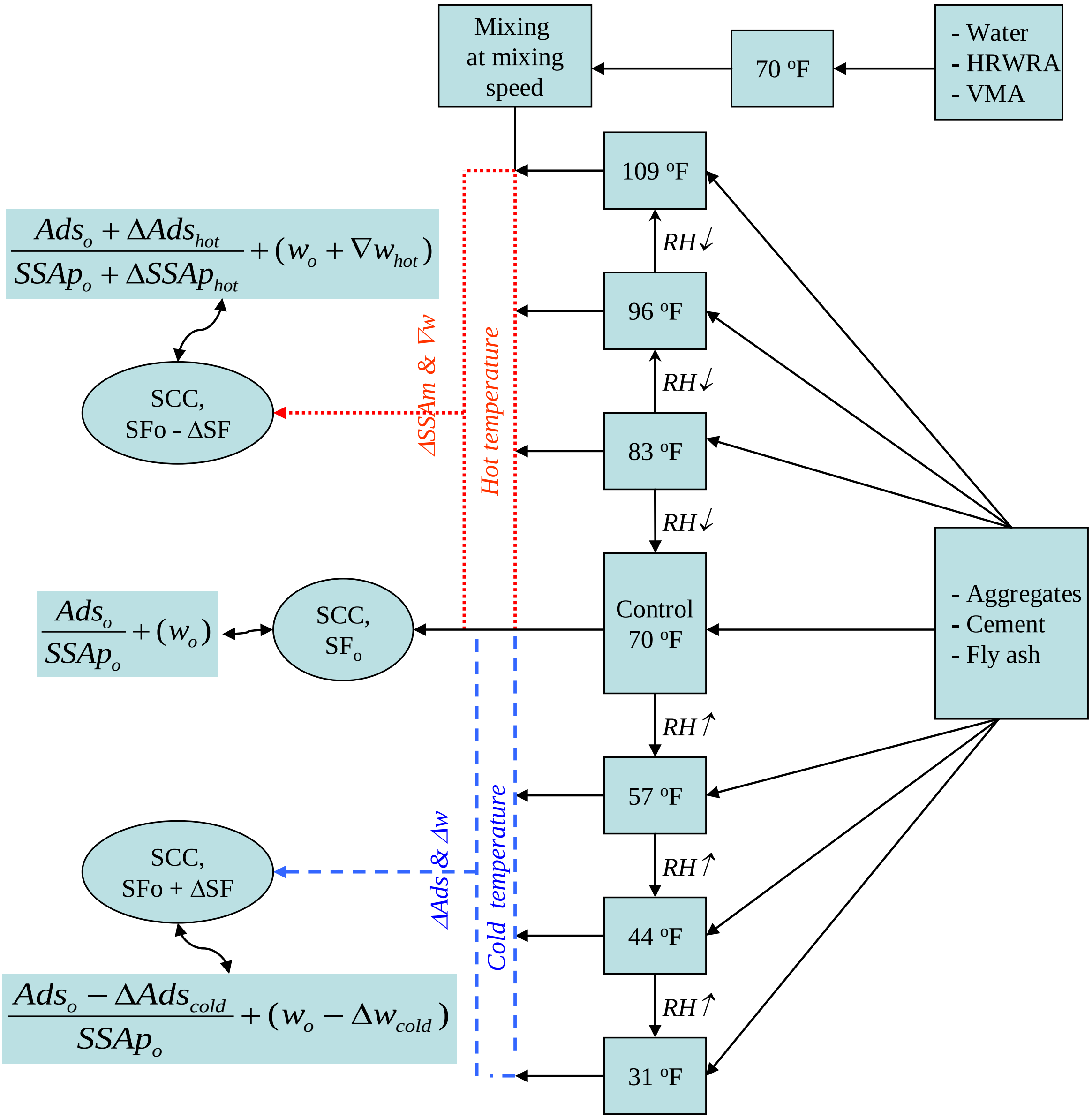
Table 5.2 and Figure 5.2 also document the effect of cold temperatures on the fresh performance of self-consolidating concrete. In general, cold temperatures marginally increased the unconfined workability, slightly reduced the flow rate (increased the plastic viscosity by inference), and barely affected the dynamic stability of freshly-mixed self-consolidating concretes. In comparing to the control temperature, the self-consolidating concretes exposed to the selected cold temperatures experienced less than 1 inch (25 mm) gain in slump flow. The decreases in T_{50} times were on average less than 30 seconds; while the dynamic stabilities remained highly stable for the 20 and 25 inches (508 and 635 mm) SCCs, and stable for the 28 inches (711 mm) matrices.

5.3.3 Mechanism of slump flow loss and gain in hot and cold temperatures

The slump flow loss and gain induced by the hot and cold temperatures, respectively, may be explained through the adsorption amount of admixture per specific surface area of concrete paste (Ads/SSAp), the change in the aggregates' moisture content, and the partial evaporation of mixing water (in the case of elevated temperatures). The flow chart of Figure 5.3 documents the mechanism of slump flow loss and gain in extreme temperatures.

There are general consensuses that increase in concrete temperature leads to an increase in the amount of cement hydrated products (SSAp) mainly at early ages[85,86]. However, there is no extensive literature regarding the adsorption behavior of polycarboxylate-based high range water-reducing admixture in hot temperatures. Burg[87] and Klieger[88] found that, in ordinary concrete, a slump loss of 0.8 to 1 inch (20 to 25 mm) was observed for each 20 ^oF (11 ^oC) temperature increase. Nawa[86] reported that the superplasticizer adsorption (Ads) on cement particle increased as the fresh concrete temperature increased. Flatt[33] et al. investigated the effect of temperature on the adsorption of Polycarboxylic-Ester (PCE) and Polycarboxylic Acid-polymers (PCA). The model powders used in the study was dead burnt MgO and $Mg(OH)_2$ which are chemically similar to $Ca(OH)_2$ and CaO, respectively. They found that in MgO at the pH of 12, the PCE adsorption plateau concentrations increased significantly with temperature, while with the PCA no effect was found. Moreover, in the $Mg(OH)_2$ medium, at a pH level of 11.3, the adsorption of polycarboxylic acid-polymers remained unaffected by the elevated temperature.

In the current literature, to our best knowledge, there is no investigation on the effect of cold temperature on the fresh performance of self-consolidating concrete. The existing literature in cold weather concreting mostly deals with the strength loss and freeze-thaw. Burg[87] reported that concrete made with the cement containing 5% of C_3A displayed over 100% slump increase when the temperature decreases from 73 to 50 ^oF



<u>LEGEND</u>

Ads_o = Adsorptions at control temperature

∇Ads_{hot} and ΔAds_{cold} = Change in Ads_o at hot and cold temperatures, respectively
$SSAp_o$ = Specific surface area of concrete paste at control temperature
$\Delta SSAp_{hot}$ = Increase in $SSAp_o$ due to hot temperature
w_o = Water contribution to the initial fluidity of the concrete at control temperature
∇w_{hot} = Decrease in w_o due to low relative humidity and hot temperature
Δw_{cold} = Increase in w_o due to high relative humidity and cold temperature
SF_o = Slump flow at control temperature
ΔSF = Change in SF
RH = Relative humidity

Figure 5.3: Mechanism of slump flow loss and gain in hot and cold temperatures

(23 to 10 ^{o}C) indicating that the vibratory-placed slump concrete can gain slump with the increase in cold temperature.

In short, it appears that additional studies on the adsorption of admixture on cement particles are warranted in order to determine the extent to which the ratio Ads/SSAp can affect the fluidity of self-consolidating concrete in a hot temperature condition.

5.3.3.1 Influence of extreme temperatures on adsorption of PC-based HRWRA

In an attempt to investigate the evolution of the adsorption amount of the selected polycarboxylate-based high range water-reducing admixtures (PC-based HRWRA) in water-cement solution at the selected temperatures, the ultraviolet-visible (UV/Vis) spectroscopy test was used by Ghafoori N., and Diawara H[82]. They found that while the PC-based HRWRA free concentration in cement-water system remained fairly uniform at temperatures ranging from 57 to 96 ^{o}F (14 to 36 ^{o}C), it decreased as the temperature moved toward the extreme cold and hot temperatures. This finding confirms the theory presented through the flow chart of Figure 5.3 to explain the mechanism of slump flow loss or gain in hot or cold temperature, respectively.

5.3.3.2 Influence of extreme temperatures on aggregates' moisture content

For the most part a segment of loss or gain in SCC workability may be credited to the available moisture in aggregates. Ghafoori N., and Diawara H[82], found also that an increase in aggregates' temperature from 31 to 70 to 109 ^{o}F (-0.5 to 21 to 43 ^{o}C), required about 5 to 3 lb/yd^3 (3 to 2 kg/m^3) of additional mixing water to maintain the same slump flow. Otherwise accounted in the design of the matrices at extreme temperatures, the corresponding aggregates' moisture contribution can affect significantly the mixing water requirement, and thus the yield stress and plastic viscosity of concrete in general and self-consolidating concrete in particular.

5.3.3.3 Evaporation of mixing water in elevated temperatures

As reported in Section 5.1.1, if the high temperature is accompanied by a low relative humidity, rapid evaporation of some mixing water takes place, resulting in the loss of workability[9,10,69]. A quick review of the various states of water in hydrated cement paste is necessary to comprehend the fluidity loss of concrete matrix as related to the evaporation of water. Concrete paste is capable of holding a significant amount of water depending on the environmental humidity and the porosity, and there is a continuous loss of water from saturated cement paste as the relative humidity decreases[12]. Capillary water, adsorbed water, interlayer water, and chemically combined water are the main states of water present in hydrated cement paste[12]. The capillary water or bulk water is free from the influence of the attractive forces exerted by the solid surface. It is divided into free water, which the removal does not cause a volume change, and water held by capillary tension, which the removal may cause shrinkage. The adsorbed water is the water that is under the influence of attractive forces water molecules. This water is generally adsorbed onto the surface of hydrated cement paste. The loss of adsorbed water is mainly responsible for the shrinkage of hydrated cement paste in drying. The interlayer water is associated with the calcium silicate hydrate, (C-S-H) structure. The C-S-H structure shrinks considerably when the interlayer water is lost. The chemically combined water is also an integral part of various cement hydrated products. It is not lost on drying and it is evolved when the hydrates decompose on heating[12]. The capillary and adsorbed waters are of interest in a freshly-mixed matrix. The interlayer and chemically combined waters are mostly important for the strength, shrinkage, and durability aspect of hardened concretes[12].

Although not measured, based on the above-mentioned discussion, it is suspected that a portion of the mixing water was evaporated and/or absorbed once it become in contact with the hot aggregates and cementitious materials, thus reducing the amount of water necessary to assist the admixture in dispersing cement particles. It is also suspected that during the cement hydration process, the capillary tension and the adsorbed water of the hydrated cement paste partially evaporated due to the low relative humidity and elevated temperature (see Table 5.1), contributing to the overall loss in slump flow.

5.3.3.4 Influence of extreme temperatures on specific surface area of hydrated cement

It is well established that the performance of fresh concrete is influenced by the amount of Portland cement hydration and its internal structure, which in turn are influenced by the environmental conditions such as temperature, relative humidity, and wind velocity[9,10,69]. The decrease in self-consolidating concrete’s workability, induced by elevated temperatures, was partially attributed to the increase in specific surface area of the concrete paste (ΔSSAp), manifested in the form of growth of cement hydrated products. During the initial hydration, water wets the cement particles and solubilizes the cement phases. Various reactions occur through several types of bonding interaction. Ca^{2+} and $H_2SiO_4^{2-}$ are hydrolyzed from the most reactive cement particles C_3A and C_3S, and C_3A is converted into ettringite (calcium aluminate trisulfate). Ettringite has larger specific surface area than other cement hydrated phases such as: gypsum ($CaSO_4$), portlandine (CH), calcium silicate hydrate (CSH), and calcite (stable polymorph of $CaCO_3$)[78]. As a result, the cement particles' surface can increase by to 2 to 2.5 times[81]. These chemical reactions increase with temperature rise, along with the kinetic energy per mole, as translated in the Arrhenius equation[89]: $R_1 = Ae^{-E/RT}$, where R_1, R, E, T, and A are the reaction rate, the gas constant, the absolute temperatures, the activation energy, and a constant, respectively. The opposite is valid in cold temperature, where the cement particles' don't expand when compared to that of the control condition.

The determination of the specific surface area of cement hydration products was not part of this investigation. However, the finding of Ludwig and Pence[90] who determined that the 7-day specific surface areas of Portland cement hydration products at 81 and 151 ^oF (27 and 66 ^oC) were equal to 103.4 and 122 $m^2\ g^{-1}$, respectively, can confirm the theory adopted herein. The progressive growth of cement hydration products in elevated temperatures (*ΔSSAp)* was a contributing factor to the slump flow loss.

In view of the above discussions, the slump flow loss of SCC in hot temperatures and gain in cold temperatures can be expressed in the following mathematical formula:

$$\textit{Slump flow loss} = f\left\{\frac{Ads}{SSAp}, w\right\} = \frac{Ads_o + \Delta Ads_{hot}}{SSAp_o + \Delta SSAp_{hot}} + (w_o + \nabla w_{hot}) \qquad (5.2)$$

$$\textit{Slump flow gain} = f\left\{\frac{Ads}{SSAp}, w\right\} = \frac{Ads_o - \Delta Ads_{cold}}{SSAp_o} + (w_o - \Delta w_{cold}) \qquad (5.3)$$

Where, *Ads/SSAp* is the adsorption amount of admixture per specific surface area of concrete paste at the target temperature. The terms Ads_o, ΔAds_{hot}, ΔAds_{cold}, $SSAp_o$, $\Delta SSAp_{hot}$, w, w_o, ∇w_{hot}, and Δw_{cold} are defined in Figure 5.2.

It seems that the contribution of SSAp in the slump flow loss was greater than that of the admixture adsorption and its related electrostatic repulsion and steric hindrance effect. In fact, despite the augmentation in Ads, as discussed earlier in Section 5.1.3.1, the increase in SSAp induced by the hot temperatures was able to reduce the overall workability of the concrete mixture. On the other hand, it is suspected that the selected cold temperatures did not affect significantly the specific surface area of the Portland cement hydrated products as the hydration continued in cold temperatures, but at a slower rate. In this case, Ads nearly overtook on the SSAp, and little to no change in the concrete workability was observed.

5.3.4 Prediction of SCC slump flow loss and gain in hot and cold temperatures

Predictive statistical analysis, at 95% level confidence, was used to relate the slump flow losses or gains of the selected self-consolidating concretes to the temperatures and initial slump flows as follows:

In hot temperature condition:

$$SF_{loss} = -7.93772 - 0.10879SF + 0.35171t_h + 0.0028649t_h^{\ 2} \qquad (5.4)$$

Or $SF_{loss} = a + b \cdot SF + c \cdot t_h + d \cdot t_h^{\ 2}$

In cold temperature condition:

$$SF_{gain} = 8.06530 - 6.14586x10^{-3}SF - 0.508539t_c + 0.011651t_c^{\ 2} - 8.57229x10^{-5}t_c^{\ 3} \qquad (5.5)$$

Or $SF_{gain} = a + b \cdot SF + c \cdot t_c + d \cdot t_c^{\ 2} + e \cdot t_c^{\ 3}$

Where:

SF_{loss} = Slump flow loss in hot temperature conditions (inch)

SF_{gain} = Slump flow gain in cold temperature conditions (inch)

SF = Initial slump flow of SCC (inch), with 20 inches ≤ SF ≤ 28 inches

t_h = Hot temperature (°F) with 70 °F ≤ t_h ≤ 109 °F

t_c = Cold temperature (°F) with 31 °F ≤ t_c ≤ 70 °F

The regression equations (5.4) and (5.5) produced R^2 and S values of 98% and 0.43 inch, and 98% and 0.052 inch, respectively, indicating a strong relationship between the dependent variable (slump flow loss or slump flow gain) and the independent variables (initial slump flow and hot or cold temperature). F and T tests were performed to confirm the significance of coefficients a, b, c, and d in the regression model. The following results were found.

For Equation (5.4):

Prob(t) = 0.21, 0.02, 0.03, and 0.00 for a, b, c, and d, respectively. Prob(F) = 0.

For Equation (5.5):

Prob(t) = 0.00, 0.23, 0.00, 0.00 and 0.00 for a, b, c, d, and e, respectively. Prob(F) = 0

The F and T tests results indicated that both the slump flow value and the temperature had a similar influence on the predictive slump flow loss or gain.

5.3.5 Remediation of slump flow loss induced by extreme temperature

Several studies have reported that both the hot and cold temperatures affected the fresh and hardened properties of concrete[9,12,83,84]. Various remediation methods to mitigate the adverse effect of extreme temperatures on concrete have been proposed. Among them, cooling or heating the materials, retempering in job site with water or superplasticizer, overdosing in mixing plant with water or superplasticizer, and others can be noted. In the present chapter only the remediation of the hot temperature condition was studied since the increased slump flow in cold temperature was relatively marginal at less than ± 1.0 inch (25 mm), well within the established limit of tolerance. The adopted remediation method consisted of overdosing the admixtures in order to eliminate the adverse impact of hot temperature on the unconfined workability, flow rate/plastic viscosity, dynamic stability, and passing ability of the trial freshly-mixed self-consolidating concretes.

5.3.5.1 HRWRA dosage requirement for the remediation of slump flow loss

Table 5.3 presents the optimum dosages of HRWRA for the remediation of slump loss induced by the elevated temperatures, and Figure 5.4 shows the required HRWRA dosages as a function of temperatures. In comparing to the control optimum dosage at 70 ^{o}F (21 ^{o}C), an average increase of only 3% in the HRWRA optimum dosage was sufficient to combat the adverse effect of the 83 ^{o}F (28 ^{o}C) temperature. On the other hand, significant increases in HRWRA optimum dosage requirement of about 13, 19, and 13%; and 26, 47, and 54% at the temperatures of 96 and 109 ^{o}F (43 and 36 ^{o}C) were obtained for the self-consolidating concretes prepared for 20, 25, and 28 inches (508, 635, and 711 mm) of slump flow, respectively.

Table 5.3: Optimum overdosed amounts of admixtures and fresh properties of remediated SCCs at various temperatures

Temp. (^{o}F)	Mix No.	HRWR (oz/cwt)	VMA (oz/cwt)	Slump Flow (in.)	T_{50} (sec.)	VSI	J Ring value (in.)
109	S7ESF20	2.90	0.00	20.50	4.72	0	1.75
	S7ESF25	4.70	0.60	25.50	2.28	0	1.50
	S7ESF28	6.00	0.90	28.50	2.05	1	1.50
96	S7ESF20	2.60	0.00	20.50	3.09	0	1.75
	S7ESF25	3.80	0.50	25.50	2.19	0	1.50
	S7ESF28	4.40	0.70	28.38	2.00	1	1.38
83	S7ESF20	2.35	0.00	20.50	3.41	0	1.45
	S7ESF25	3.30	0.40	25.50	2.35	0	1.33
	S7ESF28	4.00	0.50	28.13	2.25	1	1.25
70	S7ESF20	2.30	0.00	20.63	3.19	0	1.38
	S7ESF25	3.20	0.40	25.63	2.79	0	1.13
	S7ESF28	3.90	0.50	28.50	1.85	1	1.00

1 ^{o}F = 9/5 ^{o}C + 32, 1 oz/cwt = 65 ml/100 kg, 1 in. = 25.4 mm

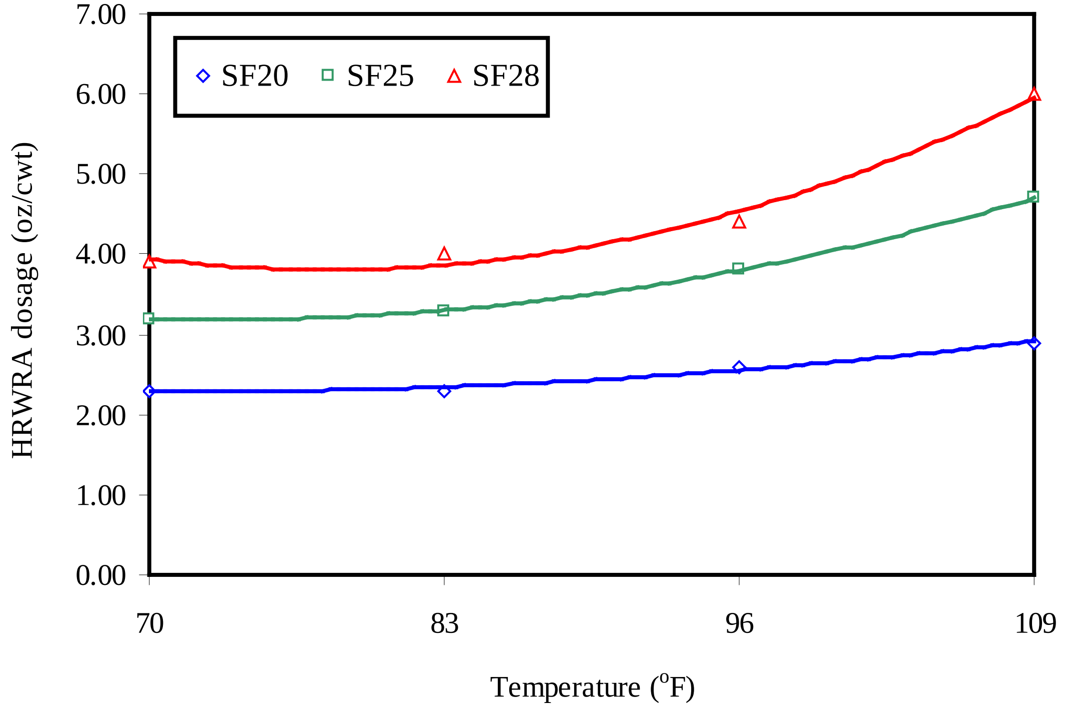


Figure 5.4: Optimum dosage of HRWRA for the overdosing remediation of slump loss at various elevated temperatures

The higher superplasticizer demand in contesting the slump flow loss of the selected SCCs, induced by the elevated temperatures, can be explained through Equations (5.5) and (5.6). The idea behind the remediation adopted technique in the present study was to find by trial and error an initial admixtures dosage so that $(Ads/SSAp)_t$ at the target temperature became equivalent to $(Ads/SSAp)_o$ at the control temperature; with the term “t” referring to the elevated temperatures (t = 83, 96, or 109 ºF (28, 43, or 36 ºC)).

- *At the control temperature of 70 ºF (21 ºC):*

$$\left(\frac{Ads}{SSAp}\right)_o = \frac{Ads_o}{SSAp_o} + w_o \tag{5.6}$$

- *At the target hot temperature “t”:*

$$\left(\frac{Ads}{SSAp}\right)_t = \underbrace{\left[\frac{Ads_o + \Delta Ads_{hot}}{SSAp_o + \Delta SSAp_{hot}} + (w_o + \nabla w_{hot})\right]}_{\textcircled{A}} + \underbrace{\left[\frac{\Delta Ads_{overd}}{SSAp_o + \Delta SSAp_{hot}}\right]}_{\textcircled{B}} = \left(\frac{Ads}{SSAp}\right)_o \tag{5.7}$$

Ⓐ Characterizes the slump flow loss

Ⓑ Characterizes the slump flow restoration

Ads_o, ΔAds_{hot}, $SSAp_o$, $\Delta SSAp_{hot}$, w_o, and ∇w_{hot} are defined in Figure 5.3. The term ΔAds_{overd} corresponds to the increase in adsorption amount of admixture brought by the additional superplasticizer to compensate for the increase in specific surface area of concrete paste, $\Delta SSAp_{hot}$, and the loss of mixing water, ∇w_{hot}, due to hot temperature and low relative humidity. ΔAds_{overd} generated additional repulsive electrostatic and steric hindrance forces between the cement particles to make-up for the loss of repulsive forces caused by the growth of the cement hydrated products due to hot temperatures. The designed optimum dosages of HRWRA for the temperature "t" were sufficient to produce the target fluidity at the target temperature.

5.3.5.2 VMA dosage requirement for the remediation of slump flow loss

Table 5.3 and Figure 5.5 display the optimum dosages of VMA for the remediation of slump loss due to elevated temperatures. At the temperature of 83 ^oF (28 ^oC), the three selected slump flow mixtures did not required any adjustment in their initial VMA dosage in attaining similar fresh performance to those of the control temperature. At the temperature of 96 and 109 ^oF (36 and 43 ^oC), the matrices made with 20, 25 and 28 inches (508, 635, and 711 mm) slump flow required 0, 25, and 40%, and 0, 50, and 80% augmentation of the dosage of VMA, respectively, when compared to that of the control temperature.

The viscosity modifying admixture is mainly used to increase the plastic viscosity and stability of self-consolidating concrete. In hot temperatures, the increase in SSAp was effective in thickening the paste, resulting in a higher plastic viscosity (T_{50} time between 2 and 5 seconds) and a higher VSI (0 or 1) of fresh self-consolidating concretes. This was the case for the selected matrices made with 20 inches (508 mm) of slump flow. However, in the case of mixtures made for 25 and 28 inches (635 and 711 mm) of slump flows; the increase in SSAp was insufficient to restore the reduced plastic viscosity and dynamic stability generated by the higher dosage of HRWRA. The additional VMA used in these mixtures helped the viscosity and stability to revert back to their acceptable levels.

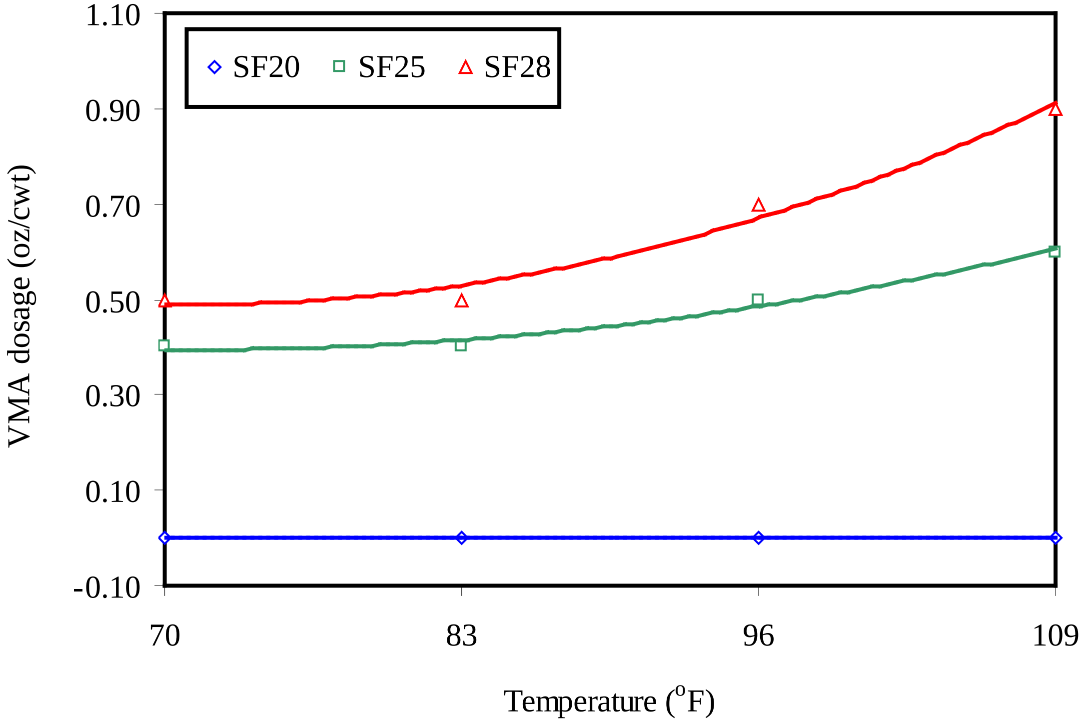


Figure 5.5: Optimum dosage of VMA for the overdosing remediation of slump loss at various elevated temperatures

5.3.5.3 Fresh properties of the remediated self-consolidating concretes

The slump flow, T_{50}, and VSI tests were used to determine the unconfined workability, the flow rate or plastic viscosity (per inference), and the dynamic stability of the remediated self-consolidating concretes at elevated temperatures. As reported in Table 5.3, the test results showed that irrespective of the selected hot temperatures, all remediated self-consolidating concretes were within the assigned target slump flows ± 1 inch (25 mm), T_{50} time between 2 and 5 seconds, and VSI of 0 (highly stable) or 1 (stable). In comparing the slump flow values at various hot temperature conditions to that measured at the control temperature, the selected remediated fresh SCCs displayed an insignificant difference of less than 1%. All T_{50} times decreased as the slump flow increased and, within the same group, remained similar to that of the reference temperature. No evidence of segregation or bleeding in slump flow was observed in any of the remediated self-consolidating concretes, indicating that a stable matrix condition was achieved through the adopted overdosing method.

The passing ability of the remediated self-consolidating concrete was determined by the J-ring value (the diameter of the unobstructed slump flow minus the diameter of the obstructed slump flow). As shown in Table 5.3, similar J-ring values to that of the control temperature were recorded. Irrespective of the hot temperatures, the calculated J-ring values of all remediated matrices were within the allowable limit of 1 to 2 inches (25 to 50 mm) indicating a moderate passing ability or minimal to noticeable blocking of the selected self-consolidating concretes.

5.3.5.4 Predictive statistical equations of HRWRA and VMA optimum dosages for remediation of slump flow loss due to elevated temperatures

The most suitable predictive relationships among the HRWRA or VMA optimum dosages, slump flow, and elevated temperatures for the remediation of slump flow loss induced by the elevated temperature were determined using a 95% confidence level. The predictive equations were tested for accuracy using R² (regression value) and S (standard deviation). The relationships are as follows:

$$HR = 1.37833x10^{-4}\left(SF^{1.8658}\right)\left(t_h^{\ 0.9279}\right) \tag{5.8}$$

$$\text{Or } HR = a\left(SF^{b}\right)\left(t_h^{\ c}\right)$$

$$VMA = 4.3460 - \frac{48.6969}{SF} - \frac{303.8431}{t_h} + \frac{11188.2922}{t_h^{\ 2}} \tag{5.9}$$

$$\text{Or } VMA = a + \frac{b}{SF} + \frac{c}{t_h} + \frac{d}{t_h^{\ 2}}$$

Where:

HR = High Range Water Reducing Admixture initial optimum dosage (oz/cwt)

VMA = Viscosity Modifying Admixture initial optimum dosage (oz/cwt)

SF = Target SCC slump flow in hot temperature condition (inch)

With 20 inches ≤ SF ≤ 28 inches

t_h = Hot temperature (^{o}F), with 70 ^{o}F ≤ t_t ≤ 109 ^{o}F

The regression equations (5.8) and (5.9) produced R² and S values of 94% and 0.29 oz/cwt inch, and 95% and 0.08 oz/cwt, respectively, that demonstrated a strong relationship between the dependent variable (HRWRA or VMA optimum dosage) and the independent variables (initial slump flow and hot temperature). F and T tests were performed to confirm the significance of coefficients a, b, c, and d in the regression model. The following results were found.

For Equation 5.8:

Prob(t) = 0.31, 0.00, and 0.00 for a, b, and c, respectively. Prob(F) = 0.

The F and T tests results indicated that both the slump flow value and the temperatures had a similar influence on the predictive HRWRA optimum dosage.

For Equation 5.9:

Prob(t) = 0.00, 0.00, 0.15, and 0.20 for a, b, c, and d, respectively. Prob(F) = 0

The F and T tests results showed that the hot temperatures had less impact than the slump flow value in the prediction of the VMA optimum dosage.

5.4 Conclusions

a) The fresh performance of self-consolidating concrete was affected by both hot and cold temperatures.

In hot temperatures, the influence was manifested in the form of significant decrease in unconfined workability, substantial increase in flow rate or plastic viscosity per inference, and improvement in dynamic stability of the freshly-mixed SCCs. In comparing to the control temperature of 70 ^oF (21 ^oC), the losses in slump flow induced by the elevated temperatures were only 5% at 83 ^oF (28 ^oC), but increased significantly to about 12 and 25%, at 96 and 109 ^oF (36 and 43 ^oC), respectively.

The cold temperature affected the fresh performance of the selected self-consolidating concretes by a marginal gain in flow ability (averaging 3%), small variation in flow rate (averaging 6%), and an increase in the resistance to segregation from VSI of 1 to 0 for the matrices only made with slump flow of 28 inches (711mm), when compared to those obtained under the control temperature. The VSI of the trial SCCs prepared with slump flows of 20 and 25 inches (508 and 635 mm) were unaffected by the selected cold temperatures.

b) The change in the fresh properties due to elevated and cold temperatures can be characterized by the adsorption amount of admixture per specific surface area of concrete paste (Ads/SSAp), the change in the aggregate's moisture content, and the partial evaporation of mixing water in the case of elevated temperatures.

c) A remediation method by way of admixture overdosing was successful to reverse the change in fresh properties of the selected self-consolidating concretes in elevated temperatures. The additional amount of admixtures increased workability (up to 96 ^{o}F (36 ^{o}C)) through generation of supplementary repulsive electrostatic and steric hindrance forces between the cement particles and was able to offset the loss of workability caused by the growth of the cement hydrated products engendered during hot temperatures. The selected remediation method was able to produce SCCs with a similar unconfined workability, flow rate or plastic viscosity per inference, dynamic stability, and passing ability to those obtained for the equivalent matrices at the control temperature.

d) The selected self-consolidating concretes did not require any remediation in cold temperatures of 57, 44, and 31 ^{o}F (14, 7, and -0.5 ^{o}C). The gains in slump flow of the trial self-consolidating concretes in cold temperatures were less than 1.0 inch (25 mm), and both the flow rate and dynamic segregation resistance were unaffected by the selected cold temperatures.

e) The predictive equations to correlate the slump flow loss or gain with the initial slump flow value and the selected hot and cold temperatures showed significant statistical relationships between the dependent and independent variables. For the remediation purpose in hot temperature, the required optimum admixtures dosages (HRWRA and VMA) were also predicted for the selected target slump flows and elevated temperatures. A strong significant statistical relationship between the dependent and independent variables of the remediated concretes were also obtained.

TASK 6

INFLUENCE OF PUMPING ON FRESH PERFORMANCE OF SELF-CONSOLIDATING CONCRETE

The aim of the present Task 6 is to evaluate the influence of pumping on the fresh performance of selected self-consolidating concretes. Three different pumping distances, namely: 100, 200 and 300 ft (30, 60 and 90 m) were used to determine the change in the unconfined workability, flow rate, dynamic segregation resistance, passing ability, rheological properties, volumetric air content, and air voids characteristics. The matrices made with 25 and 28 inches (635 and 711 mm) slump flow were investigated, and the test results before and after pumping were compared.

6.1 INTRODUCTION

Pumping concrete through pipeline is considered nowadays as one of the most convenient method of transporting concrete from the mixer to the place of deposit. The use of pumps and associated pipelines as means of transporting and placing concrete in civil engineering and building construction started in the early 1930s and has increased considerably recently. The main advantage of pumping resides in its placement of large volume of concrete on congested sites. The cost of a pumping installation may be cheaper than that of alternative methods of concrete placement. However, circumstances of each particular case should be considered in choosing the appropriate method of placement[91].

6.1.1 Concrete pumping system

The concrete pumping system consists essentially of a hopper into which the concrete is discharged from the mixer, a concrete pump, and pipes through which the concrete is pumped.

6.1.1.1 Concrete pumps

Most concrete pumps are provided with one or two pistons that force the concrete from a pumping chamber into and along a prepared pipeline. The movement of the concrete onto and out of the pumping chamber is controlled by valves. The early models of concrete pumps were operated mechanically, but most of the new models pumps are hydraulically operated. Figure 6.1 presents a diagrammatic operation of a hydraulic twin-cylinder pump. In the hydraulic pump the piston move in long slow stokes in contrast to the short faster strokes in the mechanical pump[91]. On the suction stroke the inlet valve is open and the delivery or outlet valve is closed and the concrete is then drawn from the feed hopper into the cylinder. On the delivery stroke the inlet valve is closed and the

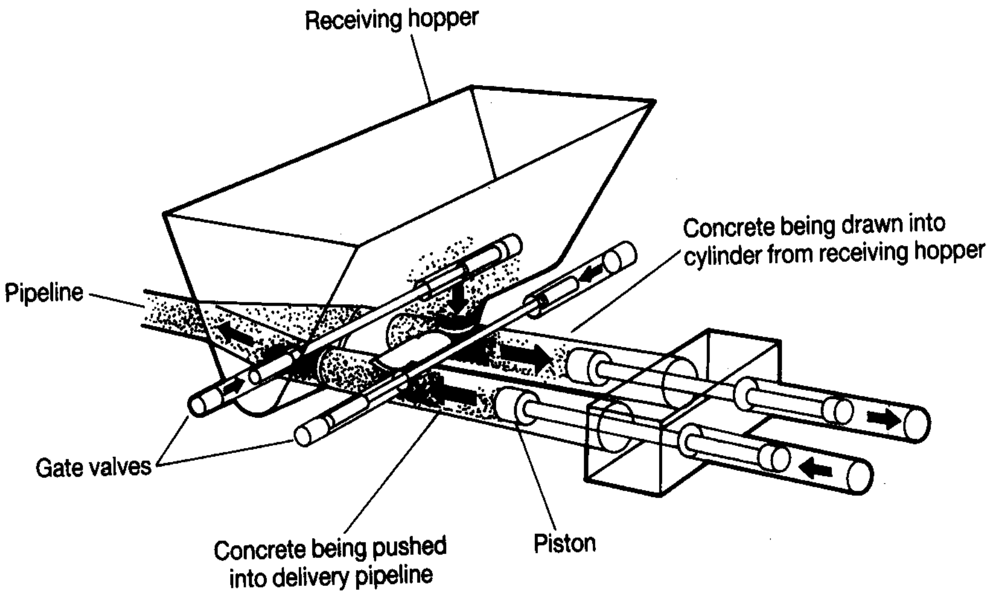


Figure 6.1: The working cycle of the concrete pump[69].

outlet valve is opened. The valves opened and closed with definite pauses so that concrete moves in a series of impulses but the pipes always remain full. The resistance to the flow of the concrete would be reduced and the power necessary to drive the pump decreased if the flow of concrete could be maintained at a constant speed. Most concrete pumps now have a remixer or agitator fitted to the hopper to minimize possible segregation of concrete[69,75,92].

There are several proprietary forms of concrete pump whose action basically is similar to that described above. The most commonly ones are: Torkret pump, Schwing and Mobil-crete pumps, Putzmeister pump, and Squeeze-Crete pump[91]. The performance of concrete pumps varies with the type of the pump and with circumstances. Squeeze pumps move concrete for distance up to 300 ft (90 m) horizontally or 100 ft (30 m) vertically. Piston pumps can deliver either through a horizontal distance of 1000 to 1500 ft (300 to 450 m) or vertically to a height of 140 ft (40 m)[10,69].

6.1.1.2 The pipelines

Pipelines used in pumping concrete are usually made of rigid steel tube in a standard unit of 10 ft (3 m), which can be connected together with quick-acting couplings. Bends and shorter lengths, and flexible pipelines made of neoprene rubber are also available. They are necessary when used in conjunction with articulated booms, at least for the section of pipeline leading from the end of the boom. This type of piping deteriorates quickly, particularly if it is not properly cleaned and maintained. Aluminum pipes must not be used because the abraded aluminum reacts with the alkalis in cement to generate hydrogen. This gas introduces voids in the hardened concrete with a consequent loss of strength[10]. The use of hard grade aluminum can solve that problem. The diameter of pipeline for large installations varies from 6 to 7 inches (150 to 180 mm). Smaller diameters ranging from 2 to 5 inches (50 to 125 mm) are used in the case of mobile pumps. These smaller diameters facilitate the handling of the pumps[16,91,92].

6.1.2 Factors affecting concrete pumping

In order to be pumpable, concrete must satisfy certain conditions regarding its matrix constituents, its fresh properties, and the site condition. Theses conditions can be summarized as follow:

6.1.2.1 Raw materials

6.1.2.1.1 Aggregate

The gradation of the aggregate should be smooth. The correct quantity and grading of the fine aggregate is of more importance than the grading of the coarse aggregate. It is important that the fine aggregate should have 15 to 20% passing a No. 52 ASTM (0.012 inch (0.3 mm)) sieve and 3% No.100 ASTM (0.006 inch (0.15 mm)) sieve[91]. The fine material in the sand acts as a lubricant in the pump, but too much fine material may cause a severe blockage or an increase in the frictional resistance in the pipeline, thus requiring a greater force to pump the concrete. Kempster[93] recommended a sand content of 30 to 40%. In America, the current practice for ordinary concrete is about 55 to 58% of coarse aggregate. Natural round shape aggregate is preferred but cubical crushed one of normal specific and low absorption is also satisfactory. The maximum coarse aggregate size should be not more than 1/3 of the pipeline diameter[91,92].

6.1.2.1.2 Water content

The water content is very important in pumpable concrete. With lower water content, the solid particles, instead of moving longitudinally in a coherent mass in suspension, would exert pressure on the walls of the pipe. When the water content is optimum, value friction develops only at the surface of the pipe and in a thin layer of lubricating mortar (0.04 to 0.1 inch (1 to 2.5 mm)). Thus, all the concrete moves at the same velocity by way of plug flow[10].

6.1.2.1.3 Cement and additive

Generally the volumetric cement content has to be at least equal to the void content of the aggregate but very fine supplementary cementitious material can be also included[10]. Pozzolans, limes and others additives have produced beneficial effect as far as pumping is concerned and sometime not. They will not help the pumping of concrete which already has an excess of fine. A minimum cement content of 5 to 6 sacks per cubic yard (470 to 564 lb/yd^3 (260 to 315 kg/m^3)) is advised[91,92].

6.1.2.2 Workability

The concrete suitable for pumping should not be too dry, too wet, harsh and gummy. Although slump is not the main factor affecting pumping, a minimum slump of 2.5 inches (63 mm) is required by ACI[91]. There may be slump loss of 1 inch (25 mm) per 1000 ft (300 m) of pipe line during the pumping depending on the cement type, the atmospheric and material temperature and the length of time the concrete remains in the pipeline[10].

6.1.2.3 Air content

Aerated concretes have being pumped satisfactory. The incorporation of an air-entrainment agent in the concrete mix can help when the friction along the pipe is too high. However, under a high pumping pressure, the air become compressed and no longer aids the mix by its ball-bearing effect[10]. The use of high content of entrained air is likely to cause difficulty with long pipelines as the contraction in volume of the air due to the increase in pressure during the delivery stroke of the pump reduces the improvement in workability and may be greater than the swept volume of the pump piston in which case no concrete would be pumped. It is advisable to not use more than 5% of entrained air[91]. The air lock due to excessive friction is the main cause of blockage during concrete pumping.

6.1.2.4 Temperature

In a very hot environment it is advisable to cover the pipeline and keep it well wetted. The high heat can lead to a quick setting, thus a precaution should be taken to eliminate delays and ensure that the concrete stay in the pipeline for the shortest time possible. When concreting in low temperature no special precaution should be taken. It is not necessary to insulate the pipeline as the temperature drop is comparatively small, about 1 to 2 ^oF (0.5 to 1 ^oC) drop per 100 ft (30 m) of exposed pipe at 0 ^oF (-18 ^oC)[91].

6.1.3 Fresh properties of pumpable concrete

Pumping as a mean of concrete placement can adversely impact the fresh properties of the concrete by changing the workability, rheology, air content and air void characteristics. An extensive report on the workability as related to the flowability, flow rate, stability and passing ability was presented in Task 3. An overview of the rheological properties, air content, and air void characteristic is presented here due to their critical role in the fresh performance of self-consolidating concrete.

6.1.3.1 Rheology

The rheology can be defined as the science of the deformation and flow of matter. There exist two main types of flow, namely: shear flow and extensional flow. In a shear flow, liquid elements flow over or past each other, and also imaginary parallel layers of liquid move in response to a shear stress to produce a velocity gradient, which is referred to as the shear rate, equivalent to the rate of increase of shear strain. In extensional flow, the liquid elements flow towards or away from each other. Extensional or stretching flows are rarely found in cement system.

The relation between the shear stress (τ) and the shear rate (γ) under a simple stable shear is used to characterize fluids. The simplest behavior of fluid is the Newtonian behavior[15], where the shear stress of a fluid is linearly associated to the shear rate as follow:

$$\tau = \eta \gamma \qquad (6.1)$$

Where:

τ is the shear stress;

η is the constant of proportionality or coefficient of viscosity; and,

γ is the shear rate.

However, most fluids are not Newtonian fluids. Several relationships were developed by various searchers to relate other fluids suspension behavior to their plastic viscosity and the shear rate. The most common rheological models applied to the fresh concrete are the followings:

Bingham $\tau = \tau_o + \mu\gamma$ (6.2)

Modified Bingham $\tau = \tau_o + \mu\gamma + b\gamma^2$ (6.3)

Herschel-Bulkley $\tau = \tau_o + a\gamma^b$ (6.4)

Robertson-Stiff $\tau = a(\gamma + b)^C$ (6.5)

De Kee $\tau = \tau_o + \mu\gamma e^{-a\gamma}$ (6.6)

Atzeni et al. $\gamma = a\tau^2+b\tau+c$ (6.7)

Where:

a, b, and c = constants.

τ = shear stress, τ_o = yield stress, μ = viscosity, and γ = shear rate

Where:

The yield value is the force necessary to start a movement of the concrete, and
The viscosity is the resistance of the concrete against an increased speed of movement.

Among the above-mentioned models, the linear Bingham flow behavior (Equation (6.2)) is the simplest type. Concentrated suspensions such as concrete, mortar or paste are accepted as Bingham viscoplastic fluids. A Bingham viscoplastic material behaves as a solid at stress below a critical stress value (i.e. the yield value), and flows like a viscous liquid when the critical stress is exceeded ($\tau > \tau_o$). The non-linear models (i.e. Equations (6.3) through (6.7)) were developed for the fluids which do not display a linear flow behavior.

6.1.3.2 Air content and air voids characteristics

The intentionally entrained air bubbles are different from the entrapped air voids, which result from mixing, handling and placing concrete. Entrained air voids are extremely small in size, between 0.0004 and 0.04 inch (10 to 1000 μm) in diameter, whereas entrapped air voids are generally 0.04 inch (1 mm) or larger in diameter, and often non-spherical in shape[94]. In developing concrete that is resistant to freezing and thawing, evenly spaced small entrained airs are recommended. The air bubbles essentially act at a location where water can travel during the freezing, relieving the pressure on concrete. The spacing and size of air voids are the two most important factors contributing in freeze-thaw resistance of concrete. While there is no agreement on the required air void characteristics, most researches have considered the followings two air-void characteristics as representative of a concrete with adequate freeze-thaw resistance:

- Spacing factor ($\bar{L}$), which is an index related to the distance between the bubbles but not the actual average spacing in the system. It should be less than 0.0079 inch (0.200 mm) to achieve a satisfactory freezing-thawing resistance[95].
- Specific surface or surface area of the air voids (α). In order to be adequate for freeze-thaw resistance, concrete mixture should have a specific surface of air voids greater or equal to 635 in^2/in^3 (24 mm^2/mm^3).

The spacing factor represents *the maximum distance that the water would have to move before reaching the air void reservoir or safety valve*[22,94]. It can be seen in Figure 6.2 that two samples can have the same percentage of air content but different spacing factor (the one on the right has a better spacing factor).

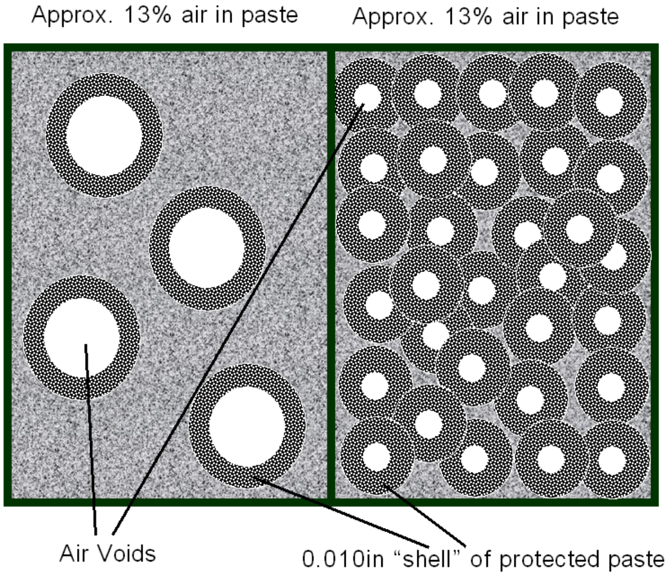


Figure 6.2: Illustration of spacing factor[95].

The following expressions are used in the computation of the spacing factor:

$$\bar{L} = \frac{3}{\alpha}\left[1.4\left(\frac{p}{A}+1\right)^{1/3} - 1\right] \text{ for } \frac{p}{A} > 4.342 \tag{6.8}$$

and

$$\bar{L} = \frac{p}{400n} \text{ for } \frac{p}{A} \leq 4.342 \tag{6.9}$$

Where: $\overline{L}$ = spacing factor, p = paste content, A = air content, n = average number of air voids intersected per linear inch (or millimeter) of traverse, α = specific surface of air voids in inches (or mm).

The specific surface of air voids *can be defined as the ratio of surface area of air voids to the volume of air void.* It gives a good indication of the air bubbles size. Generally, smaller bubbles have a higher specific surface[94,95]. The average chord length of air void (e) in inch (or mm) traversed is also used to characterize the air void. It is expressed as follow: $e = A/100n$.

6.1.4 Procedure in pumping

The pumping always begins with the lubrication of the pipeline by mortar or cement slurry. The rate of 1 yd^3 per 100 ft (2.5 m^3 per 100 m) is usually adopted for the 6 in. (150 mm) diameter pipe[91]. This lubrication is necessary so that too much grout or water is not removed from the first batch of concrete. During pumping the layer of grout around the inside of the pipeline keeps the frictional resistance to pumping within reasonable limits. In order to control the flow of the grout, a plug must be inserted in. The most convenient form of plug consists of two rubber washers connected at a suitable distance from each other by a piece of wire rope round which damp cement bags are tightly wound.

The lubrication is followed by the pumping of concrete. Normal working pressures developed by concrete pumps are between 100 and 250 lb/in^2 (700 and 1750 KPa) but much higher pressures can be developed in the event of pipe blockage. The capacity of the pump depends on the workability of the concrete. The rate of pumping is governed by the extent to which the cylinder is filled with concrete coming from the feed hopper by gravity or by the suction stroke[10,69,91]. As noted earlier, the piston pumps can deliver either through a horizontal distance of 1000 to 1500 ft (300 to 450 m) or vertically to a height of 140 ft (40 m)[10,69]. The ratio of equivalent horizontal and vertical distances varies with the consistency of the mixture and with the velocity of the concrete in the pipe. The greater the velocity the smaller the ratio: at 0.1 m/s, the ratio is about 24 and at 0.7 m/s it is about only 4.5[10]. Bends can be introduced into the pipeline but reduce the pumping distance by 40 ft (12.5 m) horizontally for 90 degree bend and 10 ft (3 mm) horizontally for 22 ½ degree bend and by proportional amounts for intermediate deflections[69]. Concrete can be pumped downhill quite successfully. However, particular care to avoid a blockage is needed where concrete is pumped downhill because air pockets may form at the highest point of the pipeline as the concrete falls away from it. This tendency may be countered by introducing a short upward slope in the pipe at the end of the descending section

Finally, the pumps and the pipeline should be completely cleaned by using one of the following three mains methods: (1) disconnect the pipes and clean them individually, (2) wash out pipes with water, and (3) clean pipes with compressed air[91]. The first method is usually performed in the case of very short pipelines. The second method is advantageous provided the concrete pump can be charged readily for pumping water or if a supplementary pressure pump is available, and provided also that the disposal of water presents no difficulties. The third method is the easiest one but required the availability of compressed air supply and can be dangerous if certain safety precautions are not observed.

6.2 EXPERIMENTAL PROGRAMS

6.2.1 Mixture proportion design

The cementitious materials used in all mixtures consisted of ASTM C 150[13] Type V Portland cement and ASTM C 618[39] class F fly ash. The Type V Portland cement had a Blaine fineness of 248 yd^2/lb (423 m^2/kg) and the following percentages of the chemical constituents: SiO_2 = 20.1%, Al_2O_3 = 4.0%, Fe_2O_3 = 3.6%, CaO = 63.5%, MgO = 2.8%, SO_3 = 2.9%, C_3A = 4%, C_3S = 58%, C_2S = 14%, Na_2O equivalent = 0.57%, loss on ignition = 2.3%, and insoluble residue = 0.44%. The fly ash had the followings chemical composition: SiO_2 = 58.2%, Al_2O_3 = 17.4%, Fe_2O_3 = 4.8%, CaO = 7.9%, SO_3 = 0.6%, moisture content = 0.0%, and loss on ignition = 4.2 %.

The aggregates from the quarry S were used in producing the trials matrices. The fine aggregate met the requirements of ASTM C 33[11]. Its bulk and saturated surface dry specific gravity, absorption, and fineness modulus were 2.75 and 2.78, 0.8%, and 3.0, respectively. The coarse aggregate had a nominal maximum size equal to 0.50 inch (12.50 mm) and complied with ASTM C 33[11] size number 7. Its bulk and saturated surface dry specific gravity, absorption, and dry rodded unit weight were 2.77 and 2.79, 0.6%, 102 pcf (1634 kg/m^3), respectively. Other concrete constituents were tap water, polycarboxylate-based high range water reducing admixture (HRWRA) and viscosity modifying admixture (VMA) complying with the ASTM C 494[23] Type F requirements, and the ASTM C 260[46] air-entraining admixture (AEA).

The mixture constituents and proportions used for the investigation are presented in Table 6.1. All matrices were prepared with a constant water-to-cementitious materials ratio of 0.4, a uniform cement factor of 658 lb/yd^3 (391 kg/m^3), and a constant amount of fly ash representing 20% of the cement weight. In proportioning the aggregates content, the optimum volumetric coarse-to-fine aggregate ratio of 0.52/0.48 (1.083) was adopted in order to generate sufficient mortar content in self-consolidating concretes. Polycarboxylate-based high range water reducing admixture (HRWRA), made by the manufacturer B, was used along with its corresponding viscosity modifying admixture (VMA). The quantities of the chemical admixtures are shown in Table 6.1. They were obtained by evaluating the consistency and stability of concrete using different trial batches until a satisfactory slump flow of 25 ± 1 inches (635 ± 25 mm) or 28 ± 1 inches (711 ± 25 mm); and a visual stability index of 0 or 1 were attained. In order for the selected matrices to be effective at providing freezing and thawing protection, an optimum dosage of air-entraining admixture was used to generate a volumetric air content of 6 ± 1%, air bubbles with diameters between 0.0004 to 0.04 inch (10 and 1000 μm), and spacing factor smaller than 0.0079 inch (0.200) mm.

6.2.2 Mixing, sampling, and testing procedures

The mixing and testing were performed at a ready-mixed plant. The concretes were completely truck-mixed in accordance with a modified ASTM C 94[70] testing method. The mixing sequence consisted of: (1) manual introduction of the required amount of air entraining admixture into a truck mixer; (2) automated loading of the dried materials into a concrete truck-mixer and mixing at a rotational speed of 18 rpm for a period of three minutes to achieve a slump of 3 to 4 inches (by a visual inspection), (3) manual addition of the required HRWRA and the VMA into the fresh matrix and mixing for three minutes, followed by a two minutes rest and a final two minutes mixing. The produced ready-mixed self-consolidating concretes were then evaluated, before and after pumping, to determine the change in the unconfined workability, flow rate, dynamic segregation resistance, J-ring passing ability, rheological properties, volumetric air

Table 6.1: Mixture proportion of SCC used in pumping

Mix No.	Portland cement (pcy)	Fly ash (pcy)	w/cm$^{(1)}$	Actual water (pcy)	Fine aggre. (pcy)	Coarse aggre. (pcy)	oz / cwt of cm$^{(5)}$ HRWRA$^{(2)}$	VMA$^{(3)}$	AEA$^{(4)}$	Paste fraction (%)	Mortar fraction (%)	Volume of coarse aggre. (%)
S7.B.SF25	658.00	131.60	0.40	332.40	1383.98	1465.42	3.30	0.60	0.3125	41.13	63.66	30.96
S7.B.SF28	658.00	131.60	0.40	332.29	1384.15	1465.60	3.90	1.00	0.2500	42.83	63.66	30.96

^{1}water-to-cementitious materials ratio, ^{2}high range water reducing admixture, ^{3}viscosity modifying admixture, ^{4}air entrainment admixture

^{5}fluid once per hundred weight of cementitious materials content

1 pcy = 0.594 kg/m^{3}

content, and air voids characteristics.

An hydraulic powered valve type concrete pump and a heavy duty flexible hose pipeline with an inside diameter of 3 inches (75 mm) and a wall thickness of 0.12 inch (3 mm) were used for the experiment. Connection between segments to compose the selected pumping distances (100, 200 and 300 ft (30, 60 and 90 m)) were done by coupling devises that permitted rapid assembly and disassembly of any joint and provide a secure sealed joint. Before the beginning of each pumping action the pipelines were lubricated with 1 yd^3 (0.76 m^3) of cement slurry. Figures 6.3 through 6.24 present the majors phases of the mixing procedure; the measurement of the selected fresh properties; and the pump and its accessories used during the investigation.

6.2.2.1 Measurement of slump flow, T_{50}, VSI and J-ring

The unconfined workability, the flow rate, the dynamic stability and the passing ability of the selected self-consolidating concretes were measured by the slump flow, T_{50}, and VSI tests; and the J-ring test, in accordance with the ASTM C 1611[49] and C 1621[50], respectively. The related testing equipments and procedures were discussed in the task 3.

6.2.2.2 Measurement of the rheological properties

Concrete is generally accepted as viscoplastic Bingham material. In such materials, the rheological properties are characterized by the yield stress and the plastic viscosity. To date, there is no standard tests method to determine the true or absolute yield stress and plastic viscosity of fresh concrete. The rheological properties of concrete are usually measured with concrete rheometer, which are for the most part, based on the principle of stirring the matrix at a controlled speed and record the resulting torque. Most rheometers provide torque versus rotational speed to evaluate the relative yield stress and plastic viscosity.

In the present investigation, a compact rheometer for fresh concrete (two-point BT2 rheometer) was used for the determination of the relative yield stress and the plastic viscosity of the selected matrices. Figure 6.25 documents the actual BT2 apparatus. The BT2 measurement provides data at two different speeds, because the two probes are mounted at different radii from the center of the sample receptacle. The mode of functioning of the BT2 avoids structural breakdown and segregation during measurements. The testing procedure consisted of: (1) placing the fresh SCC sample in

Figure 6.3: Loading of the concrete's dried ingredients

Figure 6.4: High range water reducing and viscosity modifying admixtures

Figure 6.5a: Manual addition of admixture into the fresh concrete

Figure 6.5b: Manual addition of admixture into the fresh concrete (continued)

Figure 6.6: Visual inspection of fresh concrete before pumping

Figure 6.7a: Sample collection of SCC before pumping

Figure 6.7b: Sample collection of SCC before pumping (continued)

Figure 6.8a: Slump flow test

Figure 6.8b: Slump flow test (continued)

Figure 6.8c: Slump flow test (continued)

Figure 6.9a: J-ring test

Figure 6.9b: J-ring test (continued)

Figure 6.10a: Volumetric air content test

Figure 6.10b: Volumetric air content test (continued)

Figure 6.11: Sample collection for air void analysis test

Figure 6.12: Air void analysis test set up

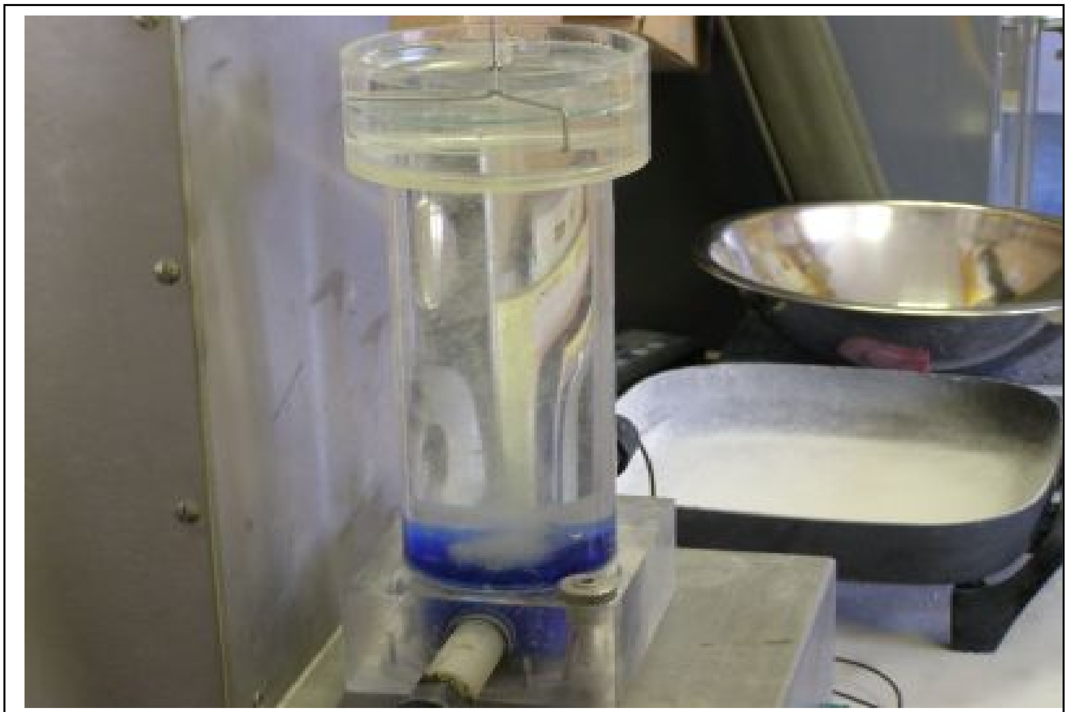


Figure 6.13: Air void analysis test in progress

Figure 6.14: Pumping test - set up of pipeline

Figure 6.15: Pumping test - lubricating pipes with cement slurry

Figure 6.16: Pumping test - loading SCC in the receiving hopper

Figure 6.17: Pumping test - post-pumping SCC sample collection

Figure 6.18a: Slump flow and T_{50} tests for post-pumped SCC

Figure 6.18b: Slump flow test for post-pumped SCC (continued)

Figure 6.19: J-ring test for post-pumped SCC

Figure 6.20: Volumetric air content test for post-pumped SCC

Figure 6.21: Air void analysis test for post-pumped SCC

Figure 6.22: Rheology test sampling for pumped SCC

Figure 6.23: Rheology test measurement for pumped SCC

Figure 6.24: Planning for the next batching

Figure 6.25: Two-point BT2 concrete rheometer

the receptacle, as shown in Figures 6.22 and 23, (2) attaching the BT2 to the support provided in the middle of the receptacle, and (3) rotating manually the BT2 by 360 degree, with the probes plunged inside the sample. The internal processor monitors the measuring data, i.e. the momentum on the probes and the angular velocity. The total duration of the test does not exceed three minutes. Upon completion of the measurement the readings may be wireless transferred and displayed at an external portable digital apparatus. The shear stress and strain rate are expressed as the torque and speed, respectively. A linear least-squared trend line fit to data is generated and its slope represents the relative viscosity while the intercept of the line represents the relative Bingham yield stress.

6.2.2.3 Measurement of air content and air void characteristics

The ASTM C 173[53] "Standard Test Method for Air Content of Freshly Mixed Concrete by Volumetric Method" was used to measure the air content of the fresh matrix. This method relies on simple displacement of air with water in a vessel of pre-calibrated volume. A newer form of air voids evaluation, referred as Air Void Analyzer (AVA) was used to determine the voids characteristics of the selected trial matrices. The test apparatus determines the volume and size distributions of entrained air voids, and calculates the spacing factor and specific surface. Manufactured by Germann Instruments, the AVA was originally, developed in Europe but validated to produce results that correlate with ASTM C 457[96] within a 95% confidence limit[95]. The ASTM C 457[96] "Standard Test Method for Microscopial Determination of Parameters of the Air-Void Content and Parameters of the Air-Void System in Concrete" is used in the United States to assure that the air-void system of hardened concrete is adequate to resist damage from a freeze-thaw environment.

The testing procedure was as follows: (1) a plexiglass cylinder (riser column) was filled with a viscous liquid (glycerin-based) at the base and topped off with water, (2) a mortar sample of 1.22 in^3 (20 cm^3) was extracted with a wire cage (to sieve out any aggregate larger than (0.24 inch (6 mm)), and (3) the mortar sample was injected with a syringe into the bottom of the riser column. From this point, the test was monitored by the computer software. A stirring rod, running in the mortar for 30 seconds, allowed the release of entrained air, which were then floated at the top of the column, where there were caught by an inverted Petri dish connected to a balance to measure the change in suspended mass. According to Stokes Law, the rate of rise in the bubbles is a function of their size, and the larger bubbles rise faster than the small ones. The viscous liquid had properties that ensured no coalescence of air bubbles, allowing them to retain the size and properties they had in the concrete. The entrapped air bubbles, characterized with a diameter greater than 0.12 inch (3 mm), were excluded. The software program calculated the "gradation" of the air bubbles, and determined the specific surface, the average spacing factor, and the total air content. The air void analyzer takes a minimum of 25 minutes to run, with the ability to do approximately one test per hour, due to set up and clean up between tests. The AVA is not meant to be a replacement for the current field tests for total air content. It does not provide a very good indication of the total air content due to the small size of the testing sample.

6.3 DISCUSSION OF RESULTS

Tables 6.2 and 6.3 present the pre- and post-pumping test results of the selected trial matrices at various pumping distances. The discussion on the fresh performance of the selected self-consolidating concretes as influenced by pumping is presented below.

6.3.1 Influence of pumping on the unconfined workability, flow rate, dynamic stability and passing ability of SCC

The slump flow, T_{50} time, VSI and J-ring tests were performed to determine the influence of pumping on the fresh performance of the selected self-consolidating concretes. The pre- and post-pumping test results at various pumping distances were compared. In general, the pumping affected the fresh performance of SCC by decreasing the unconfined workability, flow rate, and passing ability; and by increasing the dynamic segregation resistance.

Average decreases of 1.8 and 2.0 inches (45 and 50 mm) in unconfined workability of the trial self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows, respectively, were recorded after pumping. These losses were greater than the adopted 1 inch (25 mm) tolerance, indicating that a remediation of the slump loss due to pumping is necessary. In comparing the slump flow losses at various pumping distances, it can be seen from Tables 6.2 and 6.3 that the selected trial SCCs experienced slump flow losses of 6, 7 and 8% when the matrices were pumped over 100, 200 and 300 ft (30, 60 and 90 m), respectively. The small percentage difference between the slump losses indicated that the selected pumping distances had marginal effect on unconfined workability.

The impact of pumping on the flow rate was more pronounced. On average, the T_{50} times were reduced from 2.4 seconds before pumping to 1.0 second, after pumping, indicating a change from low viscosity matrix to high viscosity matrix (by inference). Indeed, decreases in T_{50} times of 59, 63 and 66%; and 51, 54 and 57% were recorded after the pumping of the self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows, over 100, 200 and 300 ft (30, 60 and 90 m), respectively. The losses in flow rate due to the increase in pumping distance were relatively small (about 3%).

Table 6.2: Pre- and post-pumping fresh properties of 25 inches slump flow SCC

Pumping distances		HRWR (oz/cwt)	VMA (oz/cwt)	AEA (oz/cwt)	Temp. (^{o}F)	Slump flow (in.)	T_{50} (sec.)	VSI	J-ring value (in.)
L = 300 ft	PRE-PUMPING	3.30	0.60	0.3125	67.40	25.75	2.63	0	1.37
	POST-PUMPING				63.20	23.75	0.90	0	1.50
L = 200 ft	PRE-PUMPING	3.30	0.60	0.3125	53.00	25.25	2.75	0	1.25
	POST-PUMPING				59.90	23.50	1.01	0	1.37
L = 100 ft	PRE-PUMPING	3.30	0.60	0.3125	59.30	25.44	2.68	0	1.19
	POST-PUMPING				59.00	23.88	1.10	0	1.25

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm, 1 ft = 304.8 mm

Table 6.2: Pre- and post-pumping fresh properties of 25 inches slump flow SCC (continued)

Pumping distances		HRWR (oz/cwt)	VMA (oz/cwt)	AEA (oz/cwt)	Relative yield stress (Nmm)	Relative viscosity (Nmm sec/m))	Volumetric test air content (%)	Air voids characteristics		
								Air content (%)	Specific surface (in^{-1})	Spacing factor (in)
L = 300 ft	PRE-PUMPING	3.30	0.60	0.3125	133.20	1.57	10.00	9.8 (7.4)[a]	835.00	0.0052
	POST-PUMPING				180.47	0.65	8.50	9.75 (7.5)	639.00	0.0067
L = 200 ft	PRE-PUMPING	3.30	0.60	0.3125	168.78	1.37	10.50	11.15 (8.4)	821.00	0.0046
	POST-PUMPING				224.35	0.60	10.00	10.35 (8.2)	710.50	0.0057
L = 100 ft	PRE-PUMPING	3.30	0.60	0.3125	162.85	1.33	7.50	8.4 (7.1)	976.00	0.0044
	POST-PUMPING				212.24	0.63	7.00	10.1 (9.1)	942.00	0.0048

[a] The number in parenthesis represents the entrained air, while the other number represents the sum of the entrapped and entrained airs

1 oz/cwt = 65 ml/100kg, 1 N = 0.225 lbf, 1 in. = 25.4 mm, 1 ft = 304.8 mm

Table 6.3: Pre- and post-pumping fresh properties of 28 inches slump flow SCC

Pumping distances		HRWR (oz/cwt)	VMA (oz/cwt)	AEA (oz/cwt)	Temp. (^oF)	Slump flow (in.)	T_{50} (sec.)	VSI	J-ring value (in.)
L = 300 ft	PRE-PUMPING	3.90	1.00	0.2500	68.50	27.94	2.25	1	1.19
	POST-PUMPING				70.10	25.75	0.96	0	1.37
L = 200 ft	PRE-PUMPING	3.90	1.00	0.2500	64.70	28.13	2.22	1	1.13
	POST-PUMPING				63.00	26.25	1.03	0	1.25
L = 100 ft	PRE-PUMPING	3.90	1.00	0.2500	66.00	28.13	2.15	1	1.00
	POST-PUMPING				68.40	26.50	1.05	0	1.12

1 oz/cwt = 65 ml/100kg, 1 in. = 25.4 mm, 1 ft = 304.8 mm

Table 6.3: Pre- and post-pumping fresh properties of 28 inches slump flow SCC (continued)

Pumping distances		HRWR (oz/cwt)	VMA (oz/cwt)	AEA (oz/cwt)	Relative yield stress (Nmm)	Relative viscosity (Nmm sec/m))	Volumetric test air content (%)	Air voids characteristics		
								Air content (%)	Specific surface (in^{-1})	Spacing factor (in)
L = 300 ft	PRE-PUMPING	3.90	1.00	0.2500	95.38	1.48	7.25	10.8 (8.9)[a]	1231.00	0.0032
	POST-PUMPING				139.66	0.36	7.00	10.8 (9.1)	939.00	0.0053
L = 200 ft	PRE-PUMPING	3.90	1.00	0.2500	118.12	1.47	5.25	7.4 (5.7)	946.00	0.0053
	POST-PUMPING				169.23	0.39	5.25	7.4 (5.4)	701.00	0.0071
L = 100 ft	PRE-PUMPING	3.90	1.00	0.2500	125.13	1.49	6.50	7.2 (5.3)	905.00	0.0056
	POST-PUMPING				173.88	0.48	6.50	6.7 (4.9)	875.00	0.0060

[a] The number in parenthesis represents the entrained air, while the other number represents the sum of the entrapped and entrained airs

1 oz/cwt = 65 ml/100kg, 1 N = 0.225 lbf, 1 in. = 25.4 mm, 1 ft = 304.8 mm

The influence of pumping on the dynamic stability of the selected matrices was evaluated through the VSI. As shown in Tables 6.2 and 6.3, the pumping affected the stability of the selected SCCs by improving the visual stability index (VSI), from 1 (stable matrix) to 0 (highly stable matrix) for the mixtures made with 28 inches (711 mm) slump flow. The 25 inches (635 mm) SCCs type remained highly stable after pumping.

The trial self-consolidating concretes were designed to produce high to moderate passing ability. After pumping, the measured J-ring values of the selected trial matrices remained within the allowable limit of 1 to 2 inches (25 to 50 mm), regardless of the pumping distance, indicating minimal to noticeable blocking of the selected self-consolidating concretes, regardless of the pumping distance. However, the test results revealed a slight decrease in the passing ability induced by the pumping distance. Average increases in J-ring value of 8 and 13% were recorded for the 25 and 28 inches (635 and 711 mm) slump flows, respectively.

6.3.2 Influence of pumping on the rheological properties of SCC

Due to lack of equipment and knowledge to determine the absolute yield stress and absolute plastic viscosity with high certainty, the relative yield stress and relative plastic viscosity were used to characterize the rheological properties of the selected self-consolidating concretes. *The relative yield stress or relative plastic viscosity of a suspension is defined as the ratio of the yield stress or plastic viscosity of the whole suspension to the yield stress or plastic viscosity of the embedded fluid medium*[97]. In the case of concrete, the inclusions in the suspension are constituted by the coarse aggregates. Therefore, *the relative yield stress or relative plastic viscosity of concrete can be defined as the ratio of the yield stress or plastic viscosity of the concrete to the yield stress or plastic viscosity of its mortar*[97].

The influence of pumping on the rheological performance of the selected matrices was investigated by comparing the pre- and post-pumping relative yield stress and relative plastic viscosity. In general, the pumping affected the rheology of the trial SCCs by increasing moderately the yield stress and decreasing significantly the plastic viscosity. Figure 6.26 illustrates the trend of the rheological properties of the selected SCCs as affected by pumping. As shown in Tables 6.2 and 6.3, the self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows experienced

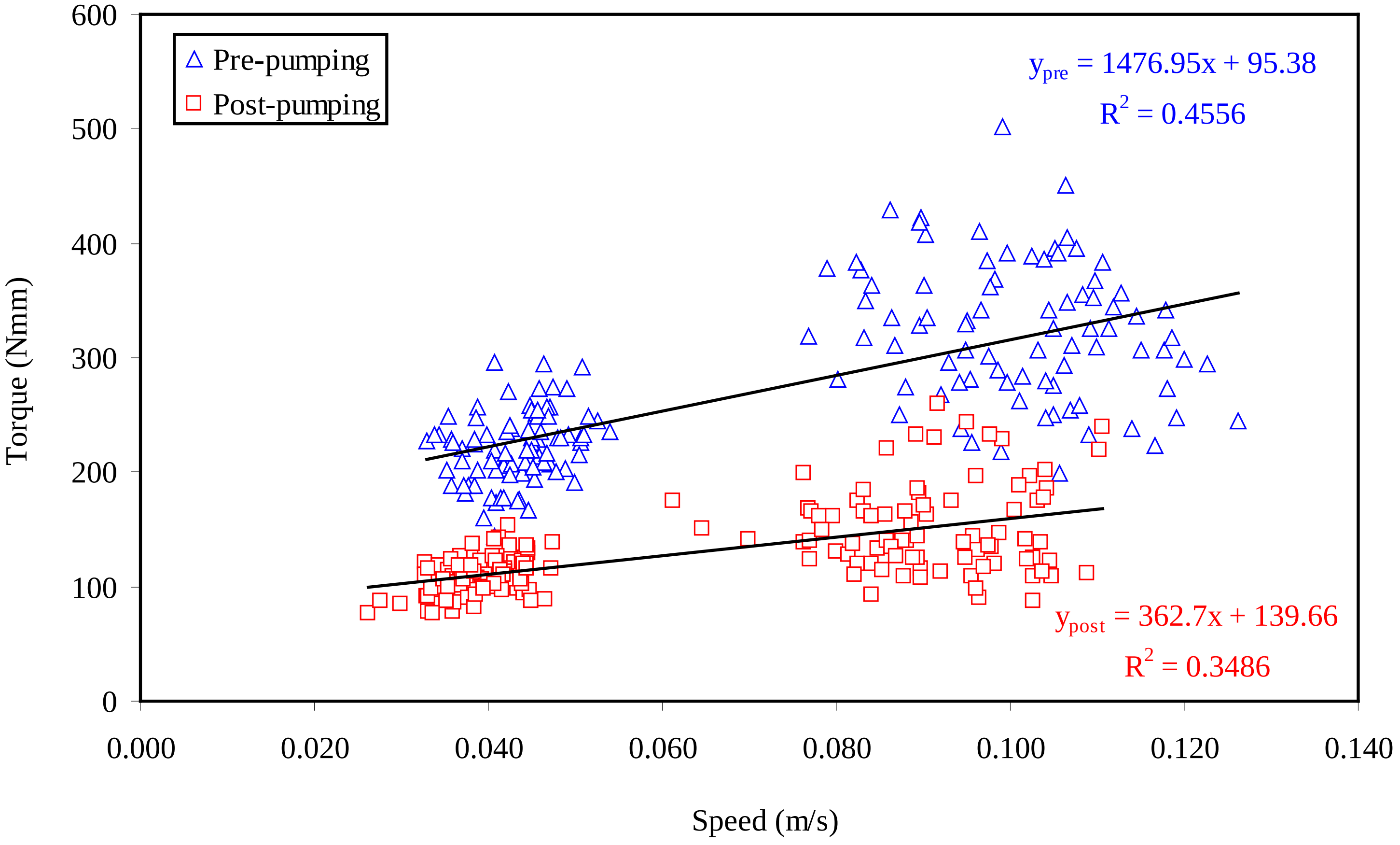


Figure 6.26: Pre- and post-pumping relatives yield stress and plastic viscosity of 28 inches slump flow SCC for 300 ft pumping distance

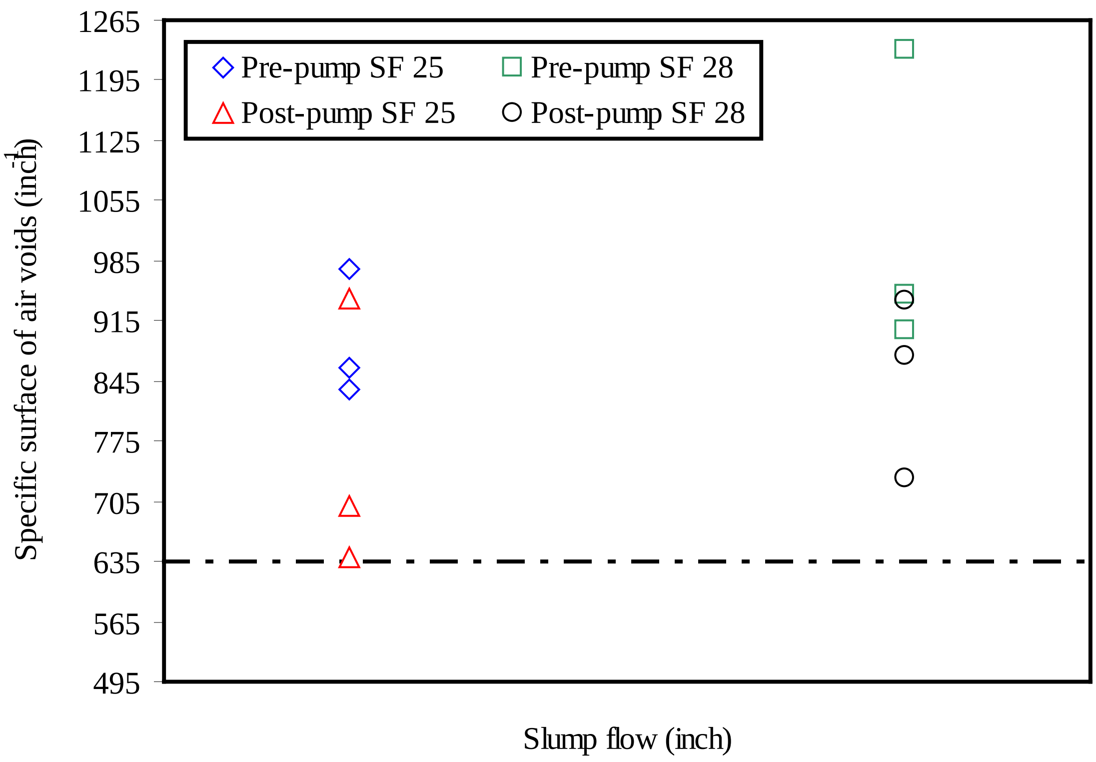


Figure 6.27: Influence of pumping on air voids specific surface

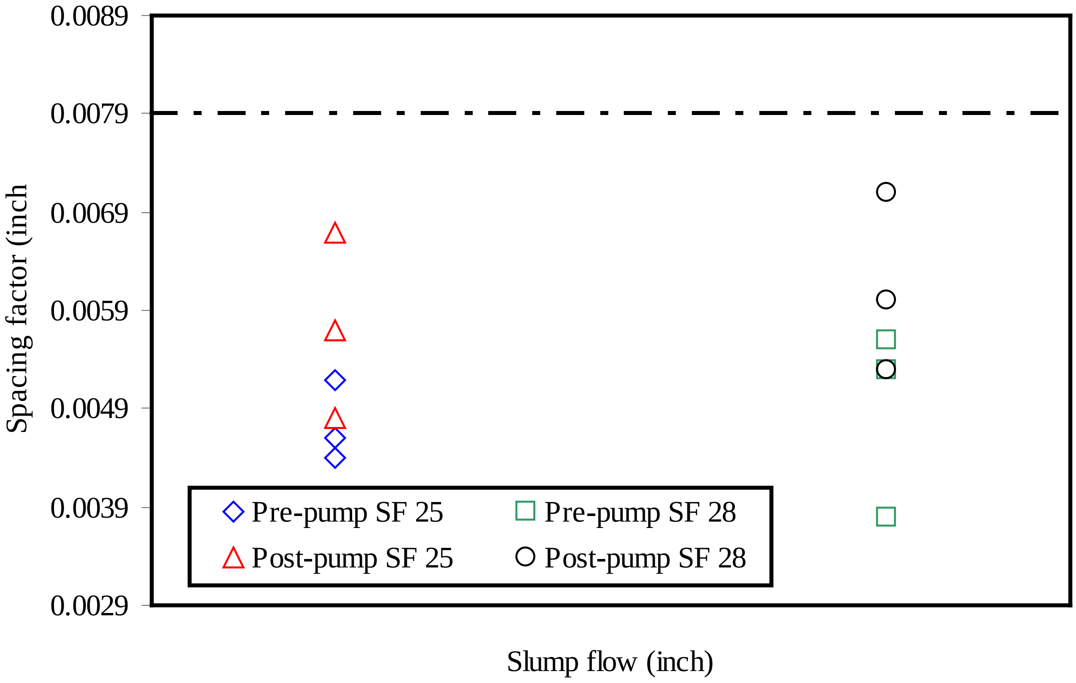


Figure 6.28: Influence of pumping on air voids spacing factor

increases in the relative yield stress of 30, 33, and 35%; and 39, 43, and 46% when pumped over 100, 200, and 300 ft (30, 60, and 90 m), respectively. At the same time, the relative plastic viscosities of same matrices were decreased by 53, 56, and 59%; and 68, 73, and 75%; respectively. These changes in the rheological properties of the post-pumped fresh SCCs confirmed the losses seen in the unconfined workability of the same matrices. Although minimal in nature, the increases in pumping distance from 100 to 200 to 300 ft (30, 60 and 90 m) induced increases in the relative yield stress and reductions of the relative plastic viscosity.

6.3.3 Influence of pumping on the volumetric air content and the air voids characteristics

In order to provide adequate freezing and thawing protection, the selected self-consolidating concretes were designed to generate: (1) air content of 6 ± 1%, (2) specific surface of air voids lower than 635 in^{-1}, and (3) spacing factor of air voids smaller than 0.0079 inch (0.200 mm). As shown in Figures 6.27 and 6.28 the specific surfaces and the spacing factors of the trials matrices, remained within the above mentioned targets before and after pumping. On the other hand, while the air content of the matrices made with 28 inches (711 mm) slump flow were within the 6 ± 1% limit, higher air contents than excepted were generated in the 25 inches (635 mm) slump flow matrices due to the discrepancy in the loading of the dried material at the ready mixed-plant. This situation did not alter the goal of the research which was to compare the air content and the air voids characteristics of SCCs before and after pumping.

In general, irrespective of the slump flow and the pumping distance, the air content obtained from the volumetric air content test method remained unaffected by the pumping action. Despite the fact that the AVA does not provide a very good indication of the total air content due to the small size of the testing sample, its displayed similar trend to the volumetric air content test results. It is important to note that, in Tables 6.2 and 6.3, the entrained air contents recorded by the AVA are presented in parenthesis, and the other numbers are the sum of the entrained and entrapped air contents.

The pumping affected the air voids characteristics by increasing the size of the air bubbles (or decreasing the specific area) accompanied with increases in the spacing factors. When the selected matrices were pumped over 100 ft (30 m), relatively small decreases in specific surface of about 3%, and increases in spacing factor of about 8% were exhibited. These changes became significant at the pumping distance of 200 and 300 ft (60 and 90 m) where the self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows displayed decreases in specific surface of 19 and 23%, and 23 and 24%, respectively. The corresponding increases in spacing factor were 24 and 29%, and 34 and 39%, respectively.

6.4 CONCLUSIONS

The influence of pumping on fresh properties of the selected self-consolidating concretes can be summarized as given below:

- The pumping adversely affected the fresh performance of the self-consolidating concrete by decreasing the unconfined workability, flow rate, and passing ability; and by increasing the dynamic segregation resistance. An average decreases of 1.8 and 2.0 inches (45 and 50 mm) in unconfined workability of the trials self-consolidating concretes made with 25 and 28 inches (635 and 711 mm) slump flows, respectively, were recorded after pumping. The matrices viscosities, as evaluated by the T_{50} time, were increased from low to high due to the pumping action.
- The impact of pumping on the rheological properties of self-consolidating concrete was manifested by a moderate increase in relative yield stress and a significant decrease in relative plastic viscosity.
- In general, irrespective of the slump flow and pumping distance, the air content obtained from the two test methods remained unaffected by the pumping action. However, the air voids characteristics were affected by the pumping without exceeding the recommend limits. The pumping generated larger sizes of air bubbles (or lower specific area) accompanied with increases in the spacing factors.
- The selected pumping distances (100, 200, and 300 ft (30, 60, and 90 m) marginally affected the fresh performance of the trial self-consolidating concretes.

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APPENDIX A

Specifications and Test Methods
for Self-Consolidating Concrete (SCC)

January 2008

TABLE OF CONTENTS

Nevada Test Procedure SCC-1: Standard Test Method for Sampling, Determining Yield and Air Content, and Making and Curing Strength

SELF-CONSOLIDATING CONCRETE SPECIFICATIONS

1. DEFINITION

Self-consolidating concrete (SCC) is a concrete that can be placed and compacted under its self-weight, with little or no vibration effort, while remaining homogenous and cohesive throughout the placing process without segregation or bleeding.

2. APPLICATIONS

Self-consolidating concrete has been used for precast/prestressed and cast-in-place concrete construction items and specifically the followings:

- concrete members for bridges: superstructures (decks and girders) and substructures (piers and abutments);
- footings;
- drilled shafts;
- walls and piles;
- ramps;
- floors and slabs;
- reinforced concrete culvert, storm drain, and sewer pipe;
- concrete flared end sections;
- reinforced concrete manhole and drop inlet sections;
- reinforced concrete elliptical culvert, storm drain and sewer pipe;
- concrete box culverts;
- architectural concrete;
- heavily reinforced areas; and
- formed repairs.

3. FORMWORK

The forms shall be designed for full hydrostatic head pressure of the concrete. When SCC is being pumped from the bottom or locally, the area of entry must be designed to withstand higher than the full hydrostatic head pressure of the concrete. Because full hydrostatic concrete pressure should be assumed when using SCC, particular attention should be paid to both the outer supports and the tie rod system and spacing to ensure that the formwork cannot deform during placing. Since SCC can reveal any deficiencies in the material, only forms that are in good conditions and have a smooth finish may be used.

When a formwork release agent is used, it should be a type that allows air to migrate in a controlled manner and escape from the concrete. The agents need to be applied extremely thinly since excess release agent at the form face and concrete interface can result in staining, retention of air bubbles, and other surface imperfections.

4. MATERIALS

Materials shall be according to the followings:

4.1 Aggregate

4.1.1 Coarse aggregate:

Materials retained on #4 sieve meeting the requirements specified in ASTM C 33 or AASHTO M 80.

The nominal maximum size of coarse aggregate shall meet the followings:

1. Not larger than 1/3 the depth of slabs or panels.
2. Not larger than 3/4 of the minimum clear depth cover.
3. Not larger than 2/3 of the minimum clear distance between reinforcing bars or between bars and forms, whichever is least.
4. In no instance shall the nominal maximum size of aggregates exceed 3/4 inch (20 mm).

4.1.2 Fine aggregate:

Materials passing #4 sieve meeting the requirements specified in ASTM C 33 or AASHTO M 6.

4.1.3 Gradation target:

In the absence of a specific gradation target, and if approved by the Engineer, the combined gradation of coarse and fine aggregates may be within the bands of the following table. Targets and production tolerances necessary to meet the requirements of the table shall be established by the Engineer. The Contractor shall submit documentation to the Engineer justifying any deviation from the approved gradation.

Aggregate gradations (Percent passing by dry weight of aggregate)		
Sieve size	¾” Operating bands	½” Operating bands
¾ inch	95 - 100	
½ inch	65 - 95	95-100
3/8 inch	58 - 83	65 - 95
No. 4	35 - 65	50 - 80
No. 8	25 – 50	30 - 60
No. 16	15 - 35	20 - 45
No. 30	10 - 35	12 - 35
No. 50	5 - 20	5 - 20
No. 100	1 - 12	2 - 12
No. 200	0 - 2	0 - 2

4.2 Cement

Cements shall conform to ASTM C 150. Cement of the same type, brand, and color from the same mill shall be used throughout any given project. Unless otherwise stated, Type II or V Portland cement shall be used.

4.3 Mineral fillers and pozzolanic/hydraulic materials

Due to the fresh property requirements of SCC, inert and pozzolanic/hydraulic additions are commonly used to improve and maintain the cohesion and segregation resistance. The addition will also regulate the cement content in order to reduce the heat of hydration and thermal shrinkage. All mineral admixtures or pozzolans meeting ASTM C 618, C 989, or C 1240 may be used.

4.3.1 Mineral fillers:

Properly ground mineral fillers are particularly suitable for SCC since they (1) offer the advantage of improved batch to batch consistency of particle size distribution and (2) provide improved control over water demand. Calcium carbonate based mineral fillers are widely used and can provide excellent rheological properties and a smooth finish. The most advantageous fraction is that smaller than 0.005 in. (0.125 mm) and, in general, it is desirable that greater than 70 percent pass a 0.0025 in. (0.063 mm) sieve.

4.3.2 Fly ash:

Fly ash has been shown to be an effective addition for SCC in providing increased cohesion, improved segregation resistance, and reduced sensitivity to change in water content. However, high level of fly ash may produce a paste fraction which is so cohesive that it can be resistant to flow. Fly ash shall comply with ASTM C 618 except with the maximum loss on ignition of 3 percent.

4.3.3 Silica fume:

The high level of fineness and practically spherical shape of silica fume results in a good cohesion and an improved resistance to segregation. However, silica fume is also very effective in reducing or eliminating bleeding which can give a rise to problem of plastic shrinkage and finishing of the top surface, leading to the formation of cold joints or surface defects if there are any breaks in concrete delivery. Silica fume shall comply with ASTM C 1240.

4.3.4 Ground blast furnace slag:

Ground granulated blast furnace slag (GGBS) provides reactive fines with low heat of hydration. A high proportion of GGBS results in a slower setting while increases the risk of segregation. GGBS shall comply with ASTM C 989 Grade 100 or higher.

4.4 Water type and quality

Water shall be potable or meet the specified test standard in AASHTO M 157. Water shall not contain iron or iron oxides.

4.5 Admixtures

The self-consolidating concrete admixture system shall consist of either a polycarboxylate-based high range water reducing admixture or a polycarboxylate-based high range water reducing admixture combined with a separate viscosity modifying admixture. The same brand and type of admixtures shall be used throughout all parts of the project. Admixtures containing chloride ions shall not be used in prestressed concrete, or in concrete containing aluminum embedment or galvanized reinforcement and/or hardware. Producer shall verify via trial that admixtures are compatible.

4.5.1 High range water reducing admixture:
The polycarboxylate-based high range water reducing admixture (HRWRA) shall be in accordance with AASHTO M 194, Type F or G, or ASTM C 494 Type F or G, or ASTM C 1017. All HRWRA admixtures must be compatible with admixtures that are present in slurry silica fume, if any.

4.5.2 Viscosity modifying admixture:
The viscosity modifying admixture (VMA) shall be evaluated according to the test methods and mixture design proportions referenced in AASHTO M 194. Although not required, a VMA is recommended as a way to enhance the resistance to segregation, homogeneity and flow of SCC.

4.5.3 Other admixtures:
Other admixtures including air entraining, accelerating and retarding may be used in the same way as in traditional vibrated concrete but advice should be sought from the admixture manufacturer on use and the optimum time for addition and they should conform to ASTM C 260 or C 494. Any coloring admixtures used shall conform to ASTM C 979.

5. MIXTURE PROPORTIONING

5.1 Aggregate ratio

A fine aggregate content of 40 % to 60 % of the combined coarse and fine aggregate weight shall be used.

5.2 Cement factor

A minimum of 639 lbs. per cubic yard (380 kilogram per cubic meter) for a w/cm ratio between 0.44 and 0.37, a minimum 825 lbs. per cubic yard (490 kilogram per cubic meter) for a w/cm ratio between 0.37 and 0.33, or a minimum of 900 lbs. per cubic yard (535 kilogram per cubic meter) for a w/cm ratio of below 0.33 shall be used.

5.3 Water-to-cementitious materials Ratio

For precast concrete, water-to-cementitious materials ratio (w/cm) shall not exceed 0.48. For prestressed/postensioned concrete, see table 1000-1 in the 2006 standard specifications.

5.4 Pozzolanic/hydraulic additions

With approval of the Engineer, pozzolanic and hydraulic materials may be substituted for a portion of the cement for the limits indicated below:

5.4.1 Fly ash:
A minimum of 20 % and a maximum of 40 % by weight shall be used.

5.4.2 Silica fume:
A minimum of 6 % and a maximum of 8 % by weight shall be used.

5.4.3 Ground granulated blast furnace slag (GGBFS):
A maximum of 40 % by weight shall be used. A minimum of 10 % fly ash shall be used with GGBFS.

5.4.4 Total Pozzolanic/Hydraulic Additions:
The total ternary combinations shall not exceed 40 %.

5.5 Air Entrainment

Units subject to freezing and thawing, deicer, and wet-dry conditions shall be fabricated from air-entrained concrete and shall conform to the following table. If approved by the Engineer, for the specified compressive strength greater than 5,000 psi (35MPa), a reduction in air content by 1 percent may be permitted.

Nominal maximum size of aggregate in. (mm)	Total air content, percent by volume	
	Severe Exposure	Moderate Exposure
Less than 3/8 (9)	9%	7%
3/8 (9)	7.5%	6%
1/2 (13)	7%	5.5%
3/4 (19)	6%	5%

6. MIXING

The batch sequence, mixing speed, and mixing time shall be appropriate to prevent cement balling and mixture foaming and shall ensure proper dispersement of all ingredients. Admixtures shall not be added directly to dry constituent materials but dispensed together with or in the mixing water. Different admixtures shall not be blended together prior to dispensing unless specifically approved by the admixture manufacturer. Wash water shall be completely discharged from the mixer before the succeeding batch is introduced. The volume of concrete shall not be less than half the capacity of the mixer.

7. TRANSPORTATION

Self-consolidating concrete should be kept agitated during transportation. Precautionary measurement should be taken into account on the impact of transportation time on fresh and hardened properties of self-consolidating concrete.

8. VIBRATION

Rodding or vibrating should not be used for self-consolidating concrete except in special circumstances. Particular attention should be given to possible external sources of vibration (i.e., nearby equipment) that may affect the SCC.

In the event an unexpected delay in placement occurs and the surface of the SCC has stiffened to the extent that a cold joint or surface blemish could form, limited rodding of the surface is permitted to restore fluidity prior to placement of additional concrete. On the occasion when a noticeable loss of workability (which might affect self-consolidation) occurs, a minimal vibration is permitted. In some structures where the formwork shape may cause air to be trapped in certain locations, external vibration or rodding is permitted in the affected area.

9. PLACEMENT

When using self-consolidating concrete, each successive batch shall be placed within a maximum time interval of 20 minutes. Plan and regulate the delivery of concrete so that minor interruptions, due to form repair, material testing, etc., will not impact the required 20 minutes time interval between successive placements.

SCC shall be placed in a continuous and timely manner to maintain its workability and specified slump flow during placement. When it is necessary by reason of emergency or other delay, to place less than a complete horizontal layer in one operation, terminate the layer by using a vertical bulkhead. If temporary storage of fresh concrete is required, an agitated holding tank can be used provided workability is not sacrificed.

Self-consolidating concrete found to have a slump flow outside conformity area may only be retempered using a superplasticizer in accordance with the supplier recommendations and the approval of Engineer.

When using self-consolidating concrete, open troughs and chutes shall extend as nearly as practical to the point of deposit. The drop distance shall not exceed 5 feet (1.5 m). The maximum drop distance shall be decreased if segregation occurs. The maximum distance of horizontal flow from the point of deposit shall be 30 feet (9 m), unless approved by the Engineer. For drilled shafts, concrete placement shall conform to the requirements of 509.03.12 & 509.03.13 of the Standard Specifications.

10. FINISHING

When using self-consolidating concrete, normal concrete finishing practices may be employed. However, finishing work can be challenging due to SCC’s high viscosity and little amount of bleeding water. Therefore, it is necessary to take appropriate measures to prevent surface drying until the time of finishing. If needed, the application of a water mist or finishing aid is permitted.

11. CURING

Normal curing practices can be used for SCC. Care should be taken to avoid premature drying, evaporation, and extremes temperature. Due to increased paste quantity, low water/fine ratio and bleed water, the initial curing for SCC should commence as soon as practicable after placing and finishing to prevent or minimize plastic shrinkage.

12. QUALITY TESTING

12.1 Aggregates

Perform the followings tests and include the results in each report:

Test number	Test	Testing frequency
Nev. T112D	Moisture content	One per day
Nev. T206F	Sieve analysis	One per day
Nev. T492C	Specific gravity &absorption (coarse)	One per 250 cu yd
Nev. T493C	Specific gravity &absorption (fine)	One per 250 cu yd

12.2 Laboratory trial batch

The trial batch shall verify (1) the requirements dealing with batching sequence time and (2) the proposed concrete mixture properties at fresh and hardened states. The followings tests may be performed:

12.2.1 Plastic properties tests

12.2.1.1 Slump flow, VSI, and T_{50} shall be tested in accordance with Nev. SCC-2. The slump flow shall be within the range of 20 to 33 inches (508 to 838 mm) spread. The allowable tolerance of the slump flow shall not exceed ±2 in. (50 mm). The visual stability index (VSI) shall not exceed 1. The T_{50} time of 2 seconds or less characterizes self-consolidating concrete with a low viscosity, and a T_{50} of 5 seconds and more is generally considered a high-viscosity SCC mixture.

12.2.1.2 The V-Funnel test, a measure of filling ability and confined workability of SCC, shall be tested in accordance with the Nev.SCC-3. A V-funnel time of 10 seconds is acceptable. V-Funnel at T5-minutes can be used to assess potential segregation of SCC.

12.2.1.3 The U-Box test, a measure of passing and filling abilities of SCC, shall be tested in accordance with the Nev.SCC-4. The acceptable SCC shall have U-Box filling height H_1-H_2 lower than 12 inches (305 mm).

12.2.1.4 J-Ring test, a measure of the passing ability of SCC, shall be conducted in accordance with the Nev. SCC-5. The difference in the spread between tests with and without the ring shall not exceed 2 inches (50 mm).

12.2.1.5 L-Box test, a measure of passing ability and flow ability of SCC, shall be conducted according to Nev.SCC-6. The ratio of H_2 to H_1 shall be within the range of 0.8 to 1.0.

12.2.1.6 Column Technique test, a measure of static segregation resistance of SCC, shall be performed in accordance with the Nev.SCC-7. The Column segregation index (SI) shall be a maximum of 15 percents.

12.2.1.7 The air content of the plastic concrete shall be tested in accordance with the ASTM C 173. The minimum specified air content of freshly-mixed SCC as noted in the contract shall be met.

12.2.1.9 Bleeding test shall be conducted in accordance with the ASTM C 232, and meet the specified requirements as noted in the contract.

12.2.1.10 Temperature test of fresh SCC shall be conducted in accordance with the ASTM C 1064 and meet the specified requirements as noted in the contract.

12.2.2 Hardened properties tests

All ASTM and AASHTO test methods used in the evaluation of SCC hardened properties shall be modified to include: (1) molds shall be filled in one layer with no rodding or vibration, and (2) exposed surface of each test specimen shall be finished using a steel trowel. All hardened properties shall meet the requirements indicated in the contract.

12.2.2.1 Static segregation – It measures static segregation of hardened SCC. The test shall be conducted in accordance with the Nev.SCC-8. The visual stability index of hardened specimens (HVSI) shall be a maximum of 1.

12.2.2.2 Compressive strength - Report the compressive strength of concrete cylinders made in accordance with ASTM C 39 at 3, 7, 14, and 28 days. Specimens shall not be cast until all specified tests relevant to flow ability, passing ability and resistance to dynamic and static segregations have been completed.

12.2.2.3 Modulus of elasticity - Report the modulus of elasticity of SCC specimens made and tested in accordance with the ASTM C 469 at 3 and 28 days.

12.2.2.4 Flexural strength - SCC specimens shall be prepared and tested per ASTM C 293 or C 78.

12.2.2.5 Shrinkage - The samples shall be prepared and tested in accordance with the ASTM C 157 and shrinkage shall not exceed 0.04% at 28 days. Use Steel molds 3 inches x 3 inches x 11.25 inches (76 x 76 x 286 mm) sizes. Report the length change of each specimen to the nearest 0.001% of the effective gage length at 3, 7, 14, and 28 days and 8 weeks.

12.2.2.6 Creep - Test samples shall be prepared and tested per ASTM C 469, or C 801, or C 209 R.

12.2.2.7 Hardened air analysis - SCC specimens shall be prepared and tested in accordance with the ASTM C 457, with 3.5% entrained air minimum or higher as required by the contract.

12.2.2.8 Freezing and thawing resistance - SCC samples shall be prepared and tested in accordance with the AASHTO T161 or ASTM C 666. Acceptable results shall not exceed 3% mass loss or exceed 20% change in dynamic relative modulus of elasticity.

12.2.2.9 Scaling resistance - SCC samples shall be prepared and tested per ASTM C 672.

12.2.2.10 Rapid chloride permeability - SCC molds shall be prepared and tested in accordance with the ASTM C 1202 or AASHTO T 277. The maximum ion penetration shall not exceed 2000 coulombs.

12.2.2.11 Abrasion resistance - SCC samples shall be prepared and tested per ASTM C 418, or C 779, or C 944.

12.3 Demonstration

Conduct demonstration to verify the field trial batches by casting partial or full-scale mock-up of the proposed SCC products. Only the SCC admixtures proposed by the contractor shall be used. Every test batch shall be at least 3 cubic yards (2.25 cubic meters).

The Contractor shall provide for the labor, materials and equipments. The Engineer shall verify the plastic properties tests, including, Slump flow, T_{50}, visual stability index (VSI), J-rings, L-box, V-funnel, column technique, Static segregation, air content, density, temperature, setting time, and bleeding. Other tests shall be performed if the Contractor plans to use them for the quality control of the production concrete.

The Engineer shall (1) perform the inspection of the saw-cut sections of the SCC, (2) observe the aggregate distribution of the saw-cut and core samples and (3) verify that the concrete is free from any sign of honeycombs, cracks, aggregate segregation, and any other defects.

The Engineer shall verify that all hardened properties meet the requirements of the contract using core of filed-cast samples. The hardened properties may include: compressive strength, modulus of elasticity, flexural strength, shrinkage, creep, hardened air analysis, freezing and thawing resistance, scaling resistance, rapid chloride permeability, and abrasion resistance.

Upon review of the tests, the Engineer shall notify the Contractor on the acceptance or rejection of the trial SCC. Additionally, a new trial SCC batch shall be required when there is a change in the mixture constituents and proportion, batch sequence, mixing speed, mixing time, or others as determined by the Engineer. The testing criteria for the new trial SCC batch shall be determined by the Engineer.

12.4 Production

12.4.1 Aggregate moisture content

In absence of in-line moisture meters, the free moisture content of aggregates shall be determined within two hours prior to each day's batching operations, at four hour intervals during continuous batching operations, and at any time a change in moisture content becomes apparent. No assumptions or approximations shall be made concerning the amount of free moisture present in any aggregate. Actual measurement is required.

12.4.2 Self-consolidating concrete

Perform the following tests and include the results in each report:

Test number	Test	Testing frequency
Nev. SCC-2	Slump flow, T_{50}, and VSI	First two trucks & every 50 cu yd thereafter
Nev. SCC-5	J-Ring	First two trucks & every 50 cu yd thereafter
Nev. SCC-6	L-Box	First two trucks & every 50 cu yd thereafter
ASTM C 1064	Temperature	First two trucks & every 50 cu yd thereafter
ASTM C 173	Air content	First two trucks & every 50 cu yd thereafter
Nev. SCC-8	Hardened stability index	First truck & every 200 cu yd thereafter
ASTM C 39	Compr. strength	First two trucks & every 50 cu yd thereafter

For the plastic properties, whenever the initial test fails, retesting shall be performed. The SCC batch will be rejected if the initial test and the retest fail.

13. QUALITY CONTROL

The Contractor shall designate a quality control supervisor who will be responsible for the execution of the quality control plan. The quality control supervisor should be familiar with SCC test methods and specification requirements. All tests shall be performed in accordance with the NDOT specifications. The Contractor shall submit a report within 24 hours after each test conducted.

The quality control plan shall be executed by the Contractor at the plant and job site. The plan shall address (1) the mixture design qualification process, (2) the materials ingredients, batching sequence, mixing time, delivery, placement, finishing, and curing, and (3) the inspection and test methods for the laboratory, demonstration, and field tests.

14. QUALITY ASSURANCE

At the discretion of the Engineer, all or part of the total tests required by the Contractor at the plant and the jobsite shall be witnessed by the Engineer or the designee. The Engineer shall perform the followings quality assurance tasks at the plant and the jobsite:

(1) For aggregate gradation, specific gravity, absorption, and moisture content, quality assurance independent sample testing and split sample testing shall be conducted as specified in the contract plan.

(2) For the mixture qualification as related to the plastic and hardened properties of SCC, sample testing and split sample testing shall be performed as specified in the contract plan.

REFERENCES

1. Colorado Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” May 2005, 3 pages.

2. Delaware Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” 3 pages.

3. Florida Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” July 2005, 6 pages.

4. Illinois Department of Transportation, “Special Provision for Self-Consolidating Concrete for Cast-In-Place Constructions,” August 2005, 7 pages.

5. Illinois Department of Transportation, “Special Provision for Self-Consolidating Concrete for Precast Products; August 2005,” 3 pages.

6. Maine Department of Transportation, “Special Provision for Precast Self-Consolidating Structures,” 1 pages.

7. Missouri Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” 4 pages.

8. Nebraska Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” 2 pages.

9. North Carolina Department of Transportation, “Special Provision for Self-Consolidating Concrete for Precast and Prestressed Concrete,” November 2005, 3 pages.

10. Pennsylvania Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” 3 pages.

11. Utah Department of Transportation, “Standard Specification for Self-Consolidating Concrete,” August 2005, 4 pages.

12. Europeans Guidelines for Self-Consolidating Concrete, May 2005; 68 pages.

13. Japan Society of Civil Engineers' Standard Specification for Design and Construction of Concrete Structures, 19 pages.

14. Precast/prestressed Concrete Institute’ Standard Specification for Self-Consolidating Concrete. 162 pages.

TEST METHODS FOR SELF-CONSOLIDATING CONCRETE

Nevada Test Procedure SCC-1

Standard Test Method for Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete

1. SCOPE

This document specifies the procedure for sampling, determining yield and air content, and making and curing strength test specimens of self-consolidating Concrete.

2. REFERENCED DOCUMENTS

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Illinois Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. SAMPLING OF FRESHLY MIXED

Sampling freshly mixed self-consolidating concrete (SCC) shall be performed according to Illinois Modified AASHTO T 141, except the elapsed time for obtaining the representative sample shall not exceed two (2) minutes. The testing personnel performing field sampling of SCC shall be qualified by the NDOT. The number of testing personnel shall be such that all tests should start within five (5) minutes of obtaining the representative sample.

4. YIELD AND AIR CONTENT OF FRESHLY MIXED SCC

The yield and air content test of SCC shall be performed according to Illinois Modified AASHTO T 121; and ASTM C 173 or AASHTO T 152, respectively, except the measure of the bowl shall be filled in one lift without vibration, rodding, or tapping.

5. MAKING AND CURING SCC STRENGTH TEST SPECIMENS

Strength test specimens of SCC shall be made according to Illinois Modified AASHTO T 23 or T 126, except for the following:

a. The specimen molds shall be filled using a suitable container in one lift without vibration, rodding, or tapping.

b. Strike off the surface of the concrete level with the top of the mold using the strike-off bar or tamping rod.

c. The slump flow, VSI, T_{50}, air content, and temperature of each batch of concrete, from which specimens are made, shall be also measured immediately after remixing.

Nevada Test Procedure SCC-2

Standard Test Method for Slump Flow, T_{50}, and Dynamic Segregation Resistance of Self-Consolidating Concrete

1. SCOPE

This document specifies the procedure for determining the flow ability, the T_{50} time, and the dynamic stability of fresh self-consolidating concrete (SCC). The average diameter of the slump flow is a measure of the flow ability in unconfined condition of SCC. The time in seconds it takes for the concrete flow to reach a diameter of 20 inches (508 mm) is the T_{50} time. The Visual Stability Index (VSI) is a value of the dynamic segregation resistance (stability) of SCC. The test is not suitable when the maximum size of the aggregate exceed 1.5 in. (40 mm). All rounding shall be according to ASTM E 29.

2. REFERENCED DOCUMENTS

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

European Guideline for Self Consolidating Concrete.

Illinois Test Procedure SCC-2, Standard Test Method for Slump Flow and Stability of Self-Consolidating Concrete.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

a. Mold and tamping rod – The mold and tamping rod shall conform to that described in AASHTO T 119.

b. Strike-off bar – *Optional* The strike-off bar shall be a flat straight bar at least of 0.125 in. x 0.75 in. x 12 in. (3 mm x 20 mm x 300 mm).

c. Base plate – The base plate shall be made from a flat plate with a plane area of at least 35 in. x 35 in. (900 mm x 900 mm). The plate shall be smooth, rigid, and nonabsorbent. The centre of the plate shall be scribed with a cross, the lines of which run parallel to the edges of the plate and with circles of 8 in. (200 mm) diameter and 20 in. (500 mm) diameter having their centers coincident with the centre point of the plate. See Figure 1.

d. Suitable container for filling inverted slump cone.

e. Measuring tape – The measuring tape shall have a minimum gradation of 0.5 in. (10 mm).

f. Stopwatch – The stopwatch shall have a minimum reading of 0.2 second.

4. MATERIALS

The sample of SCC from which test specimens are made shall be obtained according to Section I of Nevada Test SCC-1.

5. PROCEDURE

a. Clean and dampen the slump cone and base plate. Ensure excess water is removed from the testing surface as too much water may influence the visual stability index (VSI) rating.

b. Place the base plate on level, stable ground and place the cone coincident with the 8 in. (200 mm) circle on the base plate. The mold shall be placed either with the smaller diameter opening up, or inverted with the smaller diameter opening down.

c. Fill the cone without any vibration, rodding, or tapping.

d. Strike off surplus of concrete from the top of the cone using the tamping rod or strike off bar. Allow the filled cone to stand for not more than 30 seconds; during this time, remove surplus concrete from around the base of the cone and base plate surface.

e. Raise the cone vertically a distance of 9 ± 3 in. (225 ± 75 mm) in 3 ± 1 seconds without any lateral or torsional motion. Complete the test procedure from the start of filling through removal of the mold without interruption and within an elapsed time of 2.5 minutes.

f. To measure the T_{50} time, start the watch immediately the cone cease to be in contact with the base plate and record the time taken to the nearest 0.1 s for the concrete flow to reach the 20 in. (500 mm) circle at any point. This is the T_{50} time.

g. When the concrete has stopped flowing, measure the maximum diameter of the resulting slump flow and measure the diameter perpendicular to the maximum. Each measurement shall be to the nearest 0.5 in. (10 mm). If the two measurements differ by more than 2 in. (50 mm) verify base plate to be level, and test again.

h. Calculate the average of the two measured diameters. This is the slump flow.

i. By visual examination, check the concrete spread for segregation. The cement paste may segregate from the coarse aggregate to give a ring of paste extending several inches beyond the coarse aggregate. Rate the Visual Stability Index (VSI) of the SCC using the criteria in Table 1.

Table 1 Visual Stability Index of Fresh SCC (VSI) Rating Criteria

Rating	**Criteria**
0 Highly stable	No evidence of segregation or bleeding in slump flow, mixer drum/pan, or sampling receptacle (e.g. wheelbarrow).
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, or concrete in the mixer drum/pan or sampling receptacle (e.g. wheelbarrow).
2 Unstable	Slight mortar halo, ≤ 0.5 in. (≤ 10 mm) wide, and/or coarse aggregate heaping in the slump flow, and highly noticeable bleeding in the mixer drum/pan or sampling receptacle (e.g. wheelbarrow).
3 Unstable	Clearly segregated by evidence of a large mortar halo, > 0.5 in. (>10 mm), and/or large coarse aggregate pile in the slump flow, and a thick layer of paste on the surface of the concrete sample in the mixer drum or sampling receptacle (e.g. wheelbarrow).

6. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. The slump flow to the nearest 0.5 in (10 mm);

e. The T_{50} time to the nearest 0.1 second;

f. The VSI rating;

g. The time between completion of mixing and performance of the tests;

h. Any deviation from the procedure in this document;

i. The temperature of the concrete at the time of test; and

j. The time of the test.

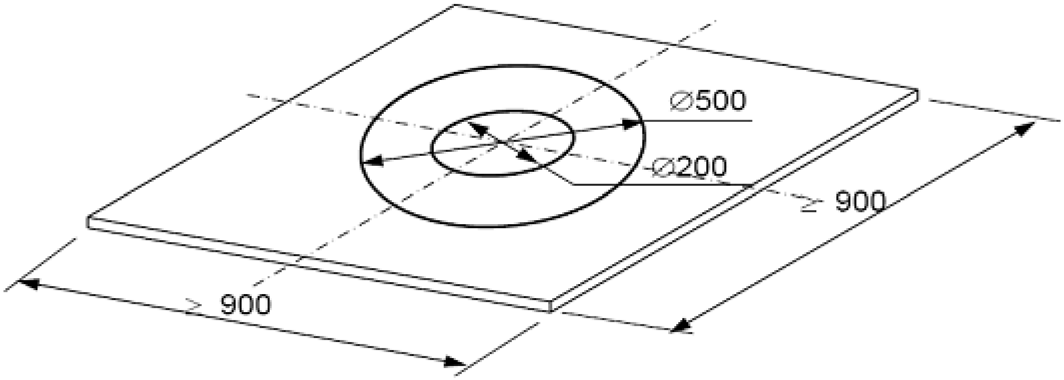

Figure 1. Base plate for slump flow test

Nevada Test Procedure SCC-3

Standard Test Method for Filling Ability and Confined Workability of Self-Consolidating Concrete by V-Funnel

1. SCOPE

This test method covers the procedure for determining the V-funnel flow time for self-compacting concrete. The V-funnel test is used to determine the flow ability in confined condition of self-consolidating concrete. The test is not suitable when the maximum size of the aggregate exceeds 3/4 in. (20 mm).

2. REFERENCED DOCUMENTS

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

European Guidelines for Self-Consolidating Concrete.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

a. V-funnel, made to the dimensions (tolerance ± 1 mm) in Figure 1, fitted with a quick release, watertight gate at its base and supported so that the top of the funnel is horizontal. The V-funnel shall be made from metal; the surfaces shall be smooth, and not be readily attacked by cement paste or be liable to rusting.

b. Container, to hold the test sample and having a volume larger than the volume of the funnel and not less than 0.42 cu ft. (12 liters).

c. Stopwatch – The stopwatch shall have a minimum reading of 0.2 second.

d. Strike-off bar – *Optional* The strike-off bar shall be a flat straight bar at least of 0.125 in. x 0.75 in. x 12 in. (3 mm x 20 mm x 300 mm).

4. MATERIALS

The sample of SCC of at least 0.42 cu ft. (12 liters) shall be obtained according to Section I of Nevada Test SCC-1.

5. PROCEDURE

A V shaped funnel is filled to its upper level with concrete. After the concrete rests for one minute in the V-funnel, the gate is opened and the time taken for the concrete to flow out of the funnel is measured and recorded as the V-funnel flow time. To perform this test the followings steps shall be taken:

a. Clean the funnel and bottom gate, and dampen all the inside surface including the gate.

b. Close the gate and pour the sample of concrete into the funnel, without any agitation or rodding, then strike off the top with the straight edge so that the concrete is flush with the top of the funnel.

c. Place the container under the funnel in order to retain the concrete to be passed.

d. After a delay of one minute from filling the funnel, open the gate and measure the time t_v, to 0.1 second, from opening the gate to when it is possible to see vertically through the funnel into the container below for the first time t_v is the V-funnel flow time.

The V-funnel at T5-minutes consists of using the same V-funnel apparatus. The SCC is filled in the V-shaped with closed gate and allowed to settle for 5 minutes. If the SCC shows segregation, the flow time increases significantly.

6. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. The V-funnel flow time (t_v) to the nearest 0.1 second;

e. The time between completion of mixing and performance of the tests;

f. Any deviation from the procedure in this document;

g. The temperature of the concrete at the time of test; and

h. The time of the test.

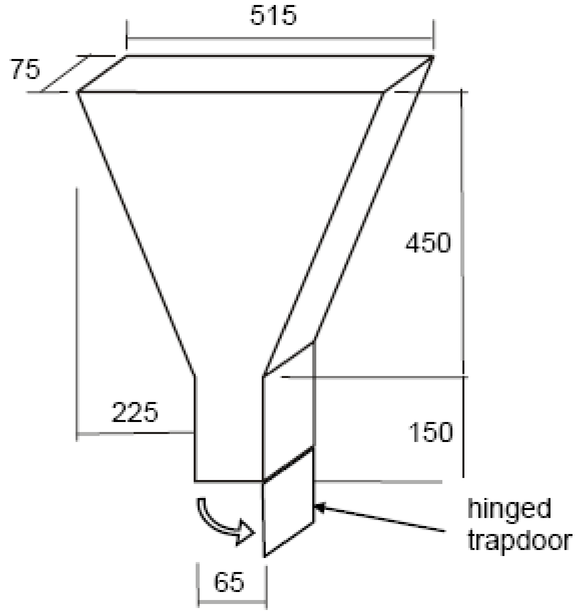

Figure 1 — V funnel

Nevada Test Procedure SCC-4

Standard Test Method for Passing Ability and Filling Ability of Self-Consolidating Concrete by U-Box

1. SCOPE

This test method covers the procedure for determining the U-Box Passing ability of self-**c**onsolidating concrete.

2. REFERENCED DOCUMENTS

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Japan Society of Civil Engineers' Standard Specification for Design and Construction of Concrete Structures.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

a. U-box, made to the dimensions (tolerance ± 1 mm) in Figure 1, fitted with a quick release. The U-box shall be made from metal; the surfaces shall be smooth, and not be readily attacked by cement paste or be liable to rusting.

b. Suitable container for filling the funnel having a volume larger than its volume.

c. Strike-off bar – *Optional* The strike-off bar shall be a flat straight bar at least of 0.125 in. x 0.75 in. x 12 in. (3 mm x 20 mm x 300 mm).

d. Measuring tape - The measuring tape shall have a minimum gradation of 0.5 inch (10 mm).

4. MATERIALS

The sample of SCC from which the specimens are made shall be obtained according to Section I of Nevada Test SCC-1.

5. PROCEDURE

The left-hand section of the U-box is filled to its upper level with concrete. Then the gate is lifted and the concrete allowed to flow upwards into the right-hand section.

The heights H_1 and H_2 of the concrete in both compartments were measured to the nearest 0.2 inch (5 mm), and their difference H_1-H_2, referred as U-box filling height, was used to evaluate the passing ability and filling ability of the SCC. To perform this test, the following steps shall be taken:

a. Clean the funnel and dampen all the inside surfaces including the gate.

b. Close the gate and pour the sample of concrete into the left hand section of the funnel, without any agitation or rodding, then strike off the top with the straight edge so that the concrete is flush with the top of the funnel.

d. Open the gate and measure the heights H_1 and H_2 in both compartments.
H_1-H_2 is the filling height of the SCC.

6. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. The U-box filling height;

e. The time between completion of mixing and performance of the tests;

f. Any deviation from the procedure in this document;

g. The temperature of the concrete at the time of test; and

i. The time of the test.

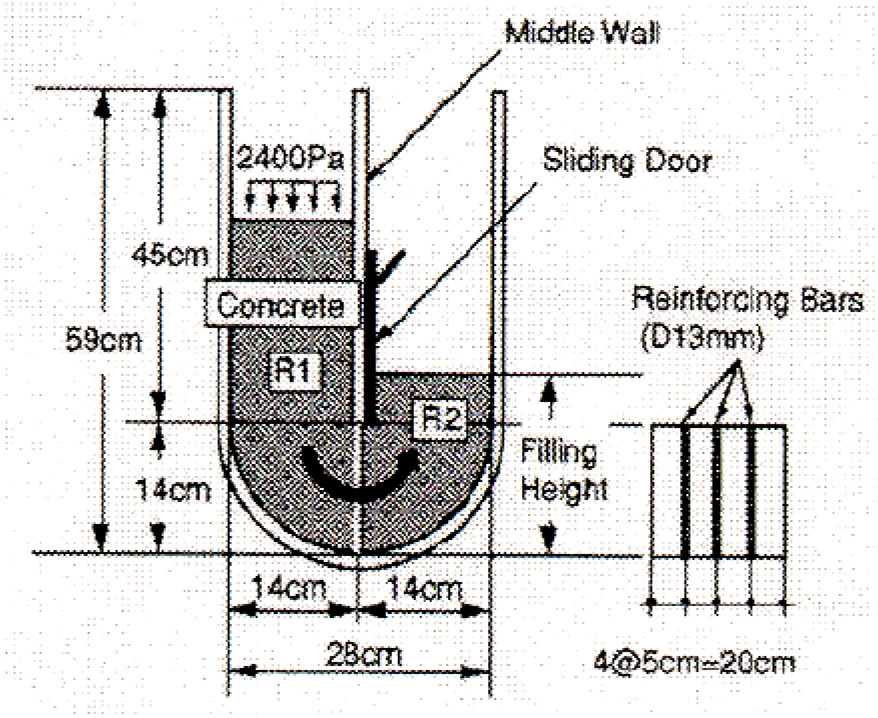

Figure 1 –U-box apparatus

Nevada Test Procedure SCC-5

Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring

1. SCOPE

This document specifies the procedure for determining the passing ability of self-consolidating concrete (SCC) using the J-Ring and slump cone. The diameter of the unobstructed slump flow versus the obstructed slump flow passing through the J-Ring is a measure of the passing ability of SCC. All rounding shall be according to ASTM E 29.

2. REFERENCED DOCUMENTS

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Testing of SCC by Florida Department of Transportation.

Illinois Test Procedure SCC-3, Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring and Slump cone.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

Nevada Test Procedure SCC-2, Standard Test Method for Slump Flow, T_{50}, and Stability of Self-Consolidating Concrete.

3. APPARATUS

a. Open steel ring, drilled vertically with holes to accept threaded sections of reinforcement bar. The section of bar can be of different diameters and spaced at different intervals. The diameter of the ring of the vertical bars is 12 inches (305 mm), and the height of 4 inches (100 mm). See Figure 1.

b. Mold and tamping rod – The mold and tamping rod shall conform to that described in AASHTO T 119.

c. Strike-off bar – *Optional* The strike-off bar shall be a flat straight bar at least of 0.125 x 0.75 x 12 inches (3 x 20 x 300 mm).

d. Base plate – The base plate shall be smooth, rigid, nonabsorbent, and be of sufficient dimensions to accommodate the maximum slump flow. The base plate as specified in Nevada Test SCC-2 is suitable.

e. Suitable container for filling inverted slump cone.

f. Measuring tape – The measuring tape shall have a minimum gradation of 0.5 in. (10 mm).

g. Stopwatch – The stopwatch shall have a minimum reading of 0.2 seconds.

4. MATERIALS

The sample of SCC from which test specimens are made shall be obtained according to Section I of Nevada Test SCC-1.

5. PROCEDURE

a. Clean and dampen the J-Ring, slump cone, and base plate.

b. Place the base plate on level, stable ground. Center the J-Ring on the base plate. The cone shall be centered within the J-Ring and upward (or inverted) with the smaller diameter opening up (or down).

c. Fill the cone without vibration, rodding, or tapping.

d. Strike off the surface of the concrete level with the top of the mold using the tamping rod or strike off bar. Remove surplus concrete from around the base of the cone and base plate surface.

e. Raise the mold vertically a distance of 9 ± 3 inches (225 ± 75 mm) in 3 ± 1 seconds without any lateral or torsional motion. Complete the test procedure from the start of filling through removal of the mold without interruption and within an elapsed time of 2.5 minutes.

f. When the concrete has stopped flowing, measure the maximum diameter of the resulting slump flow and measure the diameter perpendicular to the maximum. Each measurement shall be the nearest 0.5 inch (10 mm). If the two measurements differ by more than 2 inches (50 mm), verify base plate to be level, and test again.

g. Calculate the average of the two measured diameters. This is the J-Ring flow.

h. Calculate the difference between the J-Ring flow and the unobstructed slump flow, as tested according to Nevada Test SCC-2, of the same representative sample. This is the J-Ring value. Rate the passing ability of SCC using the criteria in Table 1.

Table 1 Passing ability rating

J-Ring value, in. (mm)	**Passing ability rating**	**Remarks**
0 – 1 (0 – 25)	0	High passing ability
> 1 – 2 (>25 – 50)	1	Moderate passing ability
> 2 (>50)	2	Low passing ability

6. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. The unobstructed slump flow (average of two measured diameters) and J-Ring flow (average of two measured diameters) to the nearest 0.5 in (10 mm);

e. J-Ring value and corresponding passing ability rating;

f. The time between completion of mixing and performance of the tests;

g. Any deviation from the procedure in this document;

h. The temperature of the concrete at the time of test; and

i. The time of the test.

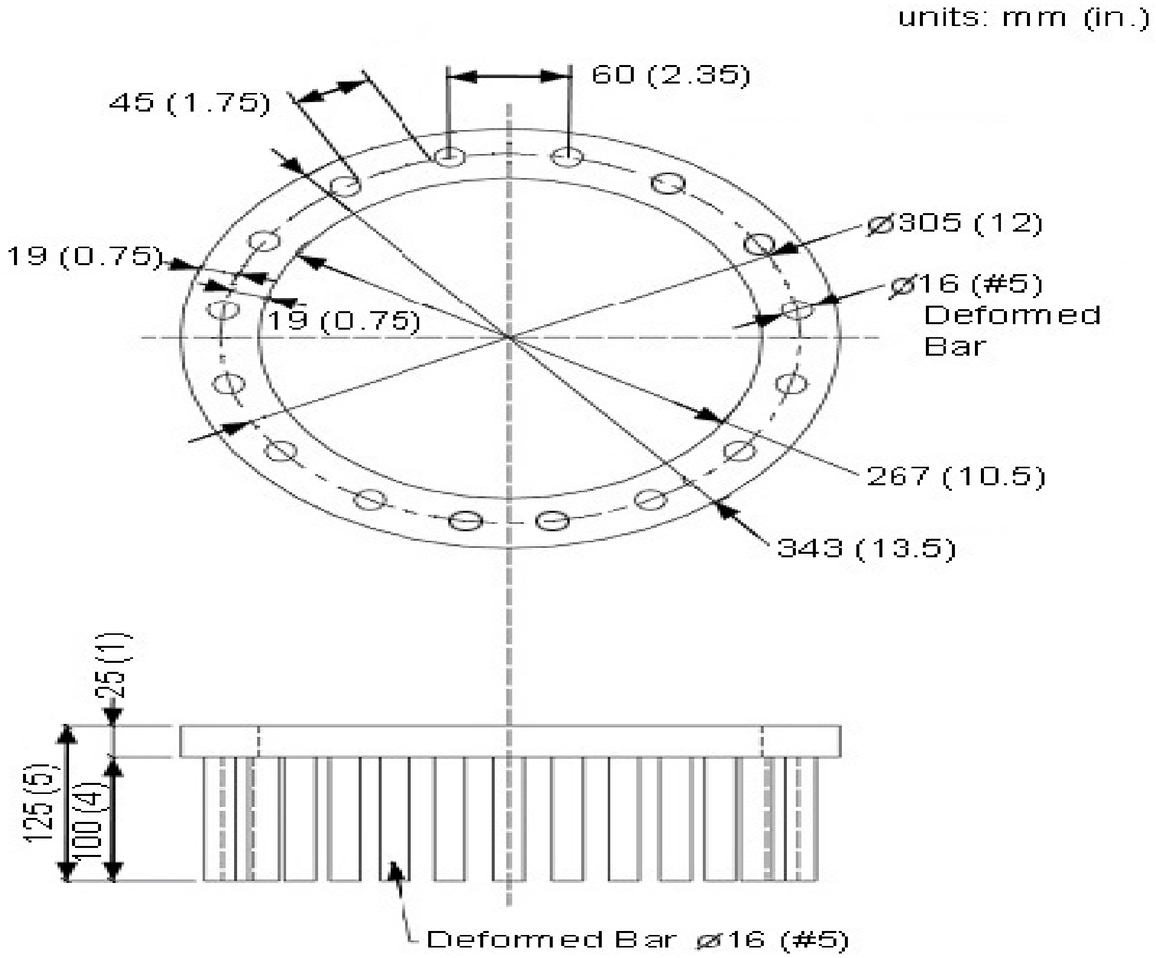

Figure 1. J-Ring apparatus

Nevada Test Procedure SCC-6

Standard Test Method for Passing Ability of Self-Consolidating Concrete by L-Box

1. SCOPE

This document specifies the procedure for determining the passing ability of self-consolidating concrete (SCC) using the L-Box test. The concrete is allowed to flow through tight openings including spaces between reinforcement bars and other obstructions without segregation or blocking. The flow heights ratio is a measure of the passing ability of SCC. The flow times (T_{20} and T_{40}) are a measure of the flow ability of SCC. All rounding shall be according to ASTM E 29.

2. REFERENCED DOCUMENTS

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

European Guidelines for Self-Consolidating Concrete.

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Illinois Test Procedure SCC-4, Standard Test Method for Passing Ability of Self-Consolidating Concrete by L-Box.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

a. L-Box, made to the dimensions (tolerance ± 1 mm) in Figure 1 and the dimensions shown in Figure 2. The L-box shall be of rigid construction with surfaces that are smooth, flat and not readily attacked by cement paste or be liable to rusting. The vertical hopper may be removable for ease of cleaning. With the gate closed, the volume of the vertical hopper shall be 0.42 cu ft. (12 liters) when filled level with the top. The assemblies holding the reinforcement bars shall have 2 smooth bars of 0.5 in. (12 mm) diameter with a gap of 2.3 in. (59 mm) for the two bar test and 3 smooth bars of 0.5 in. (12 mm) diameter with a gap of 1.6 in. (41 mm) for the three bar test. These assemblies shall be interchangeable and locate the bars in the L -box so that they are vertical and equidistant across the width of the box.

NOTE: A steel mold is preferred but 0.5 in. (10 mm) coated formwork plywood with the end grain sealed has been found to be suitable.

b. Tamping rod or strike off bar – The tamping rod shall conform to that described in AASHTO T 119. The strike-off bar shall be a flat straight bar at least of 0.125 in. x 0.75 in. x 12 in. (3 mm x 20 mm x 300 mm).

c. Suitable container for filling L-Box.

d. Measuring tape – The measuring tape shall have a minimum gradation of 0.5 inch (10 mm).

e. Stopwatch – The stopwatch shall have a minimum reading of 0.2 second.

3. MATERIALS

The sample of SCC from which test specimens are made shall be obtained according to Section I of Illinois Test SCC-1.

4. PROCEDURE

a. Clean and dampen the L-Box and place it on level, stable ground.

b. Ensure the sliding gate is shut, and pour the concrete vertically from the container into the filling hopper of the L-Box without vibration, rodding, or tapping.

c. Strike off the surface of the concrete level with the top of the L-Box using the tamping rod or strike-off bar.

d. Allow the test specimen to stand for (60 ± 10) seconds. Record any segregation.

e. Raise the sliding gate so that the concrete flows into the horizontal section of the box. Complete the test procedure from the start of filling through opening of the sliding gate without interruption and within 5 minutes.

f. *Optional.* Determine the time in seconds it takes for the concrete flow to travel 8 inches (200 mm) and 16 inches (400 mm), as measured from the time the sliding gate is lifted. These are the T_{20} and T_{40} times, respectively. Refer to Figure 2.

g. When the concrete movement has ceased, measure the heights of the resulting flow at the sliding gate, H_1, and at the end of the horizontal, H_2, to the nearest 0.25 inch (5 mm).

i. Calculate the blocking ratio as follows:

$$\textit{Blocking Ratio} = (H_2/H_1) \times 100$$

5. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. Any segregation observed while filling the L-Box;

e. Whenever two bar or three bar test;

f. The filling heights, H_1 and H_2, to the nearest 0.25 inch (5 mm);

g. The passing ratio, H_2/H_1, to the nearest 1 percent;

h. The T_{20} and T_{40} flow times to the nearest 0.2 second;

i. The time between completion of mixing and performance of the tests;

j. Any deviation from the procedure in this document;

k. The temperature of the concrete at the time of test; and

l. The time of the test.

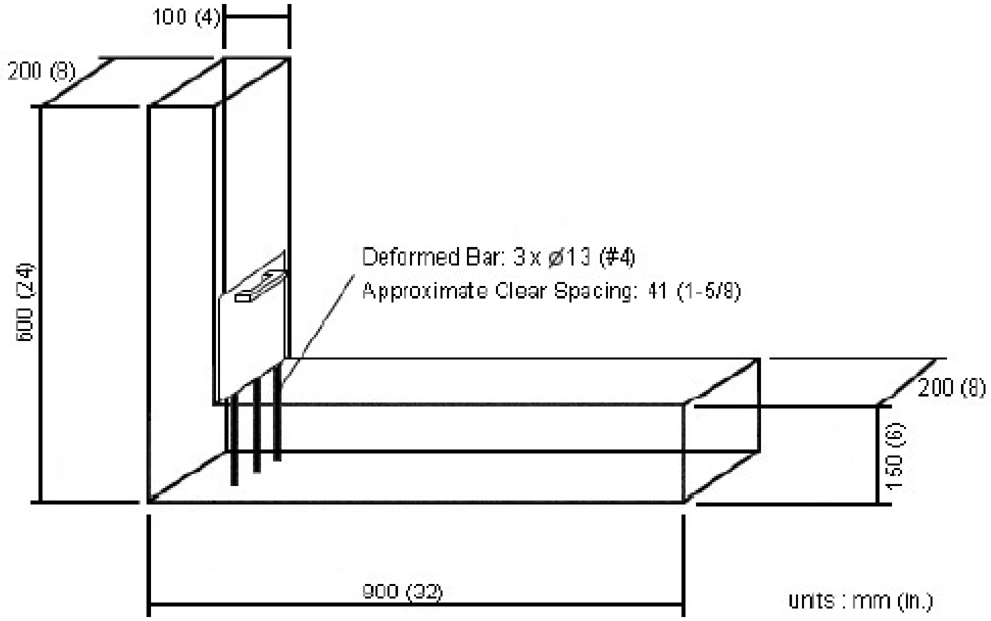

Figure 1. L-box apparatus

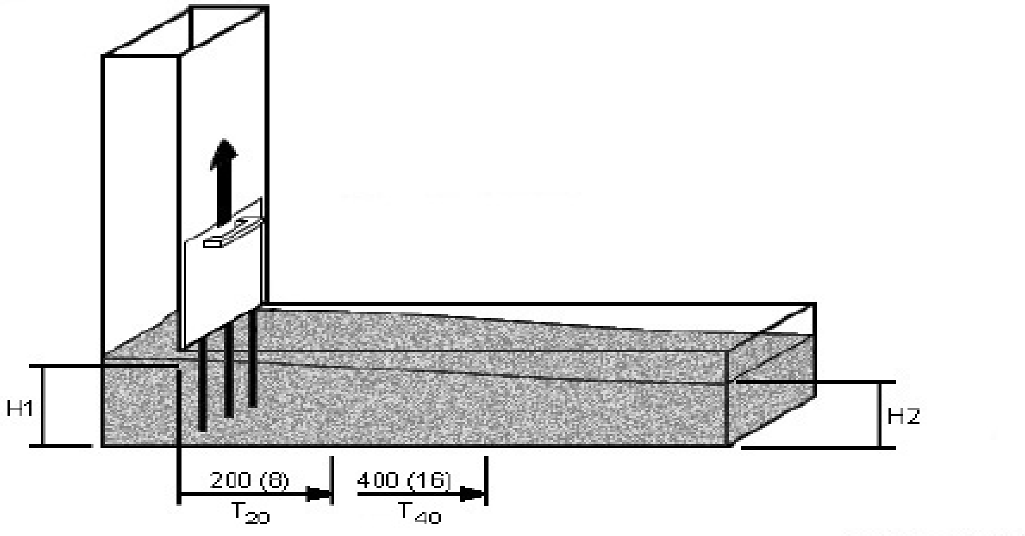

Figure 2. L-box test

Nevada Test Procedure SCC-7

Standard Test Method for Static Segregation Resistance of Self-Consolidating Concrete Using the Column Technique

1. SCOPE

This document specifies the procedure for determining the static segregation resistance (static stability) of self-consolidating concrete (SCC). The top-to-bottom retained coarse aggregate mass (weight) ratio is a measure of the static stability of SCC. All rounding shall be according to ASTM E 29.

2. REFERENCED DOCUMENTS

AASHTO M92, Standard Specification for Wire Cloth sieves for Testing Purposes.

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Illinois Test Procedure SCC-5, Standard Test Method for Static Segregation of Self-Consolidating Concrete Using the column Technique.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

a. Column Mold – The mold shall be Poly Vinyl Chloride (PVC) plastic pipe Schedule 40 meeting the requirements of D 1785. The column shall be 8 inches (200 mm) in diameter by 26 inches (660 mm) in height and separated into 3 sections. The top section shall be 6.5 inches (160 mm) in height, the middle section 13 inches (330 mm) in height, and the bottom section 6.5 inches (160 mm) in height as shown in Figure. 1. Each section shall have its ends flat and plane and be marked as “Top”, “Middle”, or “Bottom” relative to its location in the column. Couplers, brackets, clamps, or other equivalent fastening systems shall be used for securing the column sections together to form a mortar-tight joint and to secure the column to the base plate.

b. Base plate – The base plate shall be of a smooth, rigid, and nonabsorbent material, and a minimum of 12 inches (305 mm) square.

c. Collector plate – The collector plate, used to obtain concrete from the top section of the column, shall be made of any smooth, rigid, and nonabsorbent rigid material measuring at least 20 x 20 inches (510 x 510 mm) square. See Figure 2.

d. Sieve No. 4 (4.75 mm) rectangular sieve of minimum dimensions 13 x 25 inches (330 x 635 mm) manufactured according to AASHTO M 92.

e. Tamping Rod or Strike off Bar – The tamping rod shall conform to that described in AASHTO T 119. The strike-off bar shall be a flat straight bar at least of 0.125 x 0.75 x 12 inches (3 x 20 x 300 mm).

f. Suitable container for filling column mold.

g. Balance according to Nevada Specification for Portland cement concrete unit weight measurements.

4. MATERIALS

The sample of SCC from which test specimens are made shall be obtained according to Section I of Nevada Test SCC-1.

5. PROCEDURE

a. Clean and dampen the column mold and base plate.

b. Place the base plate on level, stable ground. Center and attach the mold on the base plate.

c. Remix the sample obtained in accordance with to Section I of Nevada Test SCC-1 in the sample receptacle using a shovel or scoop so that the concrete is representative of the mixture proportions and homogeneous.

d. Using a shovel, scoop, or plastic pail, immediately fill the column mold with concrete completely and above the rim, within 2 minutes.

e. After filling the mold, strike off the top surface by sliding the strike-off bar across the top rim of the mold with a sawing motion until the concrete surface is level with the top of the mold.

f. Allow the concrete to stand in the column mold undisturbed for 15 minutes.

g. Immediately following the standing period, securely hold the top section of the mold and remove the fastening system. Complete steps h – o within 20 minutes.

h. Place the cut out section of the collector plate around the column just below the joint between the "Top" and "Middle" sections to catch and collect concrete.

i. Grasp the upper section of the column mold and using a horizontal rotating motion, screed the concrete from the top section of the column on to the collector plate and then deposit it into a plastic pail.

j. Repeat steps g. – i to remove the concrete from the middle section of the column mold and discard.

k. Place the concrete sample collected from the upper section onto the No. 4 (4.75 mm sieve).

l. Wash the concrete on the No. 4 (4.75 mm) sieve so that only the coarse aggregate remains on the sieve and then deposit the coarse aggregate into a plastic pail.

m. Repeat Steps k – l for the concrete retained in the bottom section of the mold.

n. Bring the coarse aggregate obtained from both the top and bottom sections to the saturated-surface-dry (SSD) condition.

o. Determine the mass of the coarse aggregate from each of the top and bottom sections of the column mold separately to the nearest 0.1 lb (45 g).

p. Calculate the segregation index, SI, as follows:

$$SI\ \% = [(CA_B - CA_T) / ((CA_B + CA_T)/2)] \times 100, \qquad \text{if } CA_B > CA_T$$
$$SI\ \% = 0 \qquad \text{if } CA_B \leq CA_T$$

Where: CA_T = mass (weight) of coarse aggregate in the top section
CA_B = mass (weight) of coarse aggregate in the bottom section

5. REPORT

Report the following information:

a. The identification of the test sample;

b. The location where the test was performed;

c. The date when the test was performed;

d. The SSD mass (weight) of coarse aggregate obtained from the top and bottom sections of the column, CA_T and CA_B, respectively, to the nearest 0.1 lb. (45 g);

e. The Segregation Index, SI, to the nearest 1 percent;

f. The time between completion of mixing and performance of the tests;

g. Any deviation from the procedure in this document;

h. The temperature of the concrete at the time of test; and

i. The time of the test.

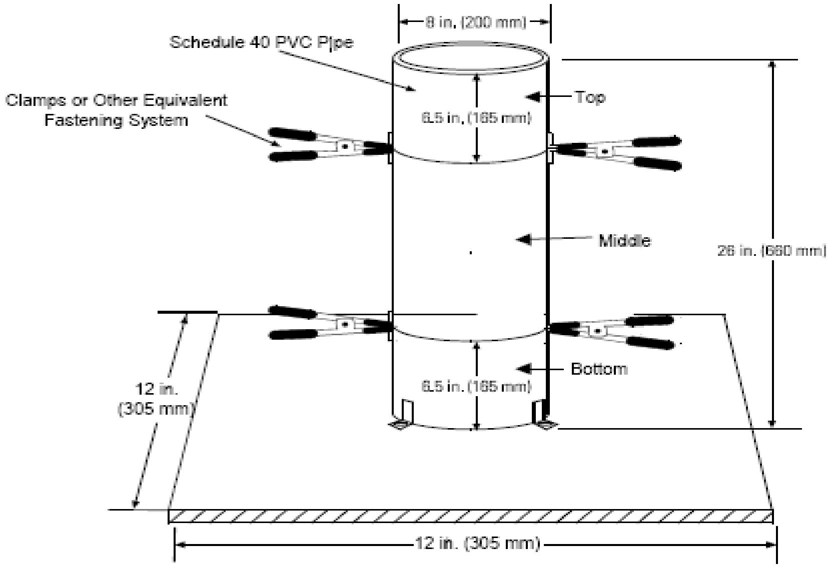

Figure 1. Column Mold

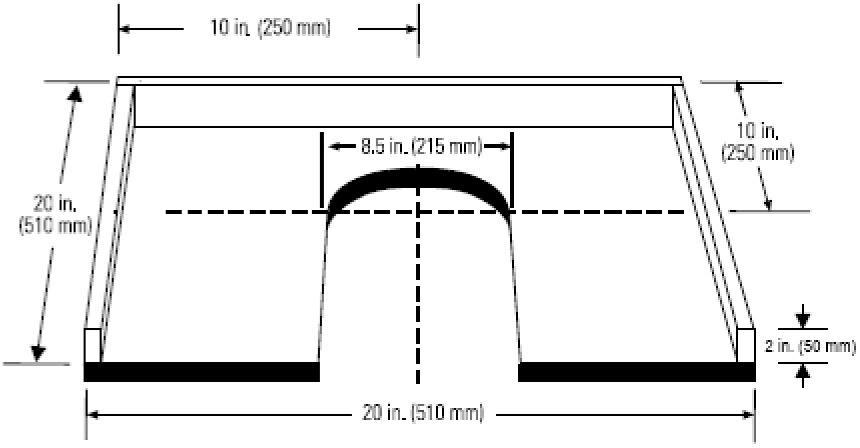

Figure 2. Example Collector Plate

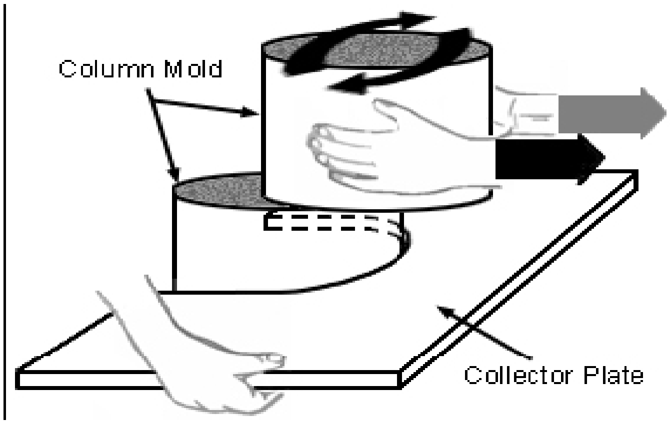

Figure 3. Horizontal rotating and twisting action

Nevada Test Procedure SCC-8

Standard Test Method for Static Segregation Resistance of Hardened Self-Consolidating Concrete Cylinders

1. SCOPE

This document specifies the procedure for determining the static segregation resistance (static stability) of hardened self-consolidating concrete (SCC). The visual assessment, using a hardened visual stability index (HVSI), of cast or cored hardened cylinders cut lengthwise in two is a measure of the stability of SCC. All rounding shall be according to ASTM E 29.

2. REFERENCED DOCUMENTS

AASHTO T 23, Making and Curing Concrete Test Specimens in the Field.

AASHTO T 26, Making and Curing Concrete Test Specimens in the Laboratory.

AASHTO T 119, Slump of Hydraulic-Cement Concrete.

ASTM E 29, Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications.

Illinois Test Procedure SCC-6, Standard Test Method for Static Segregation of Hardened Self-Consolidating Concrete Cylinders.

Nevada Test Procedure SCC-1, Sampling, Determining Yield and Air Content, and Making and Curing Strength Test Specimens of Self-Consolidating Concrete.

3. APPARATUS

The apparatus consists of:

a. Mold – The mold shall be a 6 in. x 12 in. (150 mm x 300 mm) cylinder mold and conform to AASHTO T 23 or AASHTO T 126.

b. Tamping rod or strike-off Bar – The tamping rod shall conform to that described in AASHTO T 119. The strike-off bar shall a flat straight bar at least of 0.125 in. x 0.75 in. x 12 in. (3 mm x 20 mm x 300 mm).

c. Suitable container for filling specimen molds.

d. Saw – The saw shall have a diamond or silicon-carbide cutting edge and shall be capable of cutting specimens without excessive heating or shock.

e. Core drill – The core drill shall have diamond impregnated bits attached to a core barrel.

3. MATERIALS

The sample of SCC from which fresh test specimens are made shall be obtained according to Section I of Nevada Test SCC-1. Cored specimens from hardened concrete shall be obtained according to AASHTO T 24 except that cored specimens shall be taken so that its axis is perpendicular to the concrete as it was originally placed, and have a minimum diameter of 2 in. (50 mm) and sufficient length to assess extent of static segregation resistance.

4. PROCEDURE

a. A minimum of two fresh test specimens shall be made according to AASHTO T 23 or T 126, except for the followings:

   i. The specimen mold shall be filled in one lift using a suitable container without vibration, rodding, or tapping.

   ii. Strike off the surface of the concrete level with the top of the mold using the strike-off bar or tamping rod.

   iii. The slump flow, VSI, air content, and temperature of each batch of concrete, from which specimens are made, shall be measured immediately after remixing.

b. Immediately after being struck off, the specimens shall be capped with a plastic cylinder lid and moved to the storage place where they will remain undisturbed for a minimum curing period of 24 ± 0.5 hours. The specimens shall be assigned an identification number and the date of molding, location of concrete, and mix design number shall be recorded.

c. After curing, a specimen shall be removed from its mold, and saw cut lengthwise down the center through its diameter. If the cylinder cannot be satisfactorily sawed smooth from lack of curing, then the remaining specimen(s) shall remain undisturbed for an additional minimum curing period of 24 ± 0.5 hours before being subjected to sawing.

d. Make a visual assessment of the cut plane of the hardened concrete cylinder(s) using the criteria in Table 1 and illustrated in Figures 1 – 8. The cut plane shall be wetted to facilitate visual inspection.

Table 1: Visual Stability Index of Hardened Specimens (HVSI) Rating Criteria

Rating	Criteria
0 Highly stable	No mortar layer at the top of the cut plane and no variance in size and percent area of coarse aggregate distribution from top to bottom.
1 Stable	No mortar layer at the top of the cut plane but slight variance in size and percent area of coarse aggregate distribution from top to bottom.
2 Unstable	Slight mortar layer, less than 25 mm (1 in.) tall, at the top of the cut plane and distinct variance in size and percent area of coarse aggregate distribution from top to bottom.
3 Unstable	Clearly segregated as evidenced by a mortar layer greater than 25 mm (1 in.) tall and/or considerable variance in size and percent area of coarse aggregate distribution from top to bottom.

5. REPORT

Report the following information:

a. Report the identification number and required information for each hardened specimen.

b. The location where the test was performed;

c. The date when the test was performed;

d. The HVSI rating for each hardened specimen;

e. The time between completion of mixing and performance of the tests;

f. Any deviation from the procedure in this document;

g. The temperature of the concrete at the time of test; and

h. The time of the test.

Figure 1. HVSI = 0, highly stable

Figure 2. HVSI = 0, highly stable

Figure 3. HVSI = 1, stable

Figure 4. HVSI = 1, stable

Figure 5. HVSI = 2, unstable

Figure 6. HVSI = 2, unstable

Figure 7. HVSI = 3, unstable

Figure 8. HVSI = 3, unstable

PRESCRIPTIVE MIXTURE DESIGN OF SELF-CONSOLIDATING CONCRETE

NDOT RESEARCH
Agreement No: P077-06-803

CONCLUSIONS AND RECOMMENDATIONS

Report Submitted to
Nevada Department of Transportation
Research Division
ATTN: Dr. Tie He
1263 S. Stewart Street
Carson City, NV 89712

By
Nader Ghafoori, Ph.D., P.E., Professor and Chairman

and

Hamidou Diawara, MSc, Doctorate student and Research assistant

University of Nevada, Las Vegas

Civil and Environmental Engineering Department

4505 Maryland Parkway

Box 454015

Las Vegas, Nevada 89154-4015

Phone: (702)895-3701

Fax: (702)895-3936

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CONCLUSIONS AND RECOMMENDATIONS

1.1 CONCLUSIONS

This investigation was intended to evaluate the influence of selected construction related variables, namely: admixture sources, hauling time, temperature, and pumping on the fresh characteristics of self-consolidating concrete (SCC). The admixture sources were ranked based on the optimum dosage required to attain uniform workability (i.e., the flow ability in an unconfined area, the flow rate or plastic viscosity per inference, the dynamic stability, and the passing ability in congested reinforcement areas). The effectiveness of remediation techniques to mitigate the adverse effects of the above-mentioned construction-related variables on the freshly-mixed self-consolidating concretes was also studied. Finally, statistical equations to correlate dependent variables (i.e., HRWRA and VMA dosages, compressive strength, slump flow losses or gains) with independent variables (i.e., concrete paste content, aggregate sizes, hauling time, and hot and cold temperatures) were determined. The main results and conclusions of the study are described below.

1.1.1 Influence of admixture source and slump flow on fresh performance of self-consolidating concrete

Liquid polycarboxylate-based high range water-reducing admixtures (HRWRA) and corresponding viscosity modifying admixtures (VMA), obtained from four different manufacturers, herein designated as A, B, C, and D, were investigated to find their influence on the optimum dosage and slump flow of self-consolidating concretes. The test results indicated the followings findings:

1.1.1.1 Influence of admixture source on optimum dosage

The optimum dosages requirement of admixtures in obtaining uniform unconfined workability (measured by the slump flow) and dynamic stability (evaluated by the visual stability index (VSI)) varied among the four selected admixture sources. The required optimum dosage of HRWRA was highest for the source A, followed by the sources C, B, and D in descending order. The required optimum amount of VMA was also highest for the source A, but remained uniform for the sources B, C, and D. The self-consolidating concretes prepared with a slump flow of 20 ± 1 inches (508 ± 25 mm) did not require

VMA to yield satisfactory unconfined workability and dynamic stability for all selected admixture sources.

The fundamental mechanism of action of a superplasticizer involves adsorption and electrostatic repulsion and steric hindrance forces. As such, the superplasticizer has to be first adsorbed on cement particles before being able to play a dispersing role. Based on this concept, the ultraviolet-visible (UV/Vis) spectroscopy test was used to explain the differences in admixture dosage requirements exhibited by the four admixture manufacturers. Additionally, the chemical type of the admixtures and the calculated VMA-to-HRWRA ratios were also used to explain the variation in the admixtures optimum dosage requirements.

The UV/Vis spectroscopy absorption is not a specific test to quantify or measure the actual amount of adsorption of a polymer. However, it is used to determine the actual concentration of free admixture in a cement-water-superplasticizer solution. The test results indicated that the increase in admixture concentration led to an increase in adsorption of the carboxylic group (COO^-) on cement calcium ions (Ca^{2+}) resulting in additional repulsion and dispersion between neighboring cement particles. Additionally, the UV/Vis test results revealed that the concentration of the PC-HRWRA was highest for the source D, followed by the sources B, C, and A in descending order.

The chemical type of the superplasticizers also influenced the dosage requirement in attaining uniform fresh properties. All four superplasticizers were acrylic polymers-based. The behavior of the sources B, C, and D superplasticizers was similar to that of a polycarboxylate-acid type (PCA), while the performance of the source A was comparable to that of polycarboxylate-ester type (PCE). In PCA, the acid portion is predominant when compared to the ester type. The higher acid ratio enhanced the adsorption of PCA polymers on cement grains leading to a higher dispersibility of particles. In the case of polycarboxylate-ester type (PCE), the matrix dispersibility decreased for the similar dosage to that of polycarboxylate-acid. However, the gradual dispersion of ester type admixture increased the slump flow retention of fresh self-consolidating concretes.

The calculated optimum dosages VMA-to-HRWRA ratios also revealed a trend for the four selected admixtures types. The similarity of the VMA-to-HRWRA ratios for the admixture sources B, C, and D is supportive of the hypothesis that these sources have a similar chemical composition. The VMA-to-HRWRA ratio of the source A admixture was higher than the other three admixture manufacturers, mainly due to its thickening mode of functioning which led to the higher required amount of source A VMA in producing highly stable or stable matrices.

1.1.1.2 Influence of slump flow on optimum admixture dosage

Regardless of the admixture sources and the selected self-consolidating concrete groups, the optimum dosages of HRWRA and VMA increased with an increase in slump flow. In the presence of a higher amount of HRWRA, the yield stress of the fresh matrix, i.e., the force needed to disperse its ingredients, gradually reduced as the fresh concrete was allowed to spread further. The increase in HRWRA dosage was usually accompanied by a decrease in plastic viscosity and a viscosity modifying admixture was needed to bring the plastic viscosity of the fresh matrix back to its target level.

1.1.1.3 Influence of admixture source and slump flow on fresh and hardened properties of SCC

The four selected admixture sources were able to produce self-consolidating concretes with suitable flow ability, flow rate/plastic viscosity, dynamic and static stabilities, passing ability, and filling ability. However, the performance of the selected admixtures in attaining a required fresh property varied among the admixture sources. The pair admixture sources A and D displayed higher flow ability or lower plastic viscosity than the sources B and C. The dynamic stability, passing ability, and filling ability of the matrices were similar for all four admixture sources. The admixture sources B and C exhibited better static stability than the sources A and D.

The self-consolidating concrete prepared for 20 ± 1 inches (508 ± 25 mm) slump flow displayed very low plastic viscosity, very high dynamic stability, moderate filling ability, low passing ability, and high static stability. Consequently, it is found unsuitable for congested reinforced structures. All 25 inches (635 mm) and 28 inches (711 mm) slump flow self-consolidating concretes displayed high flow ability, low plastic viscosity (by inference), high dynamic stability, moderate static stability, moderate passing ability, and moderate to high filling ability, indicating their suitability for most civil engineering applications. The low flow ability (within the acceptable limit) of the 28 ± 1 inches (711 ± 25 mm) slump flow matrix may cause a higher than normal pressure on formwork.

The selected self-consolidating concretes made with different sources of admixtures and various slump flows exhibited insignificant differences in the test results related to the air content, bleeding, time of setting, adiabatic temperature, demolded unit weight, compressive strength, and modulus of elasticity.

1.1.1.4 Statistical analysis

The relationship between the required optimum dosages of HRWRA VMA as dependent variables, and the concrete paste content, aggregate sizes and target slump flow as independent variables was found to be significant. Strong statistical relationships also existed between the compressive strength, target slump flow, and curing age.

1.1.2 Influence of hauling time on fresh performance of self-consolidating concrete

1.1.2.1 Influence of hauling time on freshly-mixed SCC

The selected hauling times affected the freshly-mixed self-consolidating concrete in the form of loss in flow ability (measured by the slump flow), decrease in plastic viscosity (evaluated by the T_{50} time), and gain in dynamic stability (determined through the VSI rating). The loss in flow ability was observed as early as 20 minutes and increased with increasing hauling time. The flow rate also increased with increasing hauling time. However, the T_{50} time of the self-consolidating concretes made with slump flow of 20, 25, and 28 inches (508, 635, and 711 mm) could not be measured after 20, 40, and 60 minutes of hauling time, respectively, due to the severe loss in slump flow.

The change in fresh properties can be characterized by the adsorption amount of admixture per specific surface area of concrete mortar Ads/SSAm. The SSAm of the matrix increased with the increase in hauling time due to the grinding of aggregate and cement particles, and the growth of the cement hydrated products. Since an actual measurement of adsorption was beyond the scope of this investigation, the Ultraviolet Visible (UV/Vis) spectroscopy test result of a companion investigation[82] was used to explain the Ads trend as affected by the hauling time. The result of the UV/Vis spectroscopy test indicated that the solution concentration of free admixture increased up to 80 minutes of hauling time. Past 80 minutes of hauling time, the solution concentration of free admixture decreased, and simultaneously the sulfate ion (SO_4^{2-}) concentration increased with elapsed time, as was the case during the induction period of cement hydration. The adsorption of PC-HRWRA on cement may have been prevented by the competitive adsorption between the sulfate ions and the dissociated carboxylic group on cement particles.

In summary, it was seen that both Ads and SSAm increased with increases in hauling time. However, the contribution of SSAm on the alteration of the workability of the freshly-mixed self-consolidating concrete was greater than that of Ads.

1.1.2.2 Remediation of the adverse influence of hauling time on freshly-mixed SCC

The overdosing method was used to remediate the adverse effects of hauling time on the fresh properties of self-consolidating concretes. The adopted remediation technique was able to produce self-consolidating concretes with a similar flow ability, plastic viscosity, dynamic stability, and passing ability to those obtained at the control hauling time. The admixture dosages increased as the hauling time increased. The rate of HRWRA dosage increment was higher at 20 minutes hauling time (0.3, 0.5, and 0.3 oz/cwt (20, 33, and 20 ml/100 kg) for 20, 25, and 28 inches (508, 635, and 711 mm) slump flows, respectively) and became constant thereafter at about 0.2 oz/cwt (13 ml/100 kg) per 10 minutes hauling time increment, independently of the slump flow. The additional amount of admixture increased its adsorption and generated supplementary repulsive electrostatic and steric hindrance forces between cement particles. These forces further dispersed cement agglomerations provoked by the grinding and hydration of the cement constituents during hauling time.

1.1.2.3 Statistical analysis

The predictive equations to correlate: (1) the actual slump flow loss with the initial slump flow value and hauling time, and (2) the required amount of overdosed admixtures (HRWRA and VMA) with the target slump flow and hauling time showed significant statistical relationships between the dependent and independent variables.

1.1.3 Influence of extreme temperatures on fresh performance of self-consolidating concrete

1.1.3.1 Influence of temperature on freshly-mixed SCC

Both the hot and cold temperatures affected the fresh properties of the selected self-consolidating concrete.

The hot temperatures affected the trial matrices by significantly decreasing their unconfined workability, substantially increasing their flow rate (or decreasing the plastic viscosity per inference), and improving their dynamic stability. The slump flow losses induced by the elevated temperatures were only 5% at 83 ^{o}F (28 ^{o}C), but increased to about 12 and 25% at 96 and 109 ^{o}F (36 and 43 ^{o}C), respectively, when compared to that obtained at the control temperature of 70 ^{o}F (21 ^{o}C).

The flow rate of the selected self-consolidating concretes increased as the temperature increased. The T_{50} time of the mixture made for 20 inches (508 mm) slump flow could not be measured in any of the selected hot temperatures since its flow spread was below the established limit of 20 inches (508 mm). At the temperatures of 96 and 83 ^{o}F (36 and 28 ^{o}C), the mixtures made for 25 and 28 inches (635 and 711 mm) slump flow displayed increases in T_{50} time of about 9 and 5%, and 54 and 40%, respectively, when compared to that of the control temperature. The 25-inches (635-mm) slump flow concrete ceased to be self-consolidating at 109 ^{o}F (43 ^{o}C) and its T_{50} could not be measured. However, the 28-inches (711-mm) matrix displayed 68% increases in flow rate at 109 ^{o}F (43 ^{o}C). In hot temperatures, the visual stability index (VSI) of the mixtures made with 28 inches (711 mm) slump flow improved from 1 (stable matrix) to 0 (highly stable matrix). The others two SCC types (slump flows of 20 and 25 inches (508 and 635 mm)) remained highly stable at the selected elevated temperatures.

The effect of cold temperature on the fresh performance of the selected self-consolidating concretes was manifested in the form of a marginal gain in flow ability (averaging 3%) and small variations in flow rate (averaging 6%) when compared to those obtained under the control temperature. In cold temperatures, the matrice made with slump flow of 28 inches (711 mm) exhibited an increase in resistance to segregation from VSI of 1 (stable) to VSI of 0 (highly stable). On the other hand, the VSI of the trial SCCs prepared with slump flows of 20 and 25 inches (508 and 635 mm) were unaffected by the selected cold temperatures.

The alteration of the fresh properties induced by the selected hot and cold temperatures were explained through the adsorption amount of admixture per specific surface area of concrete paste (Ads/SSAp), the change in the aggregate's moisture content, and the partial evaporation of mixing water in the case of elevated temperatures. A summarized explanation of the test results is given below.

- The ultraviolet-visible spectroscopy test conducted in a companion study[82] indicated that the free concentration of HRWRA-cement-water solution changed with material temperatures. The free admixture concentration remained uniform at temperatures ranging from 57 to 96 ^{o}F (14 to 36 ^{o}C) and decreased gradually as the temperatures was elevated to 109 ^{o}F (43 ^{o}C) or decrease towards the water freezing point. While the calculated concentrations do not represent the actual amounts of adsorbed HRWRA on cement particles, their increases in the solution lead to an augmentation of the adsorbed amount of the PC-HRWRA carboxylic group (COO^{-}) on cement grains, favoring further increase or decrease in electrostatic repulsion and steric hindrance forces.

- In general, the relative humidity around the raw material was increased in cold temperatures, leading to an increase in the moisture content of the aggregates. The same aggregates experienced the opposite phenomenon in hot temperatures. An increase in aggregate’s temperature from 31 to 109 ^{o}F (-0.5 to 43 ^{o}C) required about 8 lb/yd^{3} (5 kg/m^{3}) of additional mixing water to maintain the same slump flow[82]. Additionally, the mixing water was partially evaporated and/or absorbed by the elevated temperatures and low relative humidity, causing further decline in the slump flow of freshly-mixed concrete.
- The hot temperatures affected self-consolidating concrete by increasing the specific surface area of concrete paste, SSAp, through the increase rate of hydration. Despite the augmentation in adsorption as discussed above, the increase in SSAp was able to reduce the overall workability of the fresh concrete. On the other hand, the selected cold temperatures did not significantly impact the specific surface area of the cement hydrated products since continued hydration in cold temperature was at a lower rate. In this case, Ads nearly gained on SSAp, as little to no change in the workability of the fresh matrix was observed.

1.1.3.2 Remediation of the adverse effect of extreme temperature on freshly-mixed SCC

The increase in slump flow of the trial matrices in cold temperatures were less than 1.0 inch (25 mm), and both the flow rate and dynamic segregation resistance were unaffected by the selected cold temperatures. As a result, the selected self-consolidating concretes did not require any remediation in cold temperatures of 57, 44, and 31 ^{o}F (14, 7, and -0.5 ^{o}C).

A remediation method by way of admixture overdosing was successful to reverse the change in fresh properties of the selected self-consolidating concretes in elevated temperatures. The additional amount of admixtures increased workability (up to 96 ^{o}F (36 ^{o}C)) through generation of supplementary repulsive electrostatic and steric hindrance forces between cement particles and was able to offset the loss of workability caused by the growth of the cement hydrated products engendered during hot temperatures. The selected remediation method was able to produce SCCs with a similar unconfined workability, flow rate or plastic viscosity per inference, dynamic stability, and passing ability to those obtained for the equivalent matrices at the control temperature.

1.1.3.3 Statistical analysis

Predictive equations to correlate slump flow loss or gain with the target temperature and slump flow revealed a significant statistical relationship between the dependant and independent variables. For the remediation purpose in hot temperature, the required optimum admixture dosages (HRWRA and VMA) were also predicted for the selected target slump flows and elevated temperatures. A strong statistical relationship between the dependent and independent variables of the remediated concrete was also obtained.

1.1.4 Influence of pumping on fresh performance of self-consolidating concrete

The pumping adversely affected the fresh performance of the self-consolidating concrete by decreasing the unconfined workability, flow rate, and passing ability; and by increasing the dynamic segregation resistance. The impact of pumping on the rheological properties of self-consolidating concrete was manifested by a moderate increase in relative yield stress and a significant decrease in relative plastic viscosity. In general, irrespective of the slump flow and pumping distance, the air content remained unaffected by the pumping action. However, the air voids characteristics were affected by the pumping without exceeding the recommend limits. The pumping generated larger sizes of the air bubbles (or lower specific area) accompanied with increases in the spacing factors.

1.2 RECOMMENDATIONS

Future studies on the fresh performance of self-consolidating may include:

(1) Rheological study of self-consolidating concrete

The rheological properties of concrete, i.e., yield stress and plastic viscosity are of great importance. Self-consolidating concrete is considered high performance in fresh state. As such, the evaluation by mean of a standard rheometer, rather than using T_{50} time, may be helpful in understanding and controlling the fresh behavior of self-consolidating concrete.

(2) Laboratory study of self-consolidating concrete to simulate field pumping

The test results indicated that pumping adversely affected the fresh performance of the self-consolidating concrete by decreasing the unconfined workability, flow rate, and passing ability; and by increasing the dynamic segregation resistance. Pumping also impacted the rheological properties of self-consolidating concrete by a moderate increase in relative yield stress and a significant decrease in relative plastic viscosity. The air void characteristics were affected by the pumping, but did not exceed the recommend limits. The pumping generated larger sizes of air bubbles (or lower specific area) and increased voids spacing factors.

To further support and explain these findings, a laboratory study may be used by subjecting fresh matrices to shear actions in simulating the field pumping. The shear action can be created by mixing action and energy.

(3) Influence of cement type on hauled self-consolidating concrete under extreme hot temperatures

The slump flow losses observed during the present study was partly due to the rapid growth of the cement hydrated products caused by the high amount of tricalcium aluminate (C_3A) of Type V Portland cement. The use of Portland cement Types I and III, which contain a lower amount of C_3A than Type V, may produce lower slump flow losses, thus requiring a smaller amount of admixture in producing the same slump flow.

(4) The influence of supplementary cementitious material type and content on self-consolidating concrete

Since strength and durability are not of great concern due to the high cementitious materials content used in self-consolidating concrete, replacing a portion of Portland cement by fly ash can be considered. The study on the content and type of fly ash, particularly large volume fly ash, on the fresh properties of self-consolidating concrete can make a significant contribution to the state of the knowledge on this subject.

(5) Drying shrinkage and creep of self-consolidating concrete

The increase use of self-consolidating concrete in prestressed concrete applications requires mixture design and proportioning suitable for permissible drying shrinkage and creep. The high fluidity of fresh self-consolidating concrete necessitates a control of its hardened deformations.

Nevada Department of Transportation
Rudy Malfabon, P.E. Director
Ken Chambers, Research Division Chief
(775) 888-7220
kchambers@dot.nv.gov
1263 South Stewart Street
Carson City, Nevada 89712