IDEA

Innovations Deserving Exploratory Analysis Programs

Highway IDEA Program

US Specific Self Compacting Concrete for Bridges

Final Report for Highway IDEA Project 89

Prepared by:
Andrzej S. Nowak, Pascal Laumet, Artur A. Czarnecki
Maria Kaszynska, Maria M. Szerszen and Piotr J. Podhoreck
University of Michigan, Ann Arbor, MI

August 2005

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.

For information on the IDEA Program contact IDEA Program, Transportation Research Board, 500 5th Street, N.W., Washington, D.C. 20001 (phone: 202/334-1461, fax: 202/334-3471, http://www.nationalacademies.org/trb/idea)

EXECUTIVE SUMMARY

The objective of this research is to develop a US/Midwest specific guide for design and use of. self-consolidating concrete for bridges. The procedures are based on the technology currently used in Europe (the Netherlands) and Japan. The research work involves the development of mixing requirements and specification of the components. The properties of the mix and hardened concrete were tested at the University of Michigan laboratories. The SCC mix was developed using US/Midwest ingredients (cement, aggregates, water) and specific admixtures and plasticizers available on the US market. The fresh concrete mix was tested to establish required deformability, flowability and segregation resistance properties. The hardened concrete was tested to find all mechanical properties required by the American standards in general, and in particular those specific for bridge construction.

The research program involved the review of the available documentation and experience gained by the European and Japanese researchers and construction companies. The work was done in cooperation with the American concrete supply company, Premarc, Grand River Infrastructure, Inc. located in Grand Rapids, Michigan, which provided the ingredients for mixing samples and shared their expertise. In addition, materials were obtained from Master Builders, Axim and Sika.

The lab tests performed on fresh concrete include slump-flow test, V-funnel test and L-box test. The measurements were performed to determine the air content and unit weight. For hardened concrete, the test included compressive strength test, freeze-and-thaw test, splitting tensile test, flexural test and test to determine the modulus of elasticity.

In the result, the recipe for the self-consolidating concrete was developed and the required steps were described. For comparison, the lab tests were also performed on ordinary concrete. The study showed that self-consolidating concrete offers considerable advantages in comparison to the designed and tested ordinary concrete. The additional cost of ingredients (mostly superplasticizers) and more strict mixing tolerances is compensated by the superior performance and no need for use of vibrators.

The self-consolidating concrete is directly applicable in bridge engineering practice. The developed step-by-step description covers preparation of the SCC using local materials such as cement powder, aggregate, water, and special admixtures that are available in USA. The usage of SCC will shorten the construction time, it will simplify the construction procedures (self-consolidating concrete does not require any vibration), and it will provide a better quality material for bridges. The final product, SCC, is dense, durable, better compacted compared with ordinary concrete, with a smaller amount of air voids and imperfections, a smooth and finished surface, and what is very important, there is no problem with segregation, that can occur during vibration of a regular concrete. Therefore, SCC is a preferable material for construction of bridges. A better performance can be expected under cyclic loading, because fatigue changes in concrete start with air voids, imperfections, and micro-cracks caused by segregation and shrinkage. The ability

of SCC to perfectly fill the mold makes it especially useful for on-site repairs of concrete bridge elements.

ACKNOWLEDGEMENTS

The research team is grateful to Charles Arnold, the NCHRP-IDEA Panel member for his comments and support. A considerable help was obtained from Professor Joost Walraven (Technical University of Delft, The Netherlands), one of the European leaders in the area of self-consolidating concrete, who shared his experience with the team.

The research team would like to acknowledge the support obtained from the industry. They provided materials for the lab tests, including superplasticizers, fly ash, cement, sand and gravel. Thanks are due to Premarc Grand River Infrastructure, Inc., represented by Tom Grumbine, Master Builders, Sika and Axim.

Table of Contents

Table of Tables

Table of Figures

1. INTRODUCTION

Self-consolidating concrete (SCC) was first developed in Japan in 1988 and it has been successfully applied to many structures in the last decade. For the last several years, SCC has been also used in Europe (The Netherlands, Norway, France, Poland, Finland, and other countries). SCC combines a high flowability with a high segregation resistance, which results in the self-compactability without any consolidation work even when the reinforcement is very congested. The features of this new material allow for the durability assurance of concrete structures independently from the skill of the laborers. Furthermore, self-consolidating concrete has the possibility to reduce the construction cost, to reduce the number of actions at the site, to shorten the construction period and to improve the working conditions. SCC has self-compactability and can be placed in every corner of a formwork without having to vibrate it, which sometimes may lead to segregation. This material is recommended for use on the construction site for structural elements with high percentage of reinforcement and for retrofitting projects, especially in closed forms with narrow openings to pour concrete. Also, SCC is recommended in precast plants, where it is highly effective in reducing the noise, as it requires no vibration. Elements constructed with self- consolidating concrete have very clear, smooth surface without any bubbles, spallings and other imperfections, which also improves durability and slows down the degradation process.

The concrete mixture is self compactable if it shows special properties: a high deformability and a high segregation resistance. These properties are generally lost when concrete flowability is controlled by the amount of water. To control the deformability and flowability, which are in contradiction, the self-consolidating concrete is specially designed. The high deformability of concrete is obtained by adding a superplasticizer and limiting the aggregate volume, and the high segregation resistance is obtained by keeping the water/powder ratio low and also limiting the aggregate volume. According to concrete design methods, there are numerous solutions for realizing self-compactability of fresh concrete. In general, the target level of self-compactability is governed by the type of structure where SCC is applied, but the mix design system is also influenced by the materials used. When the SCC was invented in Japan, the adequate viscosity of the cement paste was categorized in three types: powder type, viscosity agent type and combination type. The design system for general purpose SCC aims at designing a high level self-compactability of fresh concrete and at obtaining adequate properties of hardened concrete. The mix proportion of SCC is designed in the following steps: determination of air content, coarse aggregate volume, fine aggregate volume, water to powder volume ratio and superplasticizer dosage.

Development of self-consolidating concrete is a very desirable achievement in the construction industry for overcoming problems associated with cast-in-place concrete. Self- consolidating concrete is not affected by the skill of workers, and shape and amount of reinforcing bar arrangement of a structure. Due to high-fluidity and resisting power of segregation of self- consolidating concrete, it can be pumped over longer distances.

Thus, it has many different advantages including:

- Faster construction
- Reduction in site manpower
- Better surface finishes (less time involved - improved productivity)
- Easier placing
- Improved durability
- Greater freedom in design
- Thinner concrete sections
- Reduced noise, absence of vibration
- Safer working environment

Currently, the use of self-consolidating concrete is being rapidly adopted in many countries. Use of this concrete should overcome concrete placement problems associated with the concrete construction industry. However, there is a need for conducting more research and development work for the measurement and standardization of the methods for the evaluation of the self- consolidating characteristics of SCC.

Self-consolidating concrete with its unique properties such as the high deformability and self-compactability is a very desirable material for bridge construction. It can be used for precast elements as well as to pour concrete on the site. SCC can be used for new constructions and for repairing and retrofitting existing ones. However, this material, when used for bridge construction, has to meet specific requirements such as AASHTO Specifications for materials and criteria for strength requirements according to ACI 214-77 (R 97), Recommended Practice for Evaluation of Strength Test Results of Concrete.

Design procedures and mix proportions established in Japan and Europe (Netherlands), have to be adjusted to US/Midwest ingredients (cement, aggregates, water, plasticizers and stabilizers), and design and manufacturing practice. SCC used on bridges has to fulfill some special requirements including freeze-and-thaw resistance, low shrinkage and repeated loading resistance. These properties can be controlled by an adequate value of air content, water/powder ratio and viscosity modifying admixtures. Further research is required to clarify the mechanism of self-compactability in regard to strength and durability of this concrete. There is a need for adjustment of the design system to be more suitable for the US conditions.

This report describes the research program including background analysis and lab tests carried out by the University of Michigan research team.

1.1 DEFINITIONS

For the purpose of this report, the following definitions should apply:

- **Admixture**: Material added during the mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete (e.g. superplasticisers).

- **Filling ability**: the ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight.
- **Mortar**: the fraction of the concrete comprising paste plus those aggregates less than 0.158 in. (4 mm).
- **Passing ability**: the ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.
- **Powder or fines**: Material of particle size smaller than 0.049 in (0.125 mm). It will also include this size fraction of the sand.
- **Self-Consolidating Concrete (SCC)**: Concrete that is able to flow under its own weight and completely fill the work-form, even in the presence of dense reinforcement, without the need of any vibration, whilst maintaining homogeneity.
- **Segregation resistance** (stability): the ability of SCC to remain homogenous in composition during the transport and placing.
- **Workability**: a measure of the ease by which fresh concrete can be placed and compacted: it is a complex combination of fluidity, cohesiveness, transportability and stickiness.

These brief definitions lead to the emphasis of the materials properties investigated during this research, as well as to properties of freshly mixed concrete.

2. RESEARCH OBJECTIVES

The objective of the proposed research is to develop a US/Midwest specific guide for design and use of self-consolidating concrete for bridges. The procedures are based on the technology currently used in Europe (the Netherlands) and Japan. The research work involves the development of mixing requirements and specification of the components. The properties of the mix and hardened concrete were tested at the University of Michigan laboratories. The SCC mix was developed using US/Midwest ingredients (cement, aggregates, water) and specific admixtures and plasticizers available on the US market. The fresh concrete mix was tested to establish required deformability, flowability and segregation resistance properties. The hardened concrete was tested to find all mechanical properties required by the American standards in general, and in particular those specific for bridge construction.

The research program involved the review of the available documentation and experience gained by the European and Japanese researchers and construction companies. The work was done in cooperation with the American concrete supply company, Premarc, Grand River Infrastructure, Inc. located in Grand Rapids, Michigan, which provided the ingredients for mixing samples and shared their expertise. In addition, materials were obtained from Master Builder, Axim and Sika.

3. MATERIAL PROPERTIES

In order to fully understand the behavior of a self-consolidating concrete, a thorough knowledge of the characteristics of its components is required. Since self-consolidating concrete, as a conventional concrete, is composed of a number of constituent materials, a discussion of the function of each of these components is essential before developing a new recipe. As a result, this section presents a short description of the constituent materials of concrete.

3.1 AGGREGATES

It is important to determine the mechanical and physical properties of the aggregates used in the development of the self-consolidating concrete. Indeed, aggregates occupy 70-80% of the volume of conventional concrete and therefore have an important influence on the final concrete properties. For self-consolidating concrete, this proportion falls between 55% and 65% but aggregates still influence largely the fresh and hardened concrete properties. Aggregates are classified in two main categories such as fine aggregates and coarse aggregates. While coarse aggregates are retained on the No. 4 sieve (4.75 mm), fine aggregates pass the sieve.

Aggregates influence mechanical and physical properties of concrete. Shape and texture of the fine aggregate affect the workability, whereas the characteristics of the coarse aggregate affect the mechanical bond. Shape can also affect strength (especially tensile strength) by increasing the surface area available for bonding with the paste. Rough textured surfaces improve mechanical bond. Also, particle size distribution is an important characteristic because it determines the paste requirements for workable concrete. From an economical point of view, the smallest amount of paste is the best since cement is known as the most expensive constituent of concrete. Therefore, the intrinsic properties of the aggregates need to be determined.

3.1.1 Sieve Analysis

The amount of paste depends on the amount of void space between the particles that must be filled, and the total surface area of the aggregate that must be coated with paste. Figure 1 illustrates the influence of various aggregate gradations on the paste requirements.

The grading of the aggregate supply is determined by a sieve analysis. A stack of sieves is used to find the gradation of a representative sample of aggregate. This representative sample of aggregate is obtained in accordance with ASTM Standard D75.

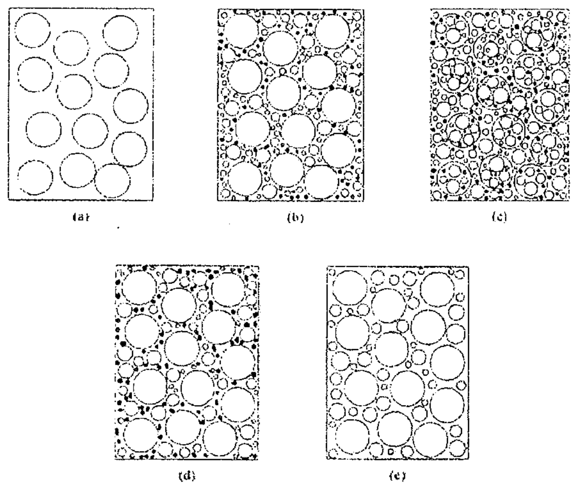

Figure 1 Schematic Representation of Aggregate Gradations in an Assembly of Aggregate Particles: (A) Uniform Size; (B) Continuous Grading; (C) Replacement Of Small Sizes By Large Sizes; (D) Gap-Graded Aggregates; (C) No-Fines Grading

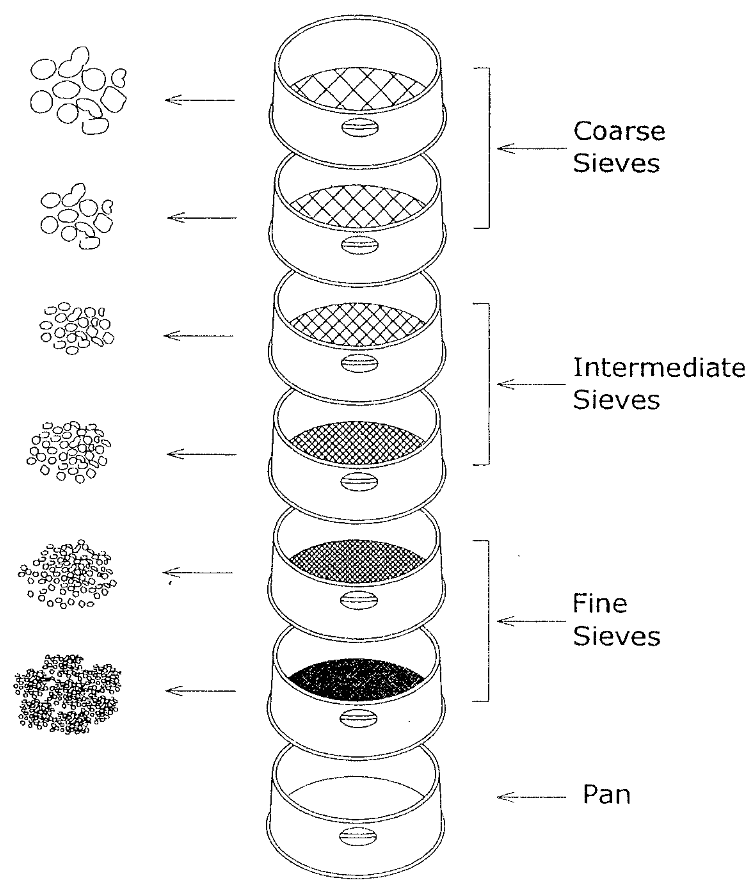

Figure 2 Different Sieve Sizes for Different Analyses

The test procedure is described by ASTM Standard C 136. Different sieves are stacked upon each other to form a column going from the largest sieve to the smallest sieve (see Figure 2). Table 1 summarizes the sieve sizes and their use (coarse or fine aggregate).

Table 1 ASTM Sieve Sizes Commonly Used for Sieve Analysis of Concrete Aggregates

	ASTM Sieve Designation	
	(mm)	(in)
Coarse Aggregates	75.0	3
	63.0	2 ½
	50.0	2
	37.5	1 ½
	25.0	1
	19.0	¾
	12.5	½
	9.5	3/8
Fine Aggregates	4.75	No. 4
	2.36	No. 8
	1.18	No. 16
	600 μm	No. 30
	300 μm	No. 50
	150 μm	No. 100

After completing a sieve analysis (according to ASTM C 136), the weight of aggregate retained on each sieve is expressed as a percentage of the total weight of the sample. This is then used to calculate the cumulative percentage retained on each successive sieve or the cumulative percentage passing on each sieve. These numbers can then be plotted graphically against sieve size to give a grading curve. It is customary to use cumulative percentage passing on the ordinate. The successive standard sieve sizes are plotted along the abscissa. ASTM C33 sets grading limits for fine and coarse aggregates based on practical experience. These limits are summarizes in Tables 2 and 3, for coarse and fine aggregates respectively. The grading curves are shown on Figure 3, for both coarse and fine aggregates. If an aggregate does not conform to the ASTM C 33 grading limits, it does not necessarily mean that concrete cannot be made with the aggregate. However, it does mean that the concrete may require more paste and is more liable to segregate during handling and placing.

As can be seen in Tables 2 and 3, and in Figure 3, the provided aggregates used in this project do conform to ASTM C 33 grading limits. Also, ASTM C 33 requires the fineness modulus of fine aggregates to lie between 2.3 and 3.1. From Table 3, the fine aggregates fineness modulus is 2.78 and therefore satisfies this requirement. The fineness modulus is used to check the uniformity of grading. When a fineness modulus is a small number, it indicates a fine grading, whereas a large number indicates a coarse material.

Table 2 Project Specific Coarse Aggregates Sieve Analysis

Sieve Size	Amount Retained (%)	Cumulative Amount Retained (%)	Cumulative Amount Passing(%)	ASTM C 33 Grading Limits
25 mm (1")	0.0	0.0	100	100
19 mm (3/4")	0.2	0.2	99.8	90-100
12.5 mm (1/2")	47.5	47.7	52.3	....
9.5 mm (3/8")	29.0	76.7	23.3	20-55
4.75 mm (No. 4)	21.5	98.2	1.8	0-10
		$\Sigma = 223$		
		+ 500 (from fine sieves No. 8 to No. 100)		

Nominal Maximum Size = 19 mm
Fineness Modulus = 723/100 = 7.23

Table 3 Project Specific Fine Aggregates Sieve Analysis

Sieve Size	Amount Retained (%)	Cumulative Amount Retained (%)	Cumulative Amount Passing(%)	ASTM C 33 Grading Limits
4.75 mm (No. 4)	1.4	1.4	98.6	95-100
2.36 mm (No. 8)	17.1	18.4	81.6	80-100
1.18 mm (No. 16)	14.5	33.0	67.0	50-85
0.6 mm (No. 30)	19.0	52.0	48.0	25-60
0.3 mm (No. 50)	25.7	77.7	22.3	10-30
0.15 mm (No. 100)	17.6	95.3	4.7	2-10
		$\Sigma = 278$		

Fineness Modulus = 278/100 = 2.78

3.1.2 Moisture Content

Since aggregates contain some porosity, water can be absorbed into the body of the particles. Also, water can be retained on the surface of the particle as a film of moisture. Therefore, it is necessary to have information about the moisture content. Indeed, if the aggregates have a tendency to absorb water, it will therefore be removed from the paste so that the water-cement ratio is effectively lowered and the workability of the concrete decreased. On the other hand, if excess water is present in the aggregate surfaces, extra water will be added to the paste and the w/c ratio of the concrete will be higher than desired.

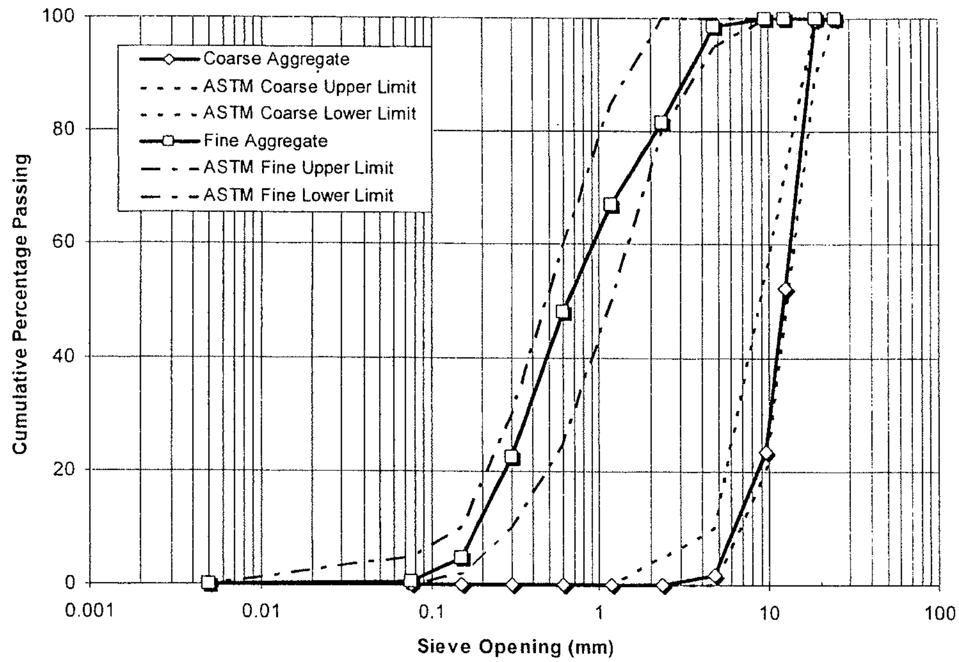

Figure 3 Coarse and Fine Aggregates Grading Curves, Including ASTM C 33 Grading Limits

To define the moisture of the aggregates, it is convenient to define four moistures states of the aggregate as shown in Figure 4:

- Oven-Dry (OD): all moisture is removed from the aggregate by heating in an oven at 105°C to constant weight. All pores are empty.
- Air-Dry (AD): all moisture is removed from the surface, but internal pores are partially full.
- Saturated-Surface-Dry (SSD): all pores are filled with water, but there is no film of water on the surface.
- Wet: all pores are completely filled with water with a film of water on the surface.

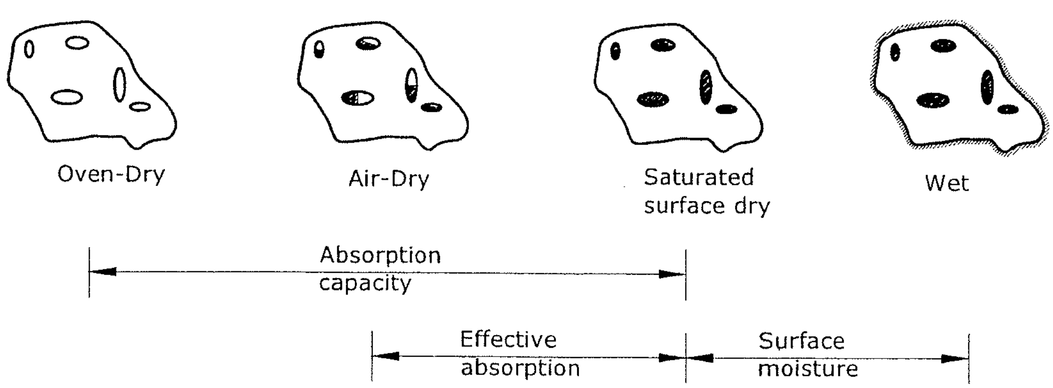

Figure 4 Moisture States of Aggregates

Of these four states, only two states (OD and SSD) correspond to specific moisture contents, and either of these states can be used as reference states for calculating moisture content. The SSD state is the better reference state because it represents the "equilibrium" moisture state of the aggregate in the concrete; that is, the aggregate will neither absorb water nor give up water to the paste. However, it is not easy to obtain a true SSD condition since it requires skill and practice. For this reason, this report summarizes the results from the Oven-Dry standpoint. Moreover, both the fine and coarse aggregates used in this project were in the OD state since they were stored in a warm storage area for an extended period of time.

For the purpose of this report, it is convenient to define two quantities. These quantities are the absorption capacity, and the surface moisture. Absorption capacity, A, represents the maximum amount of water the aggregate can absorb. It is calculated from the difference in weight between the SSD and OD states, expressed as a percentage of the OD weight:

$$A = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100\%$$

where W_{SSD} and W_{OD} represent the weight of the aggregate sample in the SSD and OD states, respectively. Most normal-weight aggregates (fine and coarse) have a absorption capacities in the range of 1 to 2%. Abnormally high absorption capacities indicate high-porosity aggregates, which may have potential durability problem. One should also may attention to pore size distribution as it is very important as far as freeze-and-thaw resistance is concerned.

The surface moisture (SM) represents water in excess of the SSD state, and it is expressed as a fraction of the SSD weight:

$$SM = \frac{W_{wet} - W_{SSD}}{W_{SSD}} \times 100\%$$

It is used to estimate the additional water required during the mix. The aggregates used in this project were in the OD state; therefore, the surface moisture was zero.

Absorption and surface moisture have been determined in accordance to ASTM Standards C 127 for coarse aggregates and C 128 for fine aggregates. Obtained results are summarized in Table 4 for both fractions of aggregates used in the project. The testing procedures are not described in this report.

3.1.3 Specific Gravity

Even though the mix design for this specific project is not done in accordance to any mix design procedures commonly utilized for ordinary concrete (for example ACI 211), it is always interesting to establish the weight-volume relationships. Densities are determined by displacement in water, specific gravities are naturally and easily calculated and can be used with any systems of units. The bulk specific gravity (BSG) is a realistic value to use since the effective volume that is occupied by aggregates in concrete includes the pores. The bulk specific gravity is defined as follows:

$$BSG = \frac{\text{weight of aggregate (solid + pores)}}{\text{weight of water displaced}}$$

The BSG of most rocks is in the range 2.5 to 2.8. A value well below this range is an indication of high porosity. The BSG of an aggregate cannot be directly related to its performance in concrete, and thus is usually not a specified quantity. However, the densities of aggregates do relate partly with the density of concrete.

The bulk specific gravities of the employed aggregates have been obtained in accordance with ASTM standard C 127 for coarse aggregates and C 128 for fine aggregates. The obtained results are summarized in Table 4. The testing procedures are not described in this report.

3.1.4 Unit Weight

Unit weight (UW) can be defined as the weight of a given volume of graded aggregate. The unit weight effectively measures the volume that the graded aggregate will occupy in concrete and includes both the solid aggregate particles and the voids between them. The unit weight is simply measured by filling a container of known volume and weighting it as described in ASTM standard C 29. The degree of compaction will influence the amount of void and therefore the unit weight. ASTM standard method calls for compaction by rodding. Moisture is also a parameter influencing the unit weight as shown in Figure 4. Consequently, ASTM standard method also calls for a moisture state as oven-dry. The unit weights of both fine and coarse normal-weight aggregates falling between the ASTM grading limits are generally in the range of 90 to 110 lbs/ft^3 (1450 to 1750 kg/m^3).

Unit weights for fine and coarse aggregates have been determined in accordance with ASTM Standard C 29. The obtained results are summarized in Table 4. The testing procedure is not described in this report.

Table 4 Physical Properties of the Aggregate Fractions

Aggregate Fractions	Specific Gravity	Water Absorption (%)	Surface Moisture (%)	Unit Weight (kg/m^3)	Fineness Modulus
Fine Aggregate	2.65	1.2	0	1750	2.78
Coarse Aggregate	2.70	1	0	1600	7.23

3.2 CEMENT

Portland cement is made of finely powdered crystalline minerals composed primarily of calcium and aluminum silicates. The addition of water to these minerals produces a paste that, when hardened, becomes of stone-like strength. Its specific gravity ranges between 3.12 and 3.16 and it weights 94 lbs/ft^3, which is also the unit weight of a commercial sack or bag of cement. The main raw materials that Portland cement is composed of are:

- Lime (CaO), from limestone
- Silica (SiO_2), from clay
- Alumina (Al_2O_3), from clay

Table 5 summarizes the chemical composition of typical Portland cement along with weight percentage of each of cement compounds. Iron oxide is occasionally added to the mixture to aid in controlling its composition.

Table 5 Composition of Portland Cement with Chemical Composition and Weight Percent

Cement Compound	Weight Percentage	Chemical Formula
Tricalcium silicate	50 %	Ca_3SiO_5 or $3CaO{\cdot}SiO_2$
Dicalcium silicate	25 %	Ca_2SiO_4 or $2CaO{\cdot}SiO_2$
Tricalcium aluminate	10 %	$Ca_3Al_2O_6$ or $3CaO{\cdot}Al_2O_3$
Tetracalcium aluminoferrite	10 %	$Ca_4Al_2Fe_{10}$ or $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$
Gypsum	5 %	$CaSO_4{\cdot}2H_2O$

The strength of cement is the result of a process of hydration. This chemical process results in recrystallization in the form of interlocking crystals producing the cement gel, which has high compressive strength when it hardens. Table 6 shows the relative contribution of each component of the cement toward the rate of gain in strength. The early strength of Portland cement is higher with higher percentage of C_3S. If moist curing is continuous, later strength levels will be greater, with higher percentage of C_2S. C_3A contributes to the strength developed during the first day after placing the concrete because it is the earliest to hydrate.

Table 6 Contribution of Each Component of Portland Cement

Component	Rate of Reaction	Heat Liberated	Ultimate Cementing Value
Tricalcium Silicate C_3S	Medium	Medium	Good
Dicalcium Silicate C_2S	Slow	Small	Good
Tricalcium Aluminate C_3A	Fast	Large	Poor
Tetracalcium Aluminoferrate C_4AF	Slow	Small	Poor

When Portland cement combines with water during setting and hardening, lime is liberated from some of the compounds. The amount of lime liberated is approximately 20% by weight of the cement. Under unfavorable conditions, this might cause disintegration of a structure owing to leaching of the lime from the cement. Such a situation can be prevented by addition to the cement of a silicious mineral such as Pozzolan or fly ash. The latter is added to the mix; therefore, the properties of fly ash are described hereafter.

For the purpose of the study, ASTM Type I Cement (provided by HOLCIM) was used throughout. This type of cement was chosen because it is the most commonly used type of cement and because no special properties were needed or specified. It was also an intention of the research to later compare the conventional concrete made with Type I cement with the developed SCC concrete.

3.3 FLY ASH

Fly ash is a fine inorganic material with pozzolanic properties, which can be added to SCC to improve its properties. Fly ash is a by-product of pulverized coal blown into a fire furnace at a power generating plant. Coal, ground to the consistency of flour ignites when blown into the furnace and a certain amount of non-burnable material residue remains as either slag or airborne particles, known as fly ash. The airborne particles are removed by mechanical collectors, electrostatic precipitators, or wet scrubbers.

Fly ash looks very similar to cement in appearance. However, when magnified, fly ash will appear as spherical particles, similar to ball bearings, whereas cement appears angular, more like crushed rock. Fly ash has cementitious qualities and, therefore, can be used as a replacement of a portion of the cement in a concrete mix. Placement and finishing of concrete made with fly ash is easier due to the spherical shape of the fly ash, which acts somewhat like a lubricant.

The fly ash used in this project is a Type C fly ash provided by HOLCIM.

Concrete made with Type C fly ash (as opposed to Type F) has higher early strengths because it contains its own lime. This allows pozzolanic activity to begin earlier. At later ages, Type C behaves very much like Type F – yielding higher strengths than conventional concrete at 56 and 90 days. One distinct advantage of using fly ash in the manufacturing of concrete is the greater density of the concrete. Other advantages of using fly ash in concrete mixes are numerous:

- Improves workability.
- Improves sulfate resistance.
- Increases resistance to freezing and thawing.
- Increases cohesiveness.
- Improves long-term strength.
- Reduces the water content of the mix.

- Reduces the heat of hydration.
- Decreases permeability.
- Resists alkali-aggregate reaction.

Fly ash is added to the self-consolidating concrete mix, but some additive is still needed to ensure the self-consolidating properties. This additive is called superplasticizer.

3.4 SUPERPLASTICIZERS

Superplasticizers belong to a class of water reducers chemically different from the normal water reducers and capable of reducing water contents by about 30%. The admixtures belonging to this class are variously known as superplasticizers, superfluidizers, superfluiddiers, superwater reducers, or high range water reducers. They were first introduced in Japan in the late 60's and in Germany in early 70's. In North America they were used from 1974. It is now common practice to use these additives to improve the flowability and extend the working time of fresh concrete. The use of the first generation superplasticizers (sulfonated naphthalene formaldehyde, NSF, and modified lignosulfonates, LSs) resulted in significant improvements in the properties of fresh concrete, and they are still widely used. However, increasing demands for better flowability, extended working time, and a reduction in concrete porosity have created a need for superplasticizers with improved performance.

Polycarboxylate Ether (PCE) superplasticizers represent a major breakthrough in concrete technology as they can provide up to 40% water reduction and impart tremendous workability that can be extended without the undesirable effects of retardation and segregation. Among others, the main advantages of PCE superplasticizers in concrete are as follows:

- Higher flowability without segregation
- Increased slump but better slump retention
- Higher early compressive strengths (allows earlier removal of forms)
- Higher ultimate strengths (allows for structural economies)
- Water/cement ratio reduced (concrete more durable, dense)
- Better impermeability to reduce sulfate attack and salt penetration
- Rheology Controlled
- No increase of corrosion (PCE superplasticizers do not contain formaldehyde, calcium chloride, or any other intentionally added chlorides)

In this project, three types of superplasticizers have been investigated and Table 7 summarizes their origins and their producers.

Table 7 Different Superplasticizers Utilized in the Project

Name of the superplasticizer	Producer	Type
GLENIUM 3200 HES	Master Builders	Polycarboxylate Ether
VISCOCRETE 5000	Sika	Polycarboxylate Ether
ALLEGRO 122	Axim	Polycarboxylate Ether

A dosage of 1-2% by weight of cement is advisable. It should be noted that the superplasticizers exert their action by decreasing the surface tension of water and by equidirectional charging of cement particles. The particular dosage of the different superplasticizers will be discussed later in this report.

3.5 WATER

Water is required in the production of concrete in order to precipitate chemical reaction with the cement, to wet the aggregates, to lubricate the mixture for easy workability. Normally, drinking water can be used in mixing. Water having harmful ingredients, contamination, silt, oil, sugar, or chemicals is disruptive to the strength and setting properties of cement. It can disrupt the affinity between the aggregate and the cement paste and can adversely affect the workability of a mix.

Since the character of the colloidal gel or cement paste is the result only of the chemical reaction between cement and water, it is not the proportion of water relative to the whole mixture of dry materials that is of concern, only the proportion of water relative to cement (water/cement ratio). Excessive water leaves an uneven honeycombed skeleton in the finished product after hydration has taken place, while little water prevents complete chemical reaction with the cement. The product in both cases is a concrete that is weaker than or inferior to normal concrete.

4. FRESH CONCRETE TESTING

Self-consolidating concrete is defined as a concrete that is characterized by a very good deformability, good resistance to segregation, and ability to fill between heavily reinforced areas without applying vibration. Consequently, the properties of fresh concrete play a very important role.

It is assumed that concrete can be classified as self-consolidating concrete when the requirements regarding density, strength development, final strength and durability are fulfilled. The three following characteristic must be satisfied for a concrete mix to be categorized as a self-consolidating concrete.

- Filling ability
- Passing ability
- Segregation resistance

In this report, all these characteristics have been investigated in order to establish the validity of the recipe.

Many different test methods have been developed in attempts to characterize the properties of SCC. So far, no single method or combination of methods has achieved universal approval and most of them have their adherents. Similarly, no single method has been found that characterizes all the relevant workability aspects. Therefore, each mix design should be tested by more than one test method for the different workability parameters.

Commonly used test methods for the different parameters are reported below:

Method	Property
• Slump-flow by Abrams cone	Filling ability
• T_{50cm} slump-flow	Filling ability
• J-ring	Passing ability
• V-funnel	Filling ability
• V-funnel at $T_{5minutes}$	Segregation resistance
• L-box	Passing ability
• U-box	Passing ability
• Fill-box	Passing ability
• GTM screen stability test	Segregation resistance
• Orimet	Filling ability

For the initial mix design of SCC all three workability parameters need to be assessed to ensure that all aspects are fulfilled. A full-scale test should be used to verify the self-consolidating characteristics of the chosen mix for a particular application.

Regarding workability, there are few requirements that are to be fulfilled at the time of placing. Also, likely changes in workability during the transport should be taken into account during production.

Typical acceptance criteria for self-consolidating concrete with a maximum aggregate size up to 20 mm are shown in Table 8.

Table 8 Acceptance Criteria for Self-Consolidating Concrete

	Method	Units	Typical range of values	
			Minimum	Maximum
1	Slump-flow by Abrams cone	[mm]	650	800
2	T_{50cm} slump flow	[sec]	2	5
3	J-ring	[mm]	0	10
4	V-funnel	[sec]	6	12
5	Time increase, V-funnel at T_{5min}	[sec]	0	+3
6	L-box	[h_2/h_1]	0.8	1.0
7	U-box	[mm]	0	30
8	Fill-box	[%]	90	100
9	GTM Screen stability test	[%]	0	15
10	Orimet	[sec]	0	5

These typical requirements shown for each test are based on current knowledge and practice. Values outside these ranges may be acceptable if the producer can demonstrate satisfactory performance in the specific conditions; e.g., large spaces between reinforcement, layer thickness less than 500 mm, short distance of flow from point of discharge, very few obstructions to pass in the formwork, very simple design of formwork, etc.

Special care should always be taken to ensure no segregation of the mix is likely as, at present, there is not a simple and reliable test that gives information about segregation resistance of SCC in all practical situations.

For the purpose of this study, the following testing methods were used:

- Slump-flow by Abrams cone
- T_{50cm} slump-flow
- V-funnel
- V-funnel at $T_{5minutes}$
- L-box
- Air content
- Unit weight

4.1 SLUMP-FLOW TEST AND T_{50CM} TEST

The purpose of these tests it to determine the time taken for the concrete to reach the 50 cm spread circle and to measure the final diameter of the concrete in two perpendicular directions. These tests are evaluated in the absence of obstructions.

Apparatus:

- Cone with the internal dimensions 200 mm diameter at the base, 100 mm diameter at the top and a height of 300 mm, see Figure 5,
- Base plate of a stiff non absorbing material, at least 700mm square, marked with a circle marking the central location for the slump cone, and a further concentric circle of 500mm diameter,
- Trowel,
- Scoop,
- Ruler,
- Stopwatch (optional),

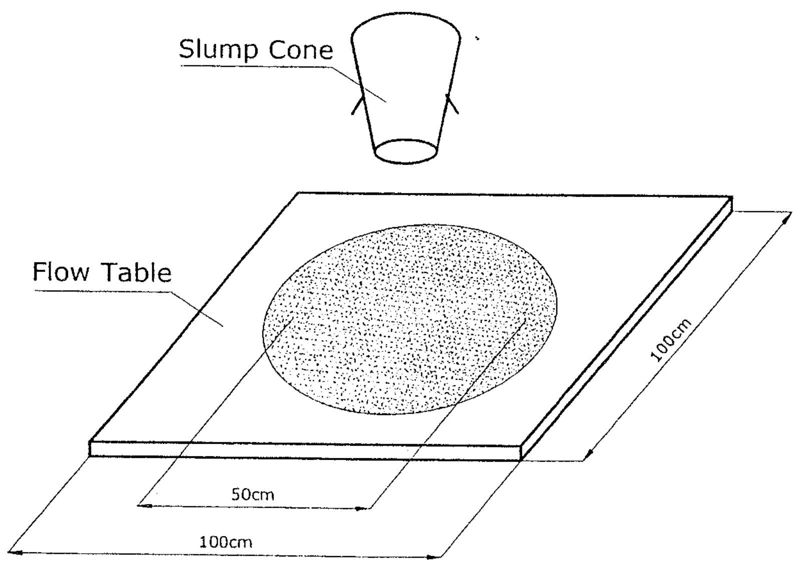

Figure 5 Slump Flow

Procedure:

- Level the base plate,
- Place the slump cone centrally on the base and hold down firmly,
- Fill the cone with concrete, to strike off the concrete level use trowel,
- Remove any surplus concrete from around the base of the cone,
- Raise the cone and allow the concrete to flow out,
    - at the same time start the stopwatch and record the time when concrete reaches the 500 mm spread circle
- Measure the final diameter of the concrete in two perpendicular directions and calculate the average value,

Interpretation of result:

Depending on the slump flow, the concrete has greater or more limited capability to fill up formwork under its own weight. For Self-Consolidating Concrete the value of at least 650mm is required, but there is no generally accepted advice on what are reasonable tolerances about a specified value. Figure 6 shows a typical slump flow of SCC.

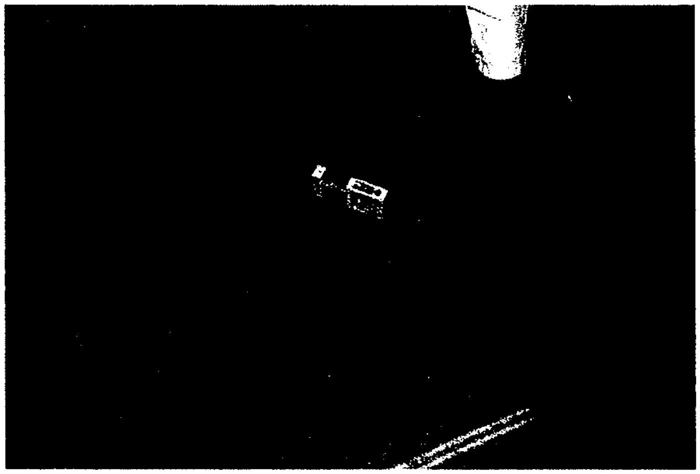

Figure 6 Typical Slump Flow of SCC

According to recent research, it can be assumed that a reasonable value for the diameter for the civil engineering applications is between 650 and 800 mm.

The next value that is measured and has to be taken into account is time taken for concrete to reach the 500 mm spread circle. A lower time indicates greater flowability. Typically, an acceptable time is 2-5 or 3-7 seconds, depending on the application.

4.2 V-FUNNEL

The described V-funnel test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate size of 20mm. The test was developed in Japan and used by Ozawa. The equipment consists of a V-shaped funnel, shown in Figure 7. The funnel is filled with about 12 liters of concrete and the time taken for it to flow through the apparatus measured.

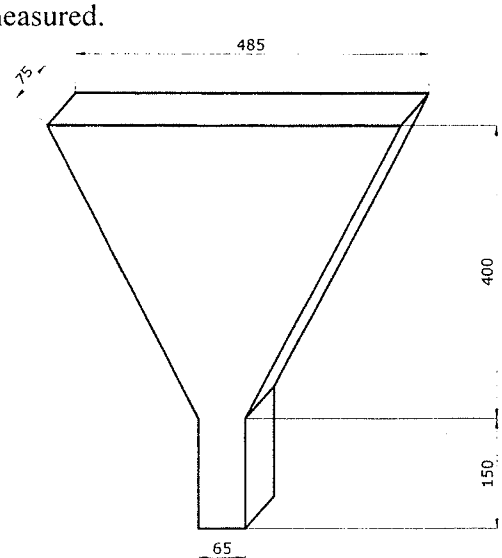

Figure 7 V-funnel

After the first flow of the concrete, the funnel is refilled with concrete that was tested and left for 5 minutes to settle. The procedure is repeated. If the concrete shows segregation then the flow time will increase significantly.

Apparatus:

- V-funnel
- Bucket (~ 12 liters)
- Trowel
- Scoop
- Stopwatch

Procedure for determining flow time

- About 12 liters of normally sampled concrete is needed to perform the test,
- Moisten the inside surface of funnel,
- Fill the V-funnel completely with concrete without compacting or tamping,
- Within 10 seconds after filling, open the trap door and allow concrete to flow out under gravity (see Figure 8),
- Measure the time between the opening of the trap door and the complete discharge of the V-funnel (the flow time). This is taken to be when light is seen from above through the V-funnel.

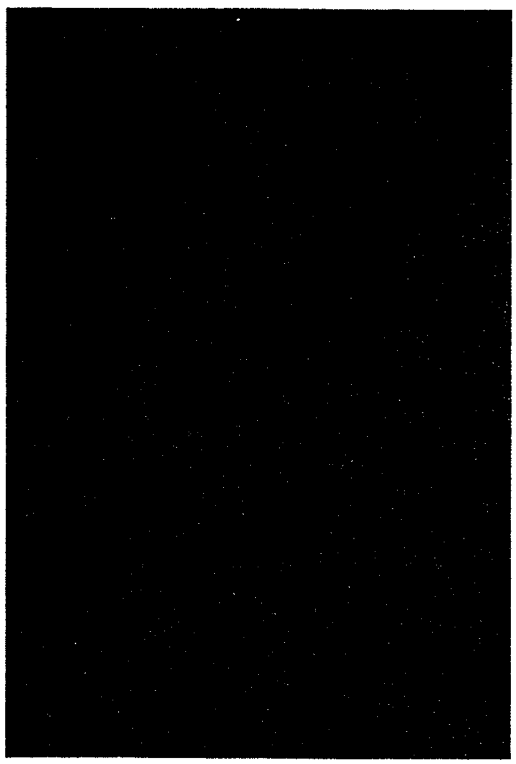

Figure 8 Flow of SCC under Its Own Gravity

Procedure for determining flow time at $T_{5\ minutes}$

- Without cleaning or moistening the inside surfaces of the V-funnel refill the V-Funnel completely with the same concrete immediately after measuring the flow time. Do not compact or tap the concrete.
- Five minutes after second fill open the trap door and allow concrete to flow out concrete under gravity.
- Measure the time between the opening of the trap door and the complete discharge of the V-funnel (the flow time at $T_{5\ minutes}$). This is taken to be when light is seen from above through the V-funnel.

Interpretation of result

This test measures the ease of flow of the concrete, shorter flow times indicate greater flowability. For SCC a flow time of 10 seconds is considered appropriate. The inverted cone shape restricts flow, and prolonged flow times may give some indication of the susceptibility of the mix to blocking. After 5 minutes of settling, segregation of concrete will be indicated by a less continuous flow with an increase in flow time.

4.3 L-Box

This test assesses the flow of concrete, and also the extent to which it is subject to blocking by reinforcement. The test is based on a Japanese design for underwater concrete. The L-box is shown in Figure 9.

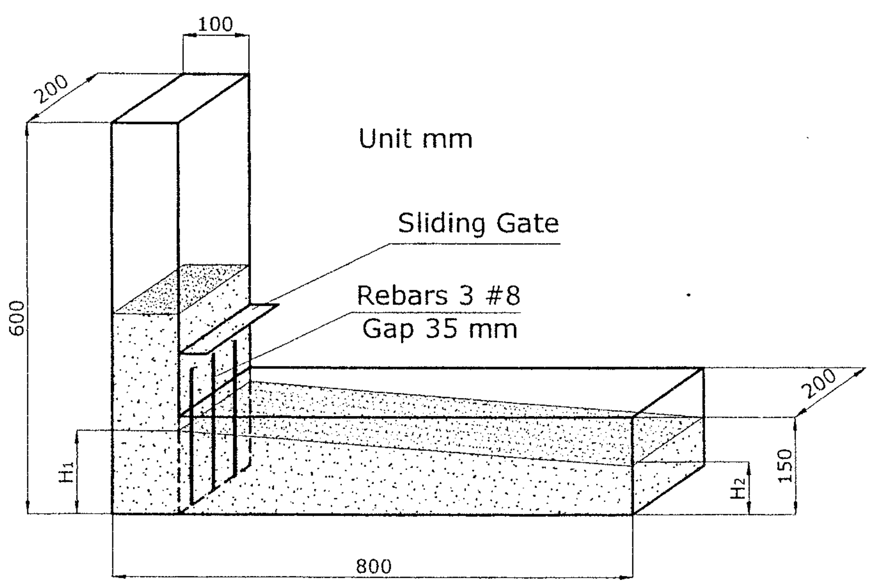

Figure 9 L-box

The L-box consists of a rectangular-section box in the shape of an 'L', with vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The vertical section is filled with concrete and the gate is lifted to let the concrete flow into the horizontal section. When the flow has stopped, the height of the concrete at the end of the horizontal section is expressed as a proportion of that remaining in the vertical section (H_2/H_1 in the diagram). It indicates the *slope* of the concrete. This is also an indication of passing ability, or the degree to which the passage of concrete through the bars is restricted.

The sections of bar can be of different diameters and spaced at different intervals: in accordance with normal reinforcement considerations, 3x the maximum aggregate size might be appropriate. The bars can principally be set at any spacing to impose a more or less severe test of the passing ability of the concrete.

Assessment of test

This is a widely used test, suitable for laboratory, and perhaps for on-site use. It assesses filling and passing ability of SCC, and serious lack of stability (segregation) can be detected visually. Segregation may also be detected by subsequently sawing and inspecting sections of the concrete in the horizontal section. Unfortunately there is no agreement on materials, dimensions, or reinforcing bar arrangement, so it is difficult to compare test results. There is no evidence of what effect the wall of the apparatus and the consequent 'wall effect' might have on the concrete flow, but this arrangement does, to some extent, replicate what happens to concrete on site when it is confined within formwork.

Apparatus

- L box of a stiff non absorbing material see Figure 9,
- Trowel,
- Scoop,
- Stopwatch,

Procedure

- About 14 liters of normally sampled concrete is needed to perform the test.
- Close the sliding gate.
- Fill the vertical section of the L-box completely with concrete without compacting or tapping and leave it to stand for 1 minute.
- Lift the sliding gate and allow the concrete to flow out into the horizontal section of the L-box (see Figure 10),
- As concrete stops flowing measure the distances H_1 and H_2, calculate H_2/H_1 (blocking ratio).
- Test has to be performed within 5 minutes of filling the box.

Interpretation of result

If the concrete flows as freely as water, it will rest horizontally and $H_2/H_1 = 1$. The nearer this test value, the 'blocking ratio', is to unity, the better the flow of the concrete. It is suggested a minimum acceptable value of 0.8. Obvious blocking of coarse aggregate behind the reinforcing bars can be detected visually.

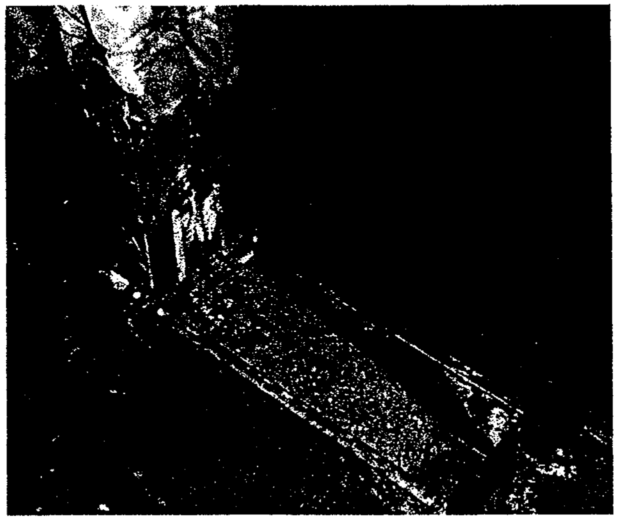

Figure 10 Flow of SCC into the Horizontal Section of L-Box

4.4 AIR CONTENT

Air content has an influence not only on fresh concrete properties but also on hardened concrete properties. Air entrainment improves the workability and cohesiveness of fresh concrete. Air-entrained concrete is usually more workable than non-air-entrained mix at the same slump. Also, bleeding and segregation are reduced in case of air-entrained mixes.

The introduction of additional void space with air entrainment, however, has a detrimental effect on strength. Generally, the loss of strength of 10-20% can be noticed for most air-entrained concrete.

Currently, there are a few methods that are commonly used to measure the air content. They are: pressure method, gravimetric method, and volumetric method For the purpose of this study, both the pressure method and the volumetric method were utilized.

4.4.1 Pressure Method

This test method is described in ASTM 231 and it covers the determination of the air content of freshly mixed concrete from observation of the change in volume of concrete with a change in pressure. The test determines the air content of freshly mixed concrete exclusively of any air that may exist inside voids within aggregate particles. For this reason, this method is only pertinent to concrete made with relatively dense aggregate particles, and it requires the determination of the aggregate correction factor.

Below is the description of the apparatus and the procedures used in the pressure method test.

Apparatus:

- Air Meter, Type B, consisting of a measuring bowl and cover assembly.
- Balance with a range of use
- Tamping rod in a form of round straight steel rod 5/8 in. in diameter, not less than approximately 16 in. in length, and should have tamping end rounded to hemispherical tip with diameter of 5/8 in.
- Internal vibrator - rigid or flexible shaft powered by electric motor with a minimum frequency of vibration of 7000 vibrations per minute, and outside diameter or side dimension at least 3/4 in. and not greater than 1 1/2 in.
- Mallet - rubber head, weight of 2.25 ± 0.50 lb for use with measure larger than 0.5 ft^3
- Strike-off bar in a form of flat straight bar of steel, at least 1/8 in. thick by 3/4 in. wide by 12 in. long
- Strike-off plate in a form of flat rectangular metal plate at least 1/4 in. thick or a glass or acrylic plate at least 1/2 in. thick
- Calibration vessel in a form of a vessel marked with serial number that matches air meter apparatus, or vessel marked with representative percent air content for air meter apparatus

Procedure for Determining Aggregate Correction Factor

- Calculate the weights of fine and coarse aggregate as follows:

$$F_s = (S/B) \times F_b$$
$$C_s = (S/B) \times C_b$$

where:

F_s = weight of fine aggregate in concrete sample under test, lb.
S = volume of measuring bowl, ft^3
B = volume of concrete produced per batch, ft^3
F_b = total weight of fine aggregate in the moisture condition used in batch,
C_s = weight of coarse aggregate in concrete sample under test, lb
C_b = total weight of coarse aggregate in the moisture condition used in batch, lb

- Place mixed aggregates (fine and coarse) in measuring bowl filled one-third full with water. Aggregates in bowl shall be covered with water at all times.
- Close the air valve between air chamber and measuring bowl, keeping both petcocks opened
- Inject water through one petcock until water emerges from opposite petcock. It will remove all entrapped air.
- Pump air into air chamber to a stabilized initial pressure line which is correct for meter
- Close both petcocks and release pressurized air into bowl containing sample
- Read the aggregate correction factor directly from air content gauge

Procedure for Determining Air Content of Concrete:

- Place a representative sample of the concrete in the measuring bowl in equal layers

- Consolidate each of the layer by the rodding or vibration (depending on the slump of concrete)
- Strike off any excess of concrete by sliding the strike-off bar across the top rim of the measuring bowl
- Place the lid of the pressure meter and clamp it to the bucket
- With petcock open and using a syringe, inject water through one petcock until all the air is displaced and expelled through the opposite petcock.
- With built-in pump, pump air to initial line on the gauge.
- Close both petcocks, and then press down on the needle valve lever to release the air into the base. Hold needle valve lever down lightly tapping the gauge until the gauge stabilizes.
- Read the percent of air in the concrete on the dial.

Calculation:

- Calculate the air content of the concrete in the measuring bowl as follows:

$$A_s = A_1 - G$$

where:

A_s = air content of the sample tested, %

A_1 = apparent air content of the sample tested, %

G = aggregate correction factor, %

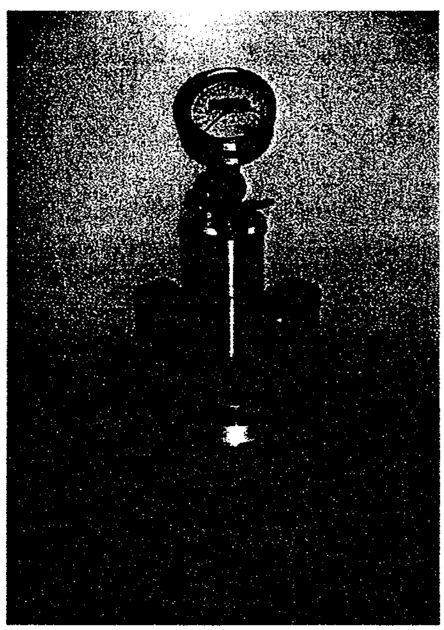

Figure 11 Air Meter, Type B, for Pressure Method. Apparatus at the University of Michigan

4.4.2 Volumetric Method

This test method is described in ASTM 173 and it covers the determination of the air content of freshly mixed concrete containing any type of aggregate, whether it be dense, cellular, or lightweight. Below is the description of the apparatus and the procedures used in the volumetric method test.

Apparatus:

- Air Meter consisting of a bowl and a top section. The bowl and top section must withstand rough field use.
- Bowl of the diameter equal to 1 to 1.25 times the height and capacity more than $0.075ft^3$.
- Top section of capacity at least 20% larger than the bowl and it should be equipped with a flexible gasket and a device to attaché the top section to the bowl. The top section should also be equipped with a transparent scale and the upper end of the neck shall have a watertight cap that will maintain a watertight seal when the meter is inverted and rolled.
- Funnel with a spout of a size permitting it to be inserted through the neck of the top section and long enough to extend to a point just above bottom of top section.
- Tamping rod in a form of a round, straight 5/8 in. diameter rod, not less than 12 in. in length, and it should have tamping end rounded to hemispherical tip with diameter of 5/8 in.
- Strike-off bar in a form of a flat, straight bar of steel at least 1/8 in. thick by 3/4 in. wide by 12 in. long
- Calibration cup having capacity of 1.00 ± 0.04 percent of volume of the bowl
- Measuring Vessel for Isopropyl Alcohol with a minimum capacity of at least 1 pt with graduations not larger than 4 oz.
- Syringe with a capacity at least that of the calibrated cup.
- Pouring vessel with capacity of approximately 1 qt.
- Scoop.
- Isopropyl alcohol.
- Mallet with rubber or rawhide head with a mass of approximately 1.25 ± 0.5 lb.

Procedure:

- Fill the bowl in three layers of approximately equal depth using metal scoop.
- Rod each layer with 25 strokes with tamping rod.
- Tap the bowl 10 to 15 times with mallet after each layer is rodded.
- Strike-off the top surface with bar until surface is flush with top of bowl.
- Attach the top section, insert funnel and add water until it appears in the neck.
- Remove the funnel and add water with a rubber syringe until the bottom of the meniscus is level with zero mark.
- Attach the cap and tighten it.
- Invert the meter and agitate for a minimum of 45 seconds, meter must not be inverted for more than 5 seconds at a time. This procedure is intended to free the concrete from the base. When the concrete has broken free, the aggregate can be heard moving in the airmeter.
- Tilt the meter at approximately 45 degrees and vigorously roll and rock it for approximately 1 minute, with neck elevated at all times.
- Set the meter upright and allow it to stand until liquid level stabilizes by not changing more than 0.25 percent within 2 minute period.

- If liquid level is obscured by foam, add alcohol by syringe in one calibrated cup increments to establish a readable liquid level.
- Record the number of calibrated cups of alcohol, and read liquid level at bottom of meniscus to nearest 0.25 percent air.
- Repeat the roll and rock procedure until two consecutive readings do not change by more than 0.25 percent air.
- Disassemble and examine the content of the meter to assure there are no portions of undisturbed, tightly packed concrete in base.
- If alcohol is added to meter in one calibrated cup increments, calculate the air content by adding the number of alcohol cups to meter reading.
- Report the air content to the nearest 0.25 percent air.

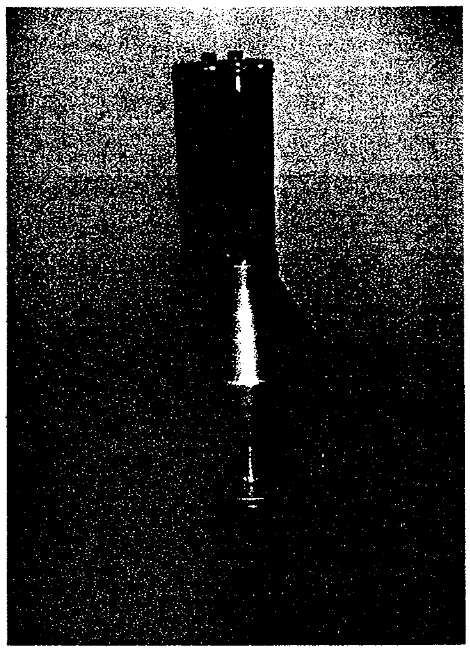

Figure 12 Air Meter Used for Volumetric Method. Apparatus at the University of Michigan

4.5 UNIT WEIGHT

Unit weight (the density) of freshly mixed concrete can be measured by weighing a known volume of concrete. Normally, the sample that is later used to determine air content is used, as this is a know volume of concrete (see section 4.4.1). Also, the unit weight can be used to approximate air content for concretes made with the same materials. The procedure to determine the unit weight is covered by ASTM C 138.

Apparatus:

- Balance in a form of a balance or scale accurate to 0.1lb or to within 0.3% of the test load, whichever is greater, with the range of use

- Tamping rod in a form of round straight steel rod 5/8 in. in diameter, not less than approximately 24 in. in length, and should have tamping end rounded to hemispherical tip with diameter of 5/8 in.
- Internal vibrator - rigid or flexible shaft powered by electric motor with a minimum frequency of vibration of 7000 vibrations per minute, and outside diameter or side dimension at least 3/4 in. and not greater than 1 1/2 in.
- Measure in a form of a cylindrical container made of steel (the measuring bowl of air meter can be used as well)
- Mallet - rubber head, weight of 2.25 ± 0.50 lb for use with measure larger than 0.5 ft^3
- Strike-off plate in a form of flat rectangular metal plate at least 1/4 in. thick or a glass or acrylic plate at least 1/2 in. thick
- Mallet with a rubber or rawhide head.

Procedure:

- Place the concrete in the measure in three layers rodding each of the layer. After each layer is rodded, tap the sides of the measure with the mallet to close any voids left by tamping rod and to release any large bubbles of air that may have been trapped
- After consolidation, strike-off the top surface of the concrete and finish it smoothly with the strike-off plate
- After strike-off, clean all excess concrete from the exterior of the measure and determine the weight of the concrete
- Calculate the net mass of the concrete in pounds, and the density (unit weight) using:

$$D = (M_c - M_m) / V_m$$

where:

M_m is the mass of the measure

M_c is the mass of the measure filled with concrete

V_m is the volume of the measure

5. HARDENED CONCRETE TESTING

Once concrete has hardened it can be subjected to a wide range of tests. This section presents a brief account of all methods that were used to test hardened concrete. These test were carried out not only to prove the ability of concrete to perform as planned, but also to discover its characteristics as it is a new type of concrete, and its history is unknown.

5.1 COMPRESSIVE STRENGTH TEST

<u>Test description</u>

The standard test method to determine the compressive strength of concrete has been conducted in accordance to the ASTM Standard C 39. This standard describes the procedure and requirements for this test and it is summarized as follows.

This test method covers determination of compressive strength of cylindrical concrete specimens such as molded cylinders and drilled cores. It is limited to concrete having a unit weight in excess of 50 lbs/ft^3 (800 kg/m^3). The tested specimens have been prepared and cured in accordance with practices C 192. This test consists of applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

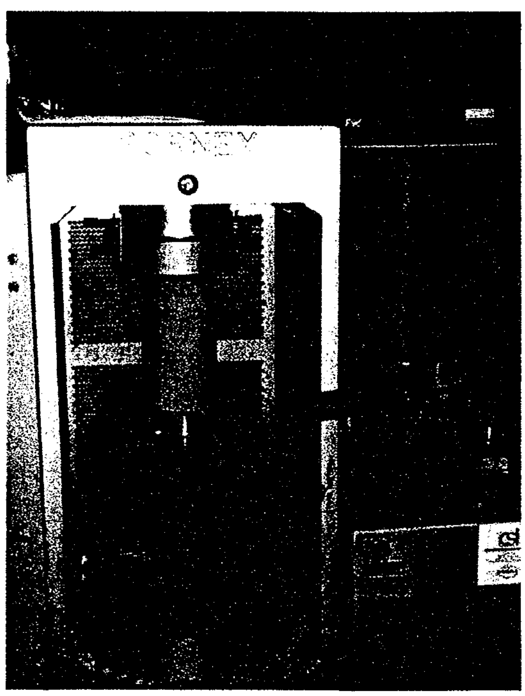

Figure 13 Cylinder Compressive Strength Apparatus at the University of Michigan

Apparatus

The apparatus must conform to the specifications described in ASTM C 39:

- The testing machine shall be of a type having sufficient capacity and capable of providing the rates of loading specified in the standard.
- The apparatus has to have proper calibration in accordance with ASTM Standard E4 and the previous verification must date less than 18 months.
- The machine must be power operated and must apply the load continuously rather than intermittently, and without shock.
- The testing equipment must have an accuracy conforming to the standard provisions.
- The testing machine shall be equipped with two steel bearing blocks with hardened faces, one of which is a spherically seated block that will bear on the upper surface of specimen, and the other a solid block on which the specimen shall rest. The bearing faces shall have a minimum dimension at least at least 3% greater than the diameter of the specimen to be tested.
- If the testing machine load is indicated in digital form, the numerical display must be large enough to be easily read. The numerical increment must be equal to or less than 0.10% of the full scale load of a given loading range.

Other specifications are fully satisfied by the apparatus utilized during the experiments conducted at the University of Michigan by the research team (see Figure 13)

Specimens:

- Specimens shall not be tested if any individual diameter of a cylinder differs from any other diameter of the same cylinder by more than 2%.
- Neither end of the specimens shall depart form perpendicularity to the axis by more than 0.5°. The ends of compression specimens that are not plane within 0.002 in. shall be sawed or ground to meet that tolerance, or capped in accordance with Practice C 617.

As specified, the specimens used in this project have been capped in accordance with Practice C 617.

Procedure:

- Compression tests of moist-cured specimens shall be made as soon as practicable after removal from moist storage.
- All test specimens for a given test age shall be broken within the permissible time tolerances prescribed in Table 9
- Place the specimen at the center of the bearing and reset the load cell. Apply load continuously and without shock. For hydraulically operated machines, the load shall be applied at a rate of movement corresponding to a laoding rate on the specimen within the range of 20 to 50 psi/s. The designated rate of movement shall be maintained at least during the latter half of the anticipated loading phase of the testing cycle. During the application of the first half of the anticipated loading phase, a higher rate of loading shall be allowed.

- Apply the load until the specimen fails, and record the maximum load carried by the specimen during the test.

Table 9 Permissible Tolerances for Compressive Strength Test (ASTM C 39)

Test Age	Permissible Tolerance
24 h	± 0.5 h or 2.1 %
3 days	± 2 h or 2.8 %
7 days	± 6 h or 3.6 %
28 days	± 20 h or 3.0 %
90 days	± 2 days or 2.2 %

Calculation:

- Calculate the compressive strength of the specimen by dividing the maximum load carried by the specimen during the test by the average cross-sectional area and express the result to the nearest 10 psi.

5.2 FREEZE-THAW TEST

A number of different tests have been developed to measure the freezing resistance of concrete. These involve subjecting concrete to different freeze-thaw cycles and measuring the internal damage by examining weight loss, length change, decrease in strength, or dynamic modulus of elasticity. For this study, monitoring of the dynamic modulus of elasticity was chosen to evaluate the freeze-thaw resistance of concrete.

The test itself was conducted in accordance with the ASTM C666-97 Standard. This standard covers the determination of the resistance of concrete specimens to rapidly repeated cycles of freezing and thawing in the laboratory. For the purpose of this study, procedure B, describe in the standard, was employed. Freezing was done in air and thawing in water.

The freeze-and-thaw apparatus consists of a suitable chamber in which specimens may be subjected to a specified freezing-and-thawing cycle, together with refrigerating and heating equipment and controls to produce continuously, automatically, reproducible cycles within the specified temperature requirements (Figures 14 and 15).

The knowledge of water content in coarse aggregates at the time of testing for freeze-and-thaw resistance is important, however, it was not available. The test was performed in accordance with the ASTM Standard C666, and the samples were cured for 14 days prior to testing. They were submerged in water.

Apparatus

The apparatus is arranged such that:

- The specimen is completely surrounded by air during the freezing phase of cycle and by water during the thawing phase of the cycle.

- The temperature of heat-exchanging medium must be uniform within 6 F throughout the specimen cabinet when measured at any time, except during the transition between freezing and thawing.
- Each specimen is supported at the bottom of its container in such way that the temperature of heat-exchanging medium is not transmitted directly through bottom of the specimen.
- Temperature measuring equipment consists of thermometers, resistance thermometers, or thermocouples capable of measuring the temperature at various points within the specimen chamber and at the centers of control specimens to within 2 F (see Figure 14).

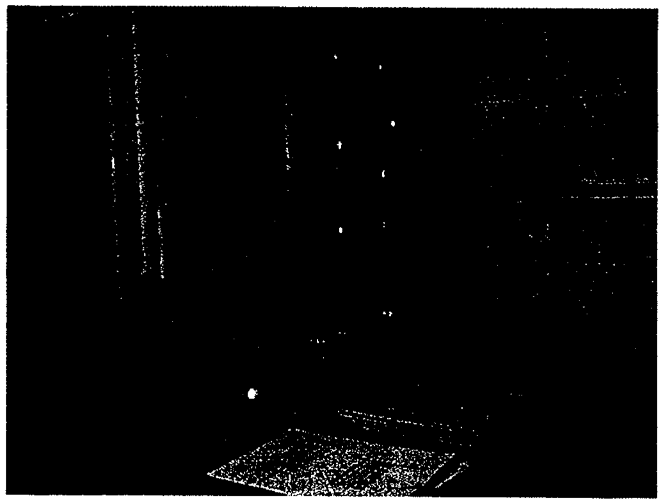

Figure 14 Control Panel of the Freeze and Thaw Machine at the University of Michigan

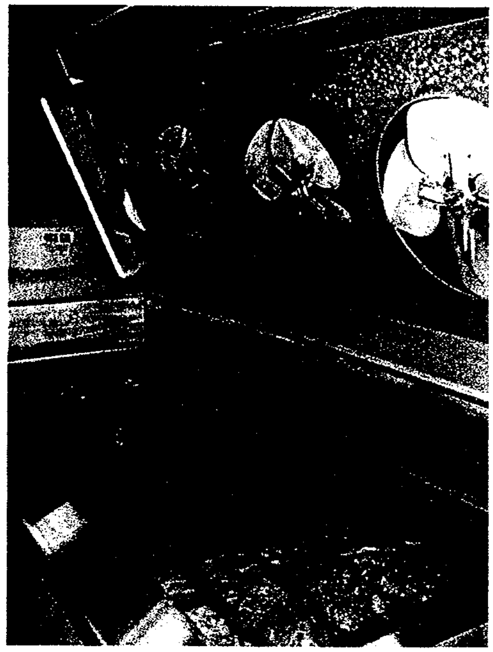

Figure 15 Specimens' Chamber of the Freeze and Thaw Machine at the University of Michigan

The nominal freezing-and-thawing cycle consists of alternately lowering the temperature of the specimens from 40 to 0°F and raising from 0 to 40°F in not less than 2 nor more than 5 hours. Not less than 20% of the time is used for thawing phase of the cycle. At the end of the cooling period the temperature at the center of the specimens must be 0°F ±3°F, and at the end of the heating period must be 40°F ±3°F, with no specimen reaching at any time a temperature lower than −3°F, and higher than 43°F.
The difference between the temperature at the center of the specimen and their surfaces cannot exceed at any time 50°F. The period of transition between the freezing-and-thawing phases of the cycle cannot exceed 10 minutes.

The specimens are prismatic with the following dimensions: L = 16 in., W = 4 in., H = 3 in. They correspond to the standard size admissible for this test. These specimens should be stored in lime water from time of removal from the molds until the time of test. All specimens to be compared should be of the same nominal dimensions.

The basic procedure described in the ASTM Standard C666-97 is as follows:

- Molded specimens are to be cured for 14 days prior to testing.
- Before testing bring the specimen to a temperature within −2°F and 4°F of the target thaw temperature and test for fundamental transverse frequency. Protect the specimens against loss of moisture between the time of removal from curing and the start of the test cycles. Start freezing-and-thawing test from the thawing phase of cycle. Specimens should be placed in the thawing water at the beginning. Tests should be done at intervals not exceeding 36 cycles of exposure to the freezing-and-thawing cycles. After each interval, specimens should be removed from apparatus and test for fundamental transverse frequency. Then return specimens to apparatus. The specimens should be ensured of completely thawing by holding

them at the end of the thaw cycle in the apparatus for a sufficient time for this condition to be attained throughout each specimen to be tested. The specimens should be protected against loss of moisture while out of apparatus.

- Tests should be continued until the specimen has been subjected to 300 cycles or until specimen's relative dynamic modulus of elasticity reaches 60% of the initial modulus. If specimen is removed because of failure, replace it for the remainder of the test by a dummy specimen. Interval should be repeated and each time fundamental transverse frequency should be tested. Special comments on any defects that develop should be taken.
- If the specimens deteriorate rapidly, they should be tested for fundamental transverse frequency and length change in interval not exceeding 10 cycles when initially subjected to freezing and thawing.

Dynamic Modulus of Elasticity

The Freeze and Thaw Cycles Test requires the measurement of the fundamental transverse frequency. In order to perform this measurement, an apparatus called PUNDIT PLUS, manufactured by CNS FARELL, was used. It is a low frequency ultrasonic test equipment for field or laboratory use, with data storage and computer output facilities. It can be used to evaluate the following properties:

- Fundamental transverse frequency
- Fundamental longitudinal frequency
- Dynamic modulus of elasticity
- Velocity
- Transit time
- Strength

The test was performed in accordance with ASTM Standard C597, Pulse Velocity Test. Above-mentioned test allows the determination of the dynamic modulus of elasticity; nevertheless, this test is not recommended by Practice C666.

For comparison purposes, however, the apparatus PUNDIT PLUS was used. Indeed, PUNDIT PLUS gives a direct reading of the dynamic modulus of elasticity. According to its manufacturer, CNS FARELL, the static modulus of elasticity can be estimated from the dynamic modulus of elasticity by an empirical relationship. This empirical relationship is shown in Table 10.

Table 10 Empirical Relationship Between Static and Dynamic Modulus of Elasticity and Pulse Velocity (From CNS FARELL)

Pulse velocity (km/s)	Modulus of elasticity	
	Dynamic (MN/m^2)	Static (MN/m^2)
3.6	24000	13000
3.8	26000	15000
4.0	29000	18000

4.2	32000	22000
4.4	36000	27000
4.6	42000	34000
4.8	49000	43000
5.0	58000	52000

From Table 10 a linear equation can be found to describe the relationship between dynamic and static modulus of elasticity. Figure 16 shows this relationship.

Calculation

- Relative Dynamic Modulus of Elasticity

The Freeze and Thaw Cycle Test requires the calculation of the Relative Dynamic Modulus of Elasticity. ASTM Standard C666-97 describes it as the following

$$P_c = \left(n_1^2 / n^2\right) \cdot 100$$

where:

P_c = relative dynamic modulus of elasticity, after c cycles of freezing and thawing, percent,

n = fundamental transverse frequency at 0 cycles of freezing and thawing,

n_1 = fundamental transverse frequency at c cycles of freezing and thawing,

- Durability Factor

The final purpose of the Freeze and Thaw Cycle Test is to determine the durability factor of the tested concrete. ASTM Standard C666-97 defines the durability factor as the following

$$DF = PN / M$$

where:

DF = durability factor for the test specimen,

P = relative dynamic modulus of elasticity at N cycles, %,

N = number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be determined, whichever is less,

M = specified number of cycles at which exposure is to be terminated.

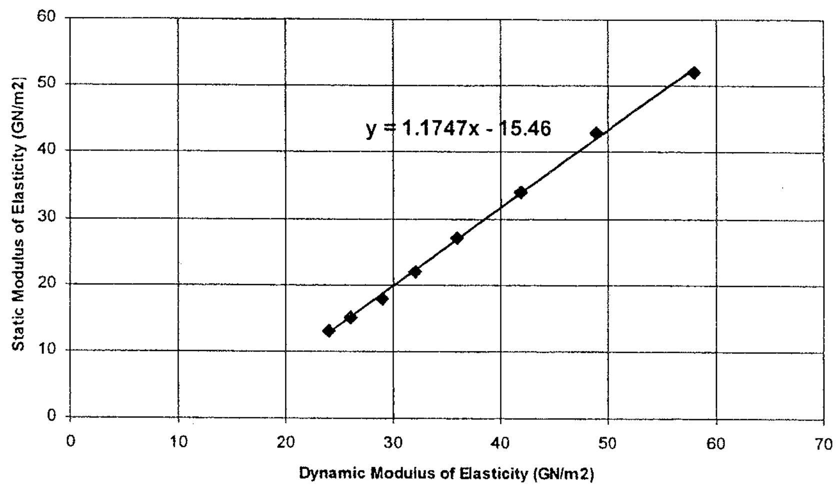

Figure 16 Empirical Relationship between Static and Dynamic Modulus of Elasticity (From CNS FARELL)

5.3 SPLITTING TENSILE STRENGTH TEST

Test description

The standard test method to determine the splitting tensile strength of concrete has been conducted in accordance to the ASTM Standard C 496. This standard describes the procedure and requirements for this test and it is summarized below.

This test method covers the determination of the splitting tensile strength of cylindrical concrete specimens, such as molded cylinders and drilled cores. This test method consists of applying a diametral compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs. This loading induces tensile stresses on the plane containing the applied load and relatively high compressive stresses in the area immediately around the applied load. Tensile failure occurs rather than compressive failure because the areas of load application are in a state of triaxial compression, thereby allowing them to withstand much higher compressive stresses than would be indicated by a uniaxial compressive strength test results.

Apparatus

The apparatus must conform to the specifications described in ASTM C 39 (see compressive strength of concrete cylinders). In addition, the necessary apparatus is composed of:

- Supplementary bearing bar if the diameter or largest dimension of the upper bearing face or the lower bearing block is less than the length of the cylinder to be tested. It shall have a width of at least 2 in. and a thickness not less than the distance from the edge of the spherical bearing block to the end of the cylinder.

- Bearing strips made of plywood of nominal 1/8 in. thick, free of imperfections, approximately 1 in. wide, and of length equal to, or slightly longer than that of the specimen. They are placed between the specimen and both the upper and lower supplementary bars seating on the bearing blocks of the testing machine. Bearing strips shall not be reused.

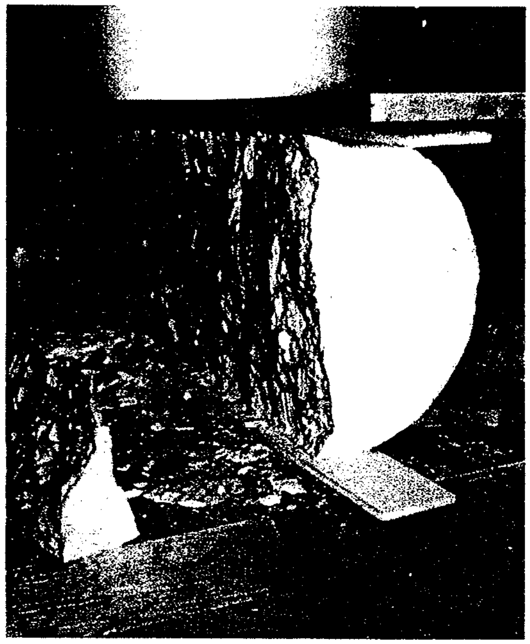

Figure 17 Splitting Tensile Strength Apparatus at the University of Michigan

Specimens:

- Test specimens shall conform to the size, molding, and curing requirements set forth in Practice C 192.
- Specimens tested at 28 days shall be in air-dry condition after 7 days moist curing followed by 21 days drying at 73 ± 3 °F and 50 ± 5 % relative humidity.

Procedure:

- Draw diametral lines on each end of the specimen using a suitable device that will ensure that they are in the same axial plane.
- Determine the diameter of the test specimen to the nearest 0.01 in. and the length the nearest 0.1 in.
- Place the specimen on the plywood strip and align so that the lines marked on the ends of the specimen are vertical and centered over the plywood strip. Place a second plywood strip lengthwise on the cylinder, centered on the lines marked on the ends of the cylinder.
- Position the supplementary bearing lengthwise on the top plywood strip directly beneath the center of thrust of the spherical bearing block.
- Apply the load continuously and without shock, at a constant rate within the range of 100 to 200 psi/min splitting tensile stress until failure of the specimen.

- Record the maximum applied load indicated by the testing machine at failure.

Calculations:
The splitting tensile strength of the specimen is calculated as follows:

$$T = \frac{2 \cdot P}{\pi \cdot l \cdot d}$$

where T = splitting tensile strength (psi), P = maximum applied load indicated by the testing machine (lbs), l = length (in.), d = diameter (in.).

5.4 FLEXURAL TEST

Test description

The standard test method to determine the flexural strength of concrete has been conducted in accordance to the ASTM Standard C 293. This standard describes the procedure and requirements for this test and it is summarized below.

This test method covers the determination of the flexural strength of concrete specimens by the use of a simple beam with center-point loading. It is used to determine the modulus of rupture of specimens prepared and cured in accordance with C 192. The strength determined will vary where there are differences in specimen size, preparation, moisture condition, or curing.

Apparatus

- The testing machine used for this test is hand operated. It has a pump that provides a continuous loading to failure in one stroke. The mechanism by which forces are applied to the specimen employs a load-applying block and two specimen support blocks. It shall ensure that all forces applied are perpendicular to the face of the specimen without eccentricity.
- Reactions shall be parallel to the direction of the applied load at all times during the test, and the ratio of the horizontal distance between the point load application and nearest reaction to the depth of the beam shall be 1.5 ± 2 %.
- The load-applying and support blocks shall not be more than 2½ in. high, measured from the center or the axis of pivot, and shall extend at least across the full width of the specimen.

Specimens:

- Test specimens shall conform to all requirements of C 192 applicable to beam and prism specimens and shall have a test span within 2 % of being three times its depth as tested. The sides of the specimen shall be at right angles with the top and bottom.

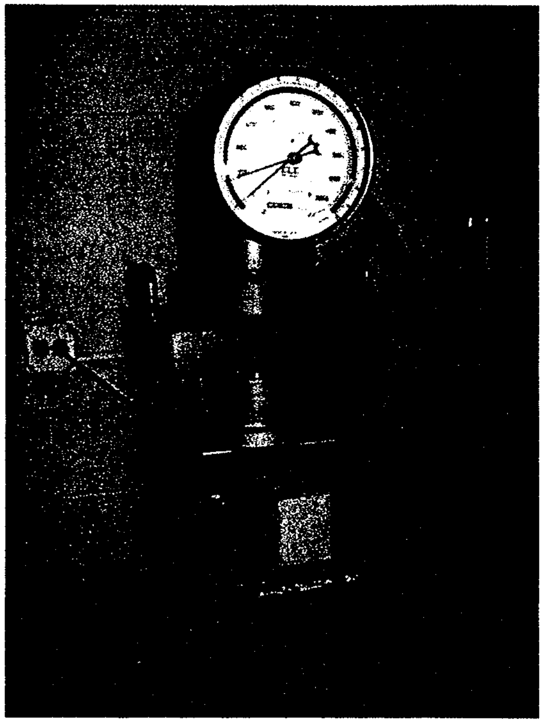

Figure 18 Flexural Strength Apparatus at the University of Michigan

<u>Procedure:</u>

- The test of moist-cured specimens shall be made as soon as practical after removal from moist storage. Surface drying of the specimen results in a reduction in the measured modulus of rupture.
- Turn the test specimen in its side with respect to its position as molded and center it on the support blocks. Center the loading system in relation to the applied force. Bring the load-applying block in contact with the surface of the specimen at the center and a load of between 3 and 6 % of the estimated ultimate load.
- Load the specimen continuously and without shock. The load shall be applied at a constant rate to the breaking point. Apply the load so that the extreme fiber increases at a rate between 125 and 175 psi/min. The loading rate is computed using the following:

$$r = \frac{2Sbd^2}{3L}$$

where r = loading rate (lbs/min), s = rate of increase in the extreme fiber (psi/min), b = average width of the specimen (in.), d = average depth of the specimen (in.), L = span length between supports (in.).

<u>Calculation:</u>

The modulus of rupture is calculated as follows:

$$R = \frac{3PL}{2bd^2}$$

where R = modulus of rupture (psi), P = maximum applied load indicated by the testing machine (lbs), b = average width of the specimen at fracture (in.), d = average depth of the specimen at fracture (in.), L = span length between supports (in.).

5.5 Modulus of Elasticity Test

Modulus of elasticity, also known as Young's modulus, is a measure of the stiffness of a given material. It is defined as the stress to strain ratio value.

For the purpose of this study, two methods to measure the modulus of elasticity were employed. Firstly, the standard test method was used, and later the pulse velocity test was carried out. The results from the two methods were compared and the conclusions drawn. Below is the description of methods used in this study.

5.5.1 Standard Test Method

The detailed description of this method can be found in ASTM C469.

Apparatus:

- Testing machine of any type that is capable of imposing a load at the rate 35±2 psi/s. The testing machine should be equipped with a spherical head and bearing block.
- Compressometer – bonded or unbonded sensing device shall be provided that is capable of measuring to the nearest 5 millionths the average deformation of two diametrically opposite gage lines, each parallel to the axis and each centered about midheight of the specimen.
    - Deformation can be measured by a dial gage used directly or with a lever multiplying system, by wire strain gage, or by linear variable differential transformer (LVDT).

Procedure:

- Place the specimen, with the strain-measuring equipment attached, in the testing machine. Special care should be given to make sure that the axis of the specimen is aligned with the center of thrust of the spherically-seated upper bearing block.
- Load the specimen at least twice, but no data should be recorded during the first loading. It is recommended to base calculations on the average of the results of the subsequent loadings.
- Record, without interruption of loading, the applied load and longitudinal strain when the longitudinal strain is 50 millionths and when the applied load is equal to 40% of the ultimate load.
- Calculate the modulus of elasticity.

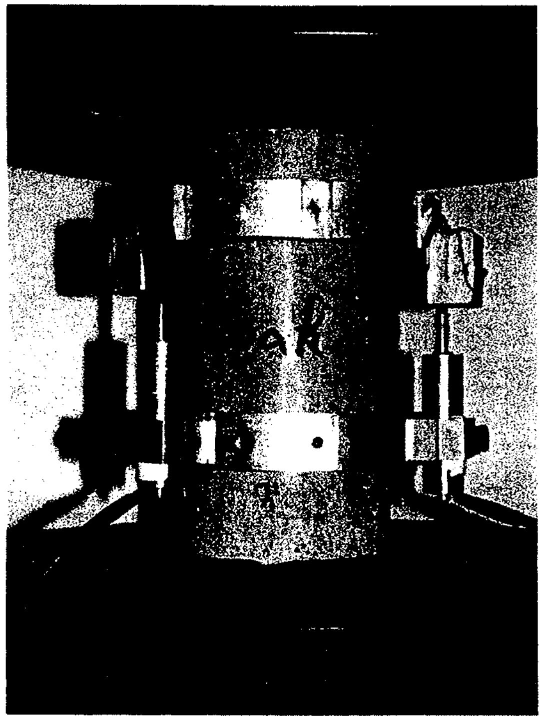

Figure 19 Test Set-up for Modulus of Elasticity

5.5.2 Pulse Velocity Test

The Standard test for rapid freezing and thawing of concrete requires the determination of the dynamic modulus of elasticity of the concrete specimens. Although Practice C 666 recommends the use of the forced resonance method or the impact resonance method, the dynamic modulus of elasticity can also be determined using the ultrasonic velocity method. This test is covered by Practice C 597. This standard describes the use of ultrasonic velocity equipment to determine the pulse velocity in the concrete and, therefore, determine the dynamic modulus of elasticity of the tested material.

Test description

The standard test method to determine the dynamic modulus of elasticity of concrete has been conducted in accordance to the ASTM Standard C 597. This standard describes the procedure and requirements for this test and it is summarized as follows.

This test method covers the determination of the propagation velocity of longitudinal stress wave pulses through concrete. During the test, pulses of longitudinal stress waves are generated by an electro-acoustical transducer that is held in contact with one surface of the concrete under test. After traversing through the concrete, the pulses are received and converted into electrical energy by a second transducer located at distance L from the transmitting transducer. The transit time T is measured electronically. The pulse velocity V is calculated by dividing L by T.

The pulse velocity, V, of longitudinal stress waves in a concrete mass is related to its elastic properties and density according to the following relationship:

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}}$$

where E = dynamic modulus of elasticity; μ = dynamic Poisson's ratio; ρ = density.

The pulse velocity can therefore be used to determine the dynamic modulus of elasticity using the following relationship:

$$E = \frac{\rho V^2(1+\mu)(1-2\mu)}{(1-\mu)}$$

The dynamic Poisson's ratio can also be determined using the ultrasonic velocity method. It is not defined in the ASTM standard C 597. However, it can still be derived as follows:

$$\mu = \frac{V_c^2 - 2V_t^2}{2(V_c^2 - 2V_t^2)}$$

where V_c = velocity of the compression (P) wave; V_t = velocity of the transverse (S) wave.
Apparatus:

- The testing apparatus, shown in Figure 20, consists of a pulse generator, a pair of transducers (transmitter and receiver), an amplifier, a time measuring circuit, a time display unit, and connecting cables. The apparatuses used at the University are the PUNDIT PLUS by CNS FARELL and the V METER by JAMES INSTRUMENTS INC.

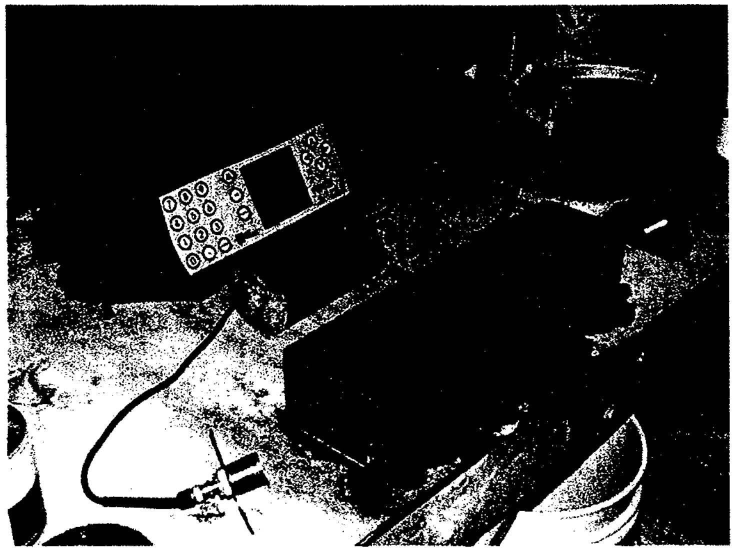

Figure 20 Ultrasonic Velocity Test Apparatus at the University of Michigan

Procedure:

- Calibrate the testing apparatus.
- Apply an appropriate coupling agent (oil, petroleum jelly, grease, moldable rubber or other viscous materials) to the transducers faces or the test surface, or both. Press the faces of the transducers firmly against the surfaces of the concrete until a stable transit time is displayed, and measure the transit time. Determine the straight-line distance between centers of transducer faces.

Calculation:

- The calculations are done in accordance with the relationship introduced previously and are done automatically by the apparatuses used at the University of Michigan.

6. Development of a Recipe for the SCC Mix

The development of a recipe for the SCC was conducted by a trial and error approach. A number of parameters, such as superplasticizer quantity and type, fly ash quantity, water content, water to cement ratio, gravel size, sequence of mixing were taken into account.

It was found that all these parameters may greatly influence the properties of freshly mixed concrete as well as the properties of hardened concrete.

Below is the table summarizing the recommended dosage of ingredients for SCC that can be found in the literature.

Table 11 Recommended Dosages of Ingredients for the Self Consolidating Concrete

Components	Recommendations
Cement	21.8 – 28.1 lb/ft^3
Powder, cement, mineral fillers, finest fraction of aggregates < 0.125 mm	24.9 – 37.4 lb/ft^3
Sand fractions (0.125 - 4 mm)	> 40 % of volume of cement mortar > 50 % of volume of cement paste
Coarse aggregate > 4 mm, max 16-20 mm	28 – 35 % of volume of concrete
Water	4.0 – 5.7 lb/ft^3
Mineral fillers, fly ash, granulated slag, quartz powder or calcareous powder and micro-silica	30 – 40 % mass of cement, even up to 60 %
Superplasticizers	According to producer recommendations, usually in a range of 0.2 – 3.0 % mass of cement
Water-cement ratio	0.2 - 0.6 with special recommendation < 0.45
Water- powder ratio	Volumetric ratio 0.8 – 1.1

By trial and error, the Project Team obtained four recipes that ensure acceptable results with the details shown in Table 12. The mixtures M I and M II were tested first. For mixture M I, gravel met the sieve testing chart provided by producer. For mixture M II, the size of gravel was restricted up to 0.5 in. (12.5 mm), with the same ratio of the remaining ingredients. For mixture M III, the total amount of binder was reduced to 32.4 lb/ft^3 (520 kg/m^3), and for mixture M IV, the cement to fly-ash ratio was changed. In all cases superplasticizer GLENIUM 3200 HES provided by Master Builders was used.

Table 12 Four Mixes for SCC Obtained by the Project Team

Component	MIX I		MIX II		MIX III		MIX IV	
	SI Units	US Units	SI Units	US Units	SI Units	US Units	SI Units	US Units
Cement	360 kg/m³	22.4 lb/ft³	360 kg/m³	22.4 lb/ft³	360 kg/m³	22.4 lb/ft³	400 kg/m³	24.9 lb/ft³
Fly Ash	200 kg/m³	12.5 lb/ft³	200 kg/m³	12.5 lb/ft³	160 kg/m³	10.0 lb/ft³	160 kg/m³	10.0 lb/ft³
Water	160 l/m³	9.9 lb/ft³	160 l/m³	9.9 lb/ft³	160 l/m³	9.9 lb/ft³	160 l/m³	9.9 lb/ft³
Sand	755 kg/m³	47.0 lb/ft³	830 kg/m³	51.7 lb/ft³	803 kg/m³	50.1 lb/ft³	769 kg/m³	47.9 lb/ft³
Gravel	924 kg/m³	57.6 lb/ft³	850 kg/m³	53.0 lb/ft³	924 kg/m³	57.6 lb/ft³	924 kg/m³	57.6 lb/ft³
Superplasticizer	5 l/m³	0.31 lb/ft³	5.7 l/m³	0.31 lb/ft³	5 l/m³	0.31 lb/ft³	5 l/m³	0.31 lb/ft³
W/C	0.44		0.44		0.44		0.4	
W/CM	0.29		0.29		0.29		0.29	

The amount of the superplasticizer and water was determined so that an appropriate slump flow was obtained. It was found that even very small quantity of water added to the mix was capable of increasing the slump flow of concrete, often causing segregation. Therefore, special care should be given to the dosage of water as well as superplasticizer.

6.1 PRELIMINARY COMPRESSIVE STRENGTH TESTS

In order to establish some preliminary properties of a new mix, ten samples from the first series of mixing were cast. They were prepared and cured in accordance with the ASTM Standard, and after 28 days their compressive strength was determined. The results are shown in Table 13.

Table 13 Compressive Strength Test Results

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Compressive Strength (mean)(psi)
10	0.07	680	9220

These samples were cast using different recipes. Therefore, further tests were needed to establish meaningful conclusions.

6.2 SELECTION OF A MIX FOR FURTHER TESTS

The selection of the preferable mix was based on fresh concrete property requirements. MIX I, III, and IV exhibited unsatisfactory performance (V-funnel, L-Box, and slump flow tests results did not match the requirements). Therefore, based on results obtained during preliminary tests, the second mix (referred to as MIX II in the previous section) was chosen. Nonetheless, some adjustments had to be done because of the dryness of materials. The gravel and sand were stored in a heated room and they had dried up since the first series of tests.

Table 14 summarizes the first mixing series. Altogether, more than 140 specimens were prepared (Figure 21). This represents a total gross weight of more than 3 tons of raw materials.

Table 14 Summary of First Mixing Series

Batch no.	Spread (cm)	T_{50} (sec)	V-Funnel flow time (sec)	L-Box (h_1/h_2)	Observations
1	55	8	12	0.80	Wet
2	73	2.7	7	0.93	Good mix
3	85	2	4.5	0.99	Some segregation
4	80	2.5	5	0.98	Good mix
5	80	3	7	0.95	Very good mix
6	83	2.5	8	0.97	Good mix
7	83	2.5	6.2	0.97	Good mix
8	83	2.5	6.2	0.97	Good mix
9	83	2.5	6.2	0.97	Good mix
10	83	2.5	6.2	0.97	Good mix

Figure 21 Test Specimens

6.3 EFFECT OF MIXING SEQUENCE

The sequence of mixing is very important and it requires a good understanding of the mix behavior. It has been observed that addition of the superplasticizer too early or in too big quantities can greatly influence the properties of the fresh concrete. Therefore, the following mixing procedure has been established to guarantee reliable results:

- Insert simultaneously coarse and fine aggregate, fly ash, and cement, and mix dry for approximately 3 minutes.
- Add water and 1/3 of the superplasticizer and mix for 3 minutes.
- Add the remaining water and superplasticizer to the mix and mix for 3 minutes
- Stop the mixer for 1 minute.
- Restart the mixer for one 1 minute.
- The concrete is ready for pouring and tests (Slump flow, V-funnel, and L-box).

To simulate a delivery time to a construction site, the concrete mix was resting without agitation for 30 minutes. During this time, the superplasticizer effect was reduced and some adjustments had to be done. It was observed that most of the time, addition of some superplasticizer could revive the SCC properties, but some water also had to be added.

6.4 EFFECT OF DIFFERENT SUPERPLASTICIZERS

To study the effect of different superplasticizers, the Project Team at the University of Michigan performed all aforementioned tests for additional two types of superplasticizer: VISCOCRETE 5000 provided by Sika, and ALLEGRO X-122 provided by Axim.

During these tests the quantity of cement, fly ash, aggregates, and water was kept at the same level while different superplasticizers were used.

When a new superplasticizer was used, it was assumed that its effect on workability of a fresh mix is similar to the effect of the previously used superplasticizer. Nevertheless, it was found that in order to meet all requirements regarding workability (filling ability, passing ability, and segregation resistance) some adjustments had to be made. Again, the new recipes were developed through trial and error approach.

Table 15 shows final mix proportioning for all three superplasticizers used during this study. It is important to note that these three different mixes were developed such that their fresh-mix properties were similar (slump flow, V-funnel, L-Box).

In order to ensure the proper workability parameters, all listed mixes were subjected to the following tests:

- Slump-flow by Abrams cone
- T_{50cm} slump-flow
- V-funnel
- V-funnel at $T_{5minutes}$
- L-Box

- Air content
- Unit weight

Table 15 Summary of Mix Proportioning of SCC for Different Superplasticizers

	Superplasticizer I		Superplasticizer II		Superplasticizer III	
Name of Superplasticizer	GLENIUM 3200 HES		VISCOCRETE 5000		ALLEGRO X-122	
Provider of the Superplasticizer	Master Builders		Sika		AXIM	
Unit	SI units	US units	SI units	US units	SI units	US units
Cement	360 kg/m^3	22.4 lb/ft^3	360 kg/m3	22.4 lb/ft^3	360 kg/m^3	22.4 lb/ft^3
Fly Ash	200 kg/m^3	12.5 lb/ft^3	200 kg/m^3	12.5 lb/ft^3	200 kg/m^3	12.5 lb/ft^3
Water	160 l/m^3	9.9 lb/ft^3	160 l/m3	9.9 lb/ft^3	160 l/m^3	9.9 lb/ft^3
Sand	830 kg/m^3	51.7 lb/ft^3	830 kg/m^3	51.7 lb/ft^3	830 kg/m^3	51.7 lb/ft^3
Gravel	850 kg/m^3	53.0 lb/ft^3	850 kg/m^3	53.0 lb/ft^3	850 kg/m^3	53.0 lb/ft^3
Superplasticizer	5.0 l/m^3	0.31 lb/ft^3	5.7 l/m^3	0.35 lb/ft^3	4.8 l/m^3	0.31 lb/ft^3
W/C	0.44	0.44	0.44	0.44	0.44	0.44
W/CM	0.29	0.29	0.29	0.29	0.29	0.29

As many as 14 batches were cast for each of the superplasticizer. The results (mean values) from these tests are summarized in Table 16.

Table 16 Summary of Fresh Concrete Properties for Different Superplasticizers

Test Description	Units	Superplasticizer Type		
		GLENIUM 3200 HES	VISCOCRETE 5000	ALLEGRO X-122
Slump Flow	[sec]	3.7	3.5	4.3
Final Slump Diameter	[cm]	76	78	72
V-Funnel	[sec]	8.5	8	9.8
V-Funnel + 5 minutes	[sec]	9.6	8.9	10.8
L-Box	[h_1/h_2]	0.95	0.97	0.93
Air-content	[%]	2.5	2.7	2.5
Unit Weight	[kg/m^3]	2425	2427	2430

7 DETAILED RESULTS AND ANALYSIS

In this section, results from all tests carried out during this study are gathered and summarized in forms of figures and tables. It should be noted that not all tests were performed for all types of superplasticizers. The use of particular superplasticizer is cited in a caption of a figure or table.

7.1 COMPRESSIVE STRENGTH TEST

As many as 60 samples were cast for both superplasticizers in order to build up the strength development curves. It was found that in case of superplasticizer provided by Sika (VISCOCRETE 5000), concrete gained slightly more strength during the first 24 hours after casting compare to concrete made with superplasticizer provided by AXIM (ALLEGRO X-122). However, the compressive strength after 90 days was greater in case of concrete made with superplasticizer provided by Sika. Given the fact that all remaining ingredients (fly ash, sand, gravel, water, cement content) were kept at the same level, it can be concluded that superplasticizer provided by Sika provides a faster strength development, and therefore should be used whenever a fast increase in strength is needed during the first few days (hours).

Figure 22 and Table 17 show the strength development curve and the summary of compressive strength of SCC made with superplasticizer VISCOCRETE 5000.

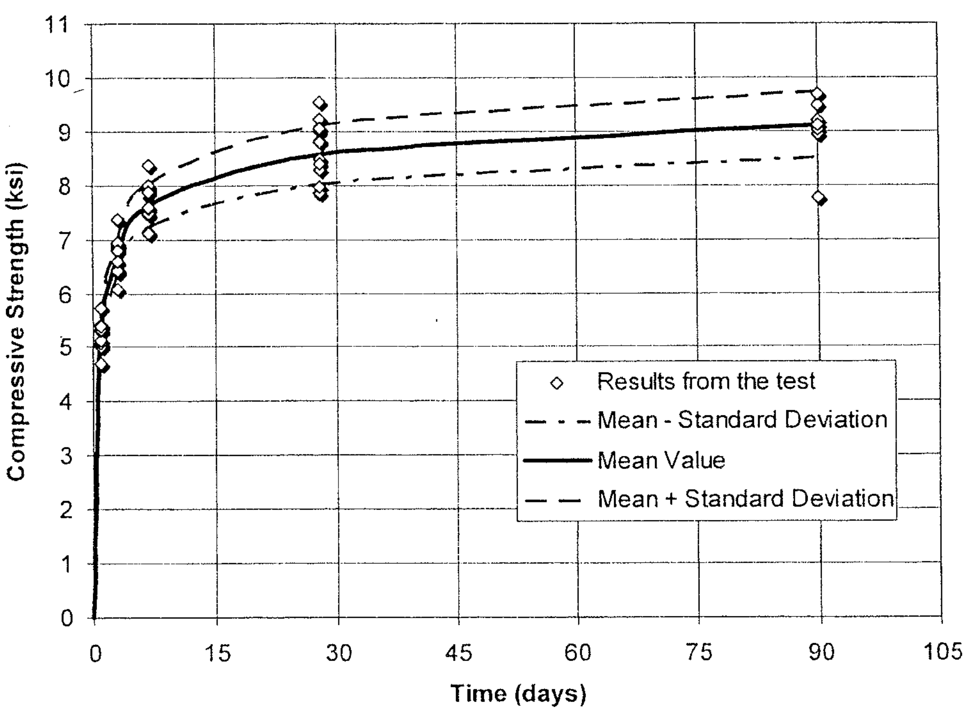

Figure 22 Strength Development Curve for SCC, Superplasticizer VISCOCRETE 5000

Table 17 Summary of Compressive Strength of SCC, Superplasticizer VISCOCRETE 5000

Test after n days	1	3	7	28	90
Mean Value (ksi)	5.26	6.66	7.62	8.57	9.12
Standard Deviation (ksi)	0.30	0.33	0.41	0.55	0.62
Coefficient of Variation (%)	5.7	4.9	5.3	6.4	6.8
Ratio of the strength after n days to the strength after 28 days (%)	61	78	89	**100**	106

As can be read from the above table, the compressive strength of concrete 24 hours after casting was equal to about 60% of the 28-day strength. It is a rather high value. Nevertheless, similar results were found by other researchers and in other studies.

Figure 23 and Table 18 show the strength development curve and the summary of compressive strength of SCC for the concrete made with superplasticizer ALLEGRO X-122.

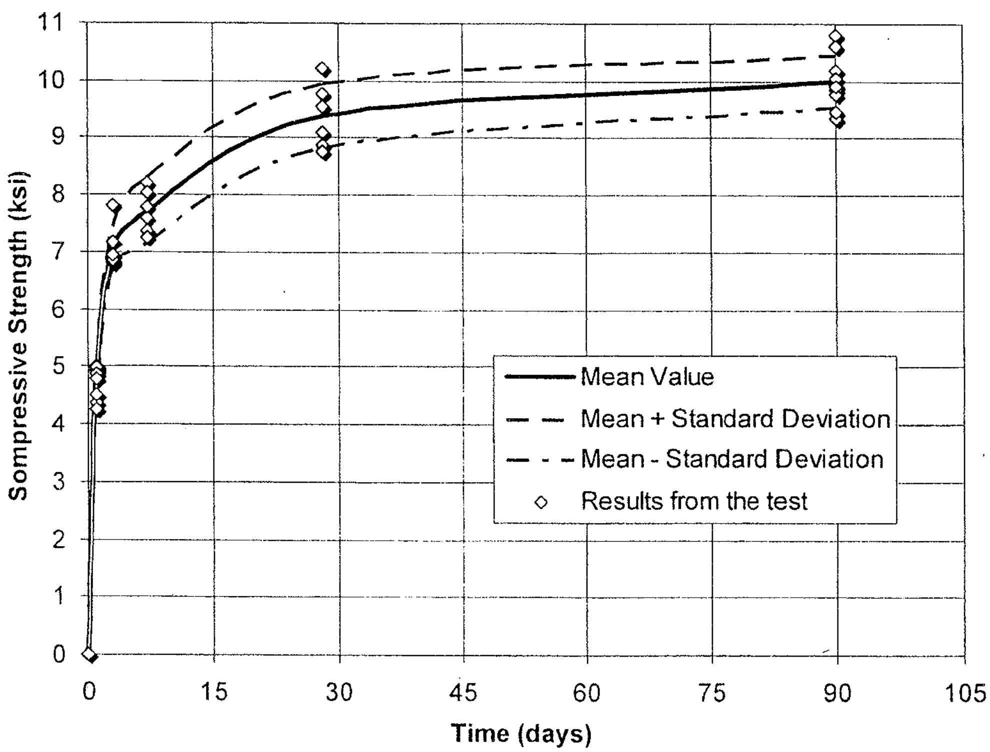

Figure 23 Strength Development Curve for SCC, Superplasticizer ALLEGRO X-122

Table 18 Summary of Compressive Strength of SCC, Superplasticizer ALLEGRO X-122

Test after n days	1	3	7	28	90
Mean Value (ksi)	4.71	7.04	7.71	9.38	9.99
Standard Deviation (ksi)	0.29	0.37	0.57	0.56	0.45
Coefficient of Variation (%)	6.2	5.2	7.4	6	4.5
Ratio of the strength after n days to the strength after 28 days (%)	50	75	82	100	106

Again, a rather fast increase in strength during the first 24 hours can also be noticed in case of this superplasticizer, ALLEGRO X-122. It is to some extent lower than it was previously. However, the trend of strength development is similar to the previous case, and small discrepancies may be attributed to slightly different ambient temperature during curing, effects of relative humidity (samples were cast in both winter and summer), and human errors during the test itself.

To sum up, it should be noted that it is commonly agreed that when admixtures, such as superplasticizers, are used to lower the water content, increase in compressive strength can be anticipated. Some researchers refer to this phenomenon as increasing the efficiency of the cement. As a result, Type I cement may behave as super-high early-strength cement exceeding even the strength gain of Type III cement.

7.2 FREEZE-THAW TEST

As was introduced in section 5.2, the dynamic modulus of elasticity was chosen to evaluate the freeze-thaw resistance of concrete. Consequently, the durability factor was calculated. The test itself was performed as described in section 5.2. Although the Standard requires conducting the test for 300 cycles or until the dynamic modulus has reached 60% of its initial value, whichever occurs first, for the first two superplasticizers (GLENIUM 3200 HES, and VISCOCRETE 5000), the test was carried out up to 644 cycles. However, for the third superplasticizer (ALLEGRO X-122), only 396 cycles were conducted.

Figures 24 and 25 show the dynamic modulus of elasticity and the durability factor, respectively, as a function of number of cycles for concrete made with superplasticizer GLENIUM 3200 HES.

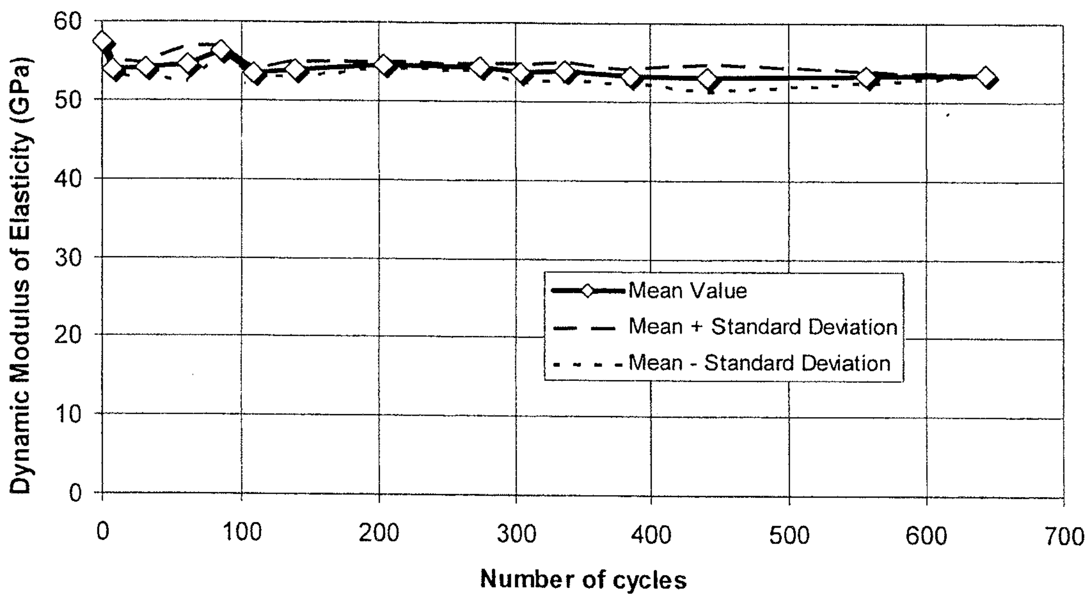

Figure 24 Dynamic Modulus of Elasticity as a Function of Number of Cycles, Superplasticizer – GLENIUM 3200 HES

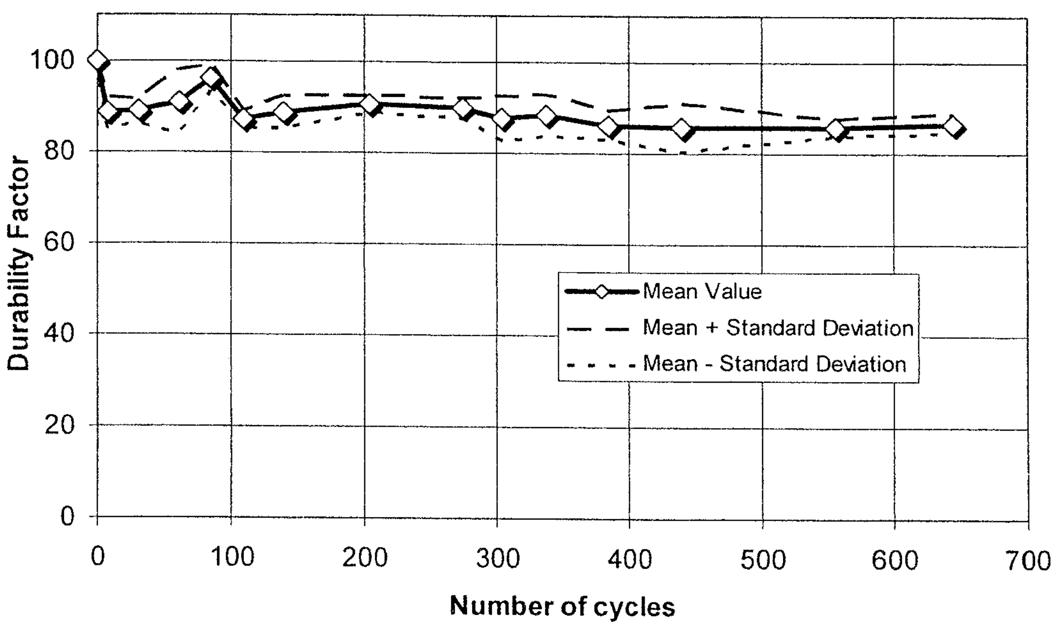

Figure 25 Durability Factor as a Function of Number of Cycles, Superplasticizer – GLENIUM 3200 HES

Figures 26 and 27 show the dynamic modulus of elasticity and the durability factor, respectively, as a function of number of cycles for concrete made with superplasticizer VISCOCRETE 5000.

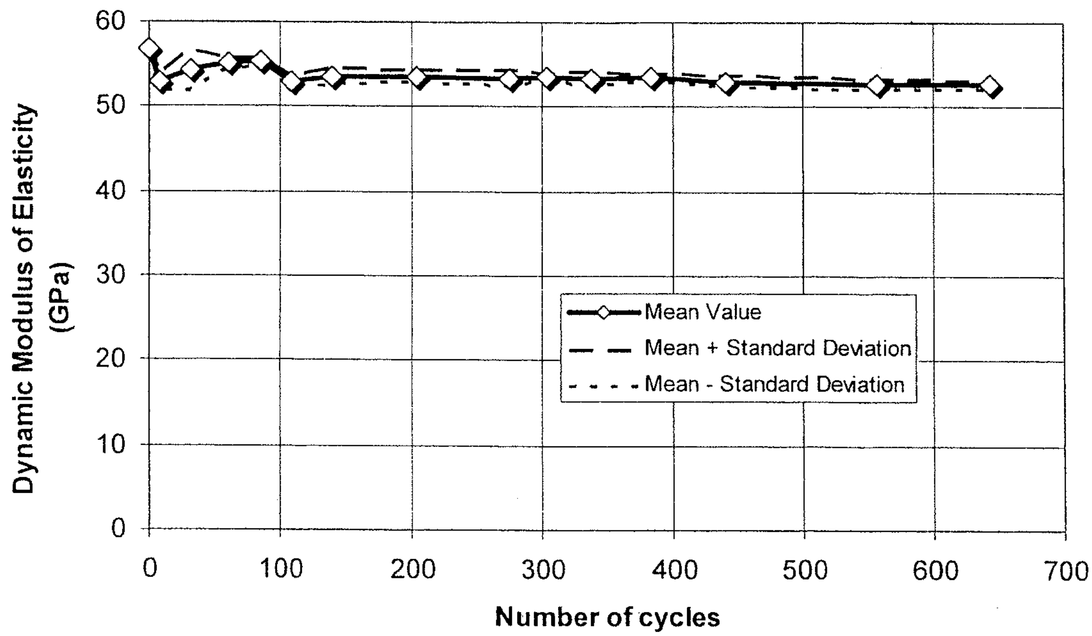

Figure 26 Dynamic Modulus of Elasticity as a Function of Number of Cycles, Superplasticizer – VISCOCRETE 5000

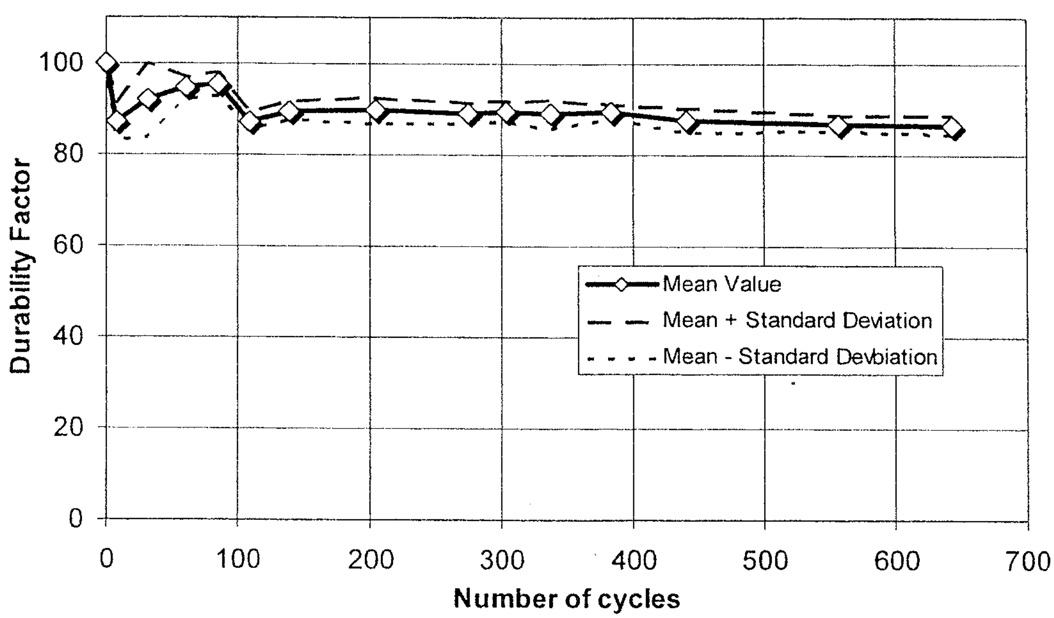

Figure 27 Durability Factor as a Function of Number of Cycles, Superplasticizer – VISCOCRETE 5000

Figures 28 and 29 show the dynamic modulus of elasticity and the durability factor, respectively, as a function of number of cycles for concrete made with superplasticizer ALLEGRO X-122.

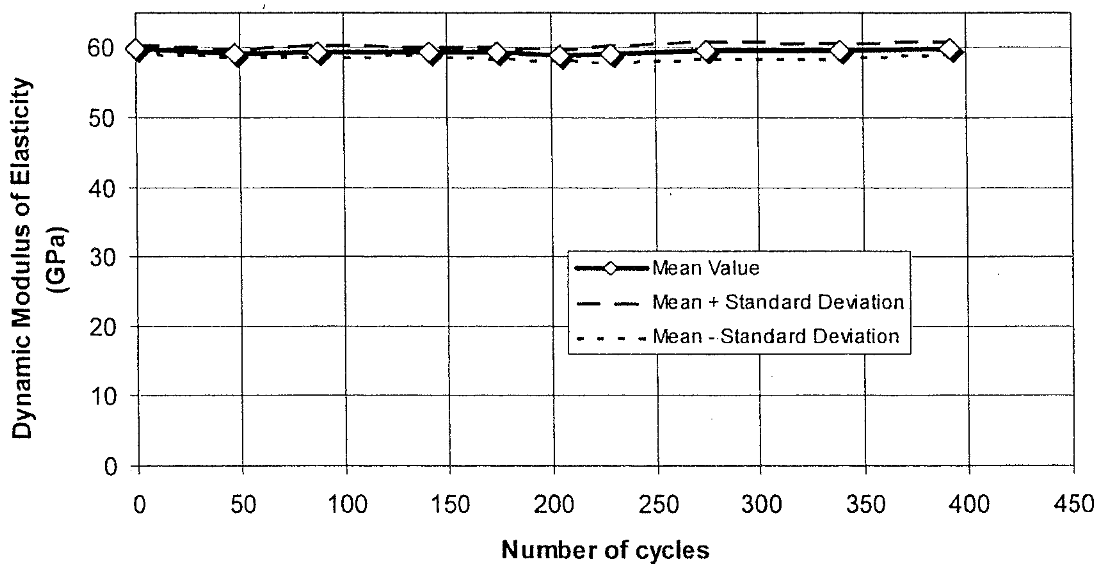

Figure 28 Dynamic Modulus of Elasticity as a Function of Number of Cycles, Superplasticizer – ALLEGRO X-122

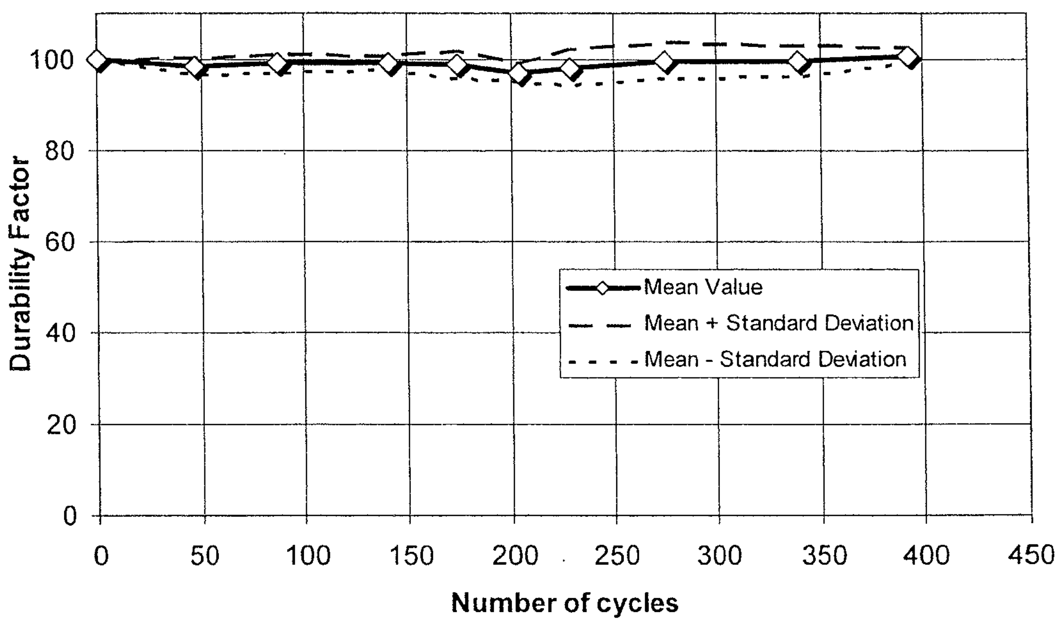

Figure 29 Durability Factor as a Function of Number of Cycles, Superplasticizer – ALLEGRO X-122

To sum up, it should be noted that the dynamic modulus of elasticity, and what follows durability factor, for the first two cases (concretes made with superplasticizers GLENIUM 3200 HES and VISCOCRETE 5000) was slightly lower comparing to a case when superplasticizer ALLEGRO X-122 was used. Indeed, as shown in section 7.1, the compressive strength of concrete made with superplasticizer ALLEGRO X-122 was slightly greater than the strength of concrete made with the two remaining superplasticizers. Also, for the first two superplasticizers, a small fluctuation of dynamic modulus of elasticity can be observed for the first 100 cycles. Nevertheless, since these measurements were taken at the beginning of the study, it is believed that all these discrepancies were caused by human errors during the measurements.

7.3 SPLITTING TEST

Since there is no standard test adopted by ASTM to provide a direct measurement of the tensile strength of concrete, the splitting test was carried out instead. The test was performed according to section 5.3 and it followed the ASTM procedure. Nevertheless, only concrete made with superplasticizer provided by AXIM was considered. The results from the test are summarized in Table 19.

Table 19 Splitting Test Results

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Splitting test after 28 days (mean)(psi)
14	0.14	105	739

7.4 FLEXURAL TEST

The theoretical maximum tensile strength (modulus of rapture) calculated using the flexural test tends to overestimate the true tensile strength as the formula to calculate tensile strength is based on linear distribution of stresses across the cross section of the beam. However, the test is considered as a very useful tool to determine the tensile strength given that concrete members tend to be loaded in bending rather than in axial tension. Thus, the results obtained during the test may be considered as a better representation of the concrete property that is of interest. The results from the flexural test are summarized in Table 20. It should be noted here that only concrete made with superplasticizer provided by AXIM was considered.

Table 20 Flexural Test Results

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Flexural test after 28 days (mean)(psi)
14	0.05	44	919

7.5 MODULUS OF ELASTICITY TEST

The test was carried out as described in section 5.5. Three linear variable displacement transducers (LVDTs) were attached to the rings (see Picture 8). The table below shows the final results of this test. The test was conducted 28 days after casting. It should be noted here that only concrete made with superplasticizer provided by AXIM was subjected to the standard test method.

Table 21 Modulus of Elasticity Test Results, Standard Test Method

Number of Samples	Coefficient of Variation	Standard deviation (ksi)	Modulus of Elasticity (mean)(ksi)
10	0.05	256	5570

In addition to a standard test method, a pulse velocity test was carried out to determine the dynamic modulus of elasticity of concrete. The test was carried out in accordance with section 5.5. Samples cast with all three types of superplasticizers were taken into account. Table 22 shows the results of this test.

Table 22 Dynamic Modulus of Elasticity Test Results, Pulse Velocity Test

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Dynamic Modulus of Elasticity (mean)(ksi)
26	0.06	460	7900

Referring to Table 10, the static modulus of elasticity may be calculated based on the dynamic modulus of elasticity. In that case, the corresponding static modulus of elasticity would be equal to 7020 ksi, which is significantly greater than corresponding value found during the standard test method. As pointed out in section 5.5.2, the pulse velocity method to determine the dynamic modulus of elasticity is not recommended by Practice C 666. Instead, the forced resonance method or the impact resonance method should be used. Therefore, the result obtained here should not be considered accurate, and they should rather serve for comparison purposes.

7.6 SHRINKAGE AND CREEP

In general, the effect of shrinkage and creep on performance of the self-consolidating concrete is similar to that of high-performance concrete. However this has not been investigated in this study and the discussion is based on the available literature and other researchers' findings.

Volume changes accompany the loss of moisture in either fresh or hardened concrete. However, the term drying shrinkage is generally reserved for hardened concrete, while plastic shrinkage is used for fresh concrete, since its response to loss of moisture is quite different. Carbonation shrinkage, which occurs when hydrated cement reacts with atmospheric carbon dioxide, can be regarded as a special case of drying shrinkage. Autogenous shrinkage, which occurs when a concrete can self-desiccate during hydration, is also a special case of drying shrinkage. Shrinkage is a paste property; in concrete the aggregate has a restraining influence on the volume changes that will take place within the paste.

Plastic shrinkage occurs when the fresh concrete loses water. If not prevented, this loss can caused cracking. The most common situation is surface cracking due to evaporation of water from the surface, but suction of water from the concrete by sub-base or by formwork materials can cause cracking or can aggravate the effects of surface evaporation. Plastic shrinkage is most of the time prevented by the curing method. It is admitted that the most effective method of control is to ensure that the concrete surface is kept wet until the surface has been finished and routine curing begun. Temporary wet coverings, waterproof sheeting, or a fog spray are appropriate methods.

Autogenous shrinkage is a phenomenon that occurs mostly in case of low w/c ratio. It is described as the drying out of concrete during hydration. Indeed, if no additional water beyond that added during mixing is provided, then it is possible that concrete will begin to dry out even if no moisture is lost to the surroundings, simply by internal consumption of water during the hydration phase. The phenomenon is known as self-desiccation and leads to autogenous shrinkage. This cause of shrinkage is relatively rare and, therefore, will not be further discussed.

The drying shrinkage of hardened concrete is a much more important phenomenon than the previously introduced forms of shrinkage. Moisture loss is again the underlying cause. The drying shrinkage has been thoroughly investigated for conventional concrete and to some degree also for the self-consolidating concrete.

It is generally admitted that the drying shrinkage is mostly affected by the aggregates. The drying shrinkage of concrete can be than that of pure paste because of the restraining influence of the aggregates. Aggregates are usually dimensionally stable under changing moisture conditions. The amount of restraint provided by aggregate depends on the amount of aggregate in concrete, its stiffness, and the maximum size of the coarse aggregate. It is generally accepted that to mitigate high drying shrinkage, a large amount of coarse aggregate and a low water content are needed.

Reports and papers by other researchers indicate that the self-consolidating concrete is affected in the same way as normally vibrated concrete by the water cement ratio and the specimen curing procedure. In the majority of publications, it is admitted that shrinkage can be a concern at the early age of concrete (Bouzabaa 2001, Holschemaker 2002). It was shown that the drying shrinkage of SCC is 10 to 50% higher than that of conventional concrete (Holschemaker 2002). There is a substantially steeper rise of the deformations particularly for young concretes aged up to 28 days, which decreases with an increasing age. On the other side, Persson (2001) compared normal concrete and self-consolidating concrete and concluded that the elastic modulus, creep and shrinkage of SCC did not differ significantly from the corresponding properties of normal concrete. Ravindrarajah (2003) observed that the drying shrinkage increases gradually with a decreasing rate. He also states that the drying shrinkage seems to decrease with a bigger dosage of superplasticizers.

In summary, on the long run, shrinkage is not more important for SCC than for normal concrete. However, it seems that an early age drying shrinkage requires more research, and so does long term shrinkage, that appears to be lower than that of the normal concrete

8 COMPARISON OF CONVENTIONAL CONCRETE AND SCC

For comparison purposes, the developed self-consolidating concrete was compared to a conventional concrete, designed as for a typical reinforced concrete bridge slabs by the Michigan DOT. Samples of the conventional concrete were made of the same material constituents (coarse and fine aggregates, as well as cement) as in case of self-consolidating concrete. The appropriate mix design was done in accordance with the ACI 211.1 mix design procedure. ACI 211.1 guaranties an economic, workable mix which leads to satisfactory strength and durability of the designed concrete.

ACI 211.1 requires the specifications of several assumptions. These assumptions regard the job parameters, and the materials parameters. For this specific project, the assumptions are listed below:

- Structure: concrete slab lightly reinforced (reinforcement spacing 3 in.)
- Type of consolidation: vibration.
- Dimensions of the structural member: 12 in.
- Minimum spacing between the rebars: 3 in.
- Required compressive strength: 4000 psi.
- Exposure conditions: severe freeze-thaw exposure
- Desired slump: 2 in.

From a material standpoint, the following properties were taken into account:

- Cement Type I: specific gravity = 3.15
- Fine aggregate:
    - Bulk specific gravity = 2.65
    - Absorption capacity = 1.2 %
    - Surface moisture = 0 %
    - Fineness modulus = 2.60
- Coarse aggregates:
    - Nominal maximum size = 19 mm
    - Bulk specific gravity = 2.70
    - Absorption capacity = 1 %
    - Surface moisture = 0 %
    - Dry-rodded unit weight = 1600 kg/m^3

The design procedure was followed and the resulting mix is summarized in Table 23.

Also, as shown in Table 23, the designed concrete contains air entraining admixture. Indeed, the exposure conditions requires an air-entrained concrete (6 %) so that it is able to resist the severe freeze and thaw cycle that Michigan can offer. The coarse and fine aggregates are in the oven-dry state and the water has been adjusted to take into account their absorptions.

Table 23 Proportioning of the Conventional Concrete Designed in Accordance with ACI 211.1

Materials	Quantities	
	US Units	SI Units
Cement	21.2 lb/ft^3	340 kg/m^3
Coarse Aggregates	63.9 lb/ft^3	1024 kg/m^3
Fine Aggregates	46.5 lb/ft^3	745 kg/m^3
Water	11.5 lb/ft^3	184 kg/m^3
Air Entraining Admixture	0.0106 lb/ft^3	0.17 kg/m^3
Total	143.1 lb/ft^3	2293 kg/m^3

Figure 30 shows the graphical representation of constituents of the designed conventional concrete. It also shows the comparison between SCC and the conventional concrete. It is important to note that the SCC mix has higher content of paste and mortar compared to the conventional concrete. This phenomenon is very characteristic for SCC mixes.

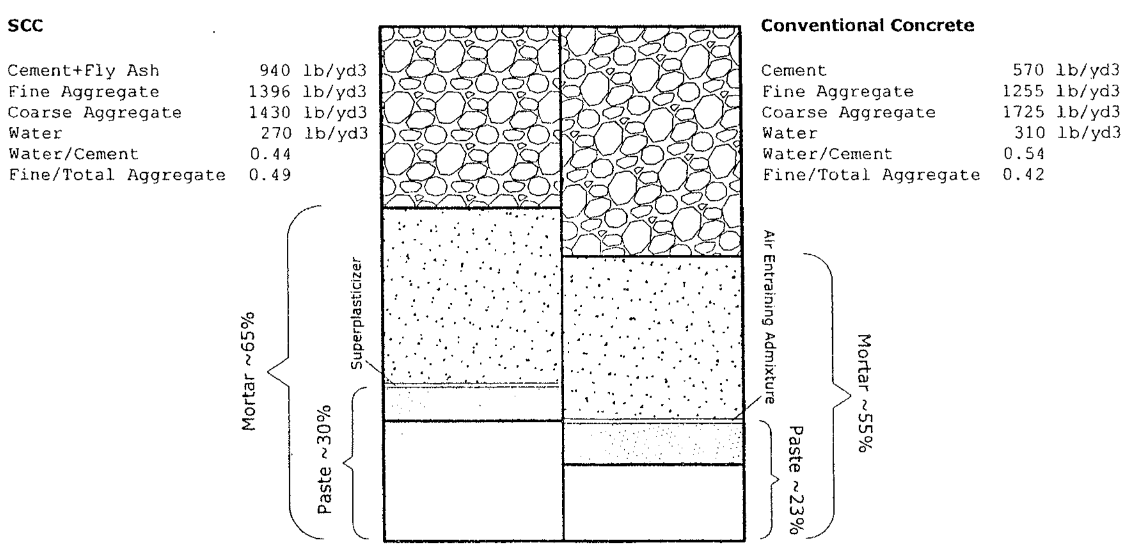

Figure 30 Comparison of Constituents of SCC and Conventional Concrete

For the purpose of this study, the following properties of the conventional concrete were determined and compared to corresponding properties of SCC:

- Compressive strength
- Freeze-thaw resistance
- Tensile strength
- Flexural strength

The designed conventional concrete was mixed and samples prepared in accordance with ASTM Standard. As many as 40 samples were cast and subjected to compressive strength test. The results of this test are shown in Figure 31 and Table 24.

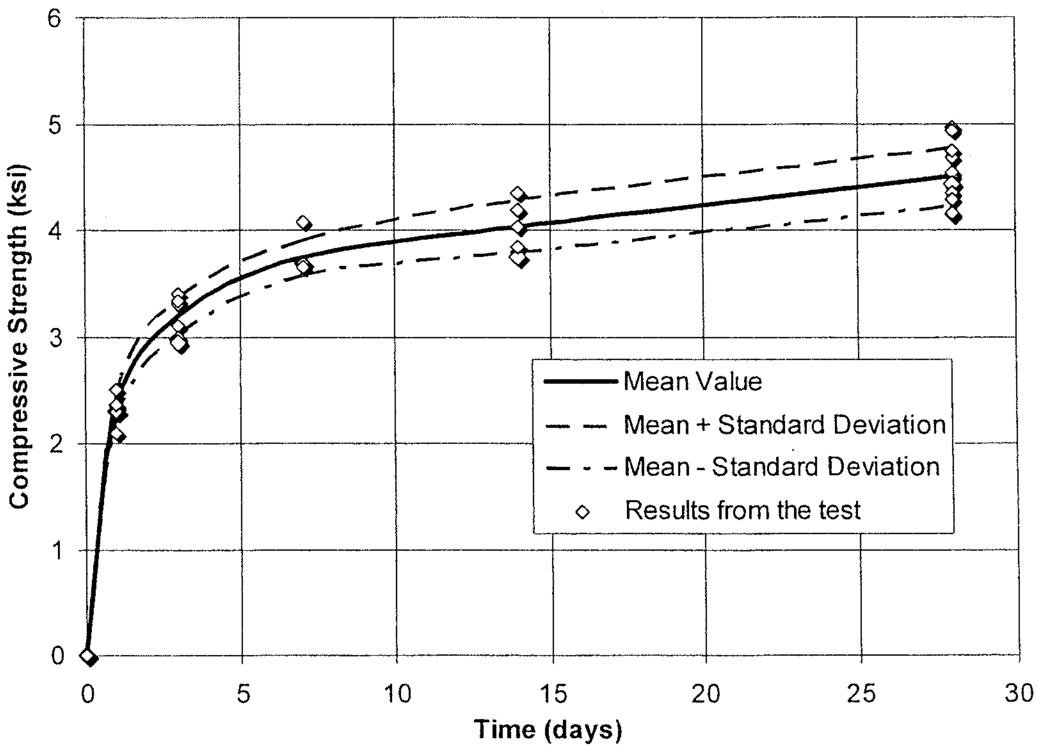

Figure 31 Strength Development Curve for Conventional Concrete

Table 24 Summary of Compressive Strength of Conventional Concrete

Test after n days	1	3	7	28
Mean Value (ksi)	2.32	3.20	3.74	4.49
Standard Deviation (ksi)	0.12	0.189	0.176	0.28
Coefficient of Variation (%)	0.05	0.05	0.04	0.06
Ratio of the strength to the strength after 28 days (%)	51	71	83	100

Also, 14 samples were cast to carry out freeze-thaw test. They were subjected to 447 cycles, which is more that required by the ASTM Standard. The dynamic modulus of elasticity was measured, and then the durability factor calculated. Figures 32 and 33 show the dynamic modulus of elasticity and the durability factor, respectively, as a function of number of cycles for the conventional concrete.

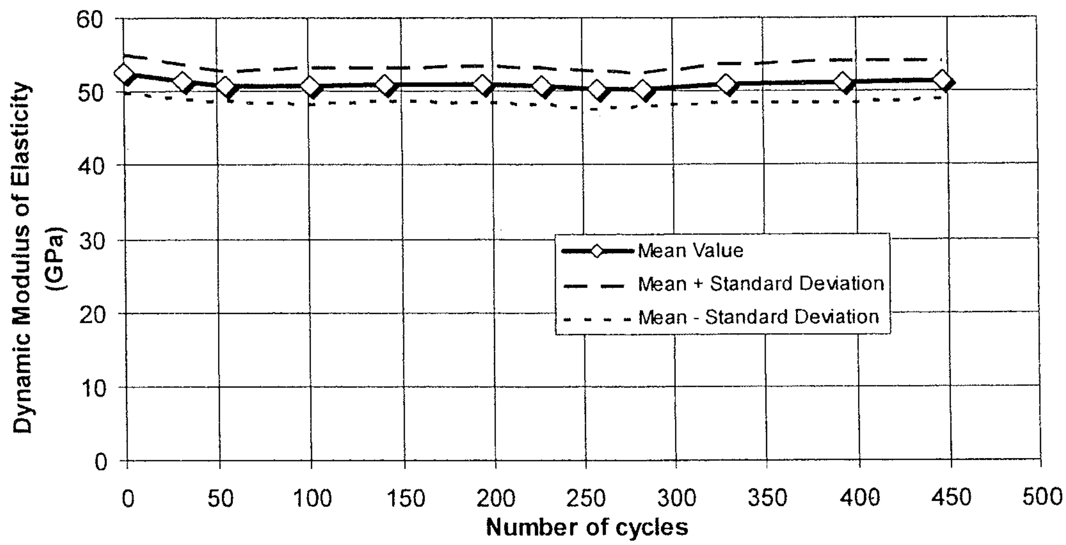

Figure 32 Dynamic Modulus of Elasticity as a Function of Number of Cycles, Conventional Concrete

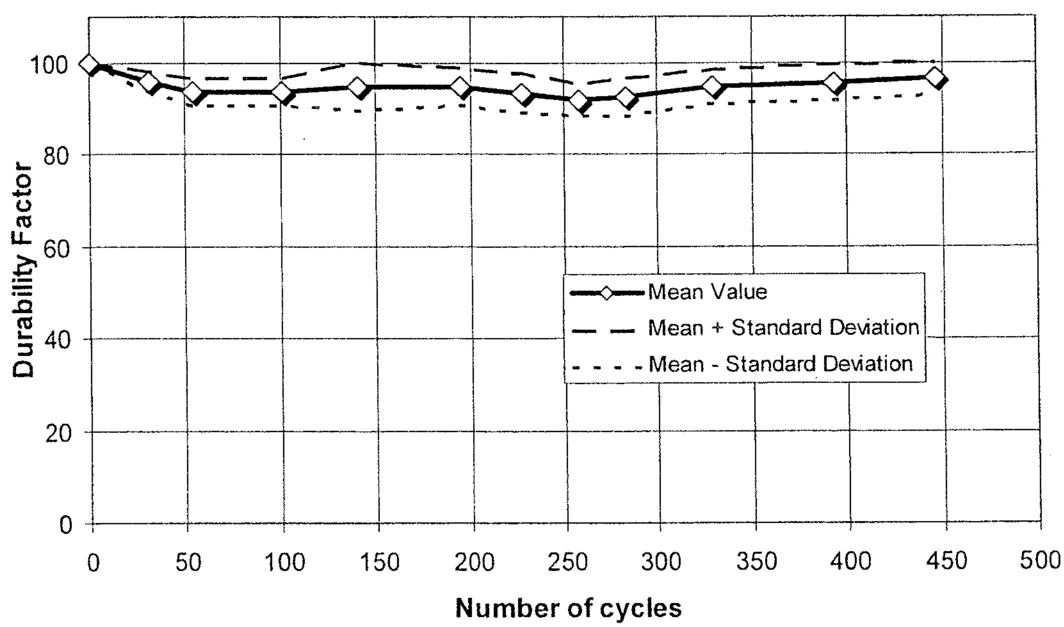

Figure 33 Durability Factor as a Function of Number of Cycles, Conventional Concrete

Fourteen samples were also cast to perform the splitting test. The test was carried out in the same manner as it was in case of SCC (see section 5.3). The results of the test are summarized in Table 25.

Table 25 Splitting Test Results of Conventional Concrete

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Splitting test after 28 (mean)(psi)
14	0.17	87	510

The next step was to perform a flexural test to obtain a modulus of rupture. The procedure is outlined in section 5.4. Table 26 summarizes the test results.

Table 26 Flexural Test Results of Conventional Concrete

Number of Samples	Coefficient of Variation	Standard deviation (psi)	Flexural test after 28 days (mean)(psi)
14	0.09	67	689

After performing all these tests, the results from testing SCC and the conventional concrete were gathered together. The summary is shown in Table 27. It should be noted that the goal of this summary is strictly for information and comparison purposes. It is not an intention of the authors of this report to either favor or diminish SCC or conventional concrete.

Table 27 Comparison of Mechanical Properties of SCC and Conventional Concrete

Mechanical Property	Conventional Concrete	Self-Consolidating Concrete (SCC)	Increase of Mechanical Property
Compressive Strength (28-day)	4500 psi	9000 psi	100%
Splitting Test	510 psi	740 psi	45 %
Flexural Test	690 psi	920 psi	33%
Modulus of Elasticity (28-day)	4070 ksi	5570 ksi	37%

Also, for information and comparison purposes, the authors of this report gathered prices of all constituents of both SCC and the conventional concrete. The unit prices are based on the National Building Cost Manual. As seen in Table 28, the price per cubic meter of self-consolidating concrete is more than that of conventional concrete. Depending on the selected superplasticizer, self-consolidating concrete is 40% to 60 % more expensive than conventional concrete. However, the gain in mechanical properties and labor costs are not negligible. Self-consolidating concrete does not require any vibration, or finishing of the surface once demolded. Therefore, the reduction in labor costs on site or in plant definitely counterbalances the increase in material costs. All these observations make self-consolidating concrete very appealing from the constructors' viewpoint.

Table 28 Unit Price Comparison Between SCC and Conventional Concrete

	Unit Price	SCC		Conventional Concrete	
		Proportions (kg/m^3)	Price ($\$/m^3$)	Proportions (kg/m^3)	Price ($\$/m^3$)
Coarse Aggregates	22 $/T	850	18.7	1024	22.5
Fine Aggregates	15.5 $/T	830	12.9	745	11.5
Cement	125 $/T	360	45.0	340	42.5
Fly Ash	50 $/T	200	10.0	---	---
Air Entrainer	10 $/L	---	---	0.17	1.7
Superplasticizer	4.7-7.9 $/L	5 L	23.5 - 39.5	---	---
Total			**110.1-126.1**		**78.3**

9 CONCLUSIONS AND RECOMMENDATIONS

This study focused on the development of a US-specific self-consolidating concrete. It presents the mixing requirements, specification of the components, the properties of freshly mixed concrete as well as the properties of hardened concrete. Included are also discussions on equipment and procedure for testing SCC.

Based on available documentation and experience gained by the European and Japanese researchers and construction companies, the University of Michigan research team successfully developed a self-consolidating concrete mix. A trial-and-errors procedure was adopted for the mix design and it yielded excellent results. The designed mix was established by evaluating the fresh concrete properties using such tests as the V-funnel test, the slump flow test, and the L-Box test. All these tests are widely accepted in Europe and Japan to estimate the flowability, passing ability and segregation resistance of the self-consolidating concrete. Moreover, three different types of superplasticizers were investigated and various design mixes found.

The hardened concrete properties of the developed design mixes were investigated in accordance to the corresponding ASTM standards. The compressive strength, the splitting tensile strength, the modulus of rupture, the static and dynamic modulus of elasticity, and the freeze - thaw resistance have been researched for the designed mixes.

The developed self-consolidating concrete mixes exhibit early compressive strength development (5 ksi at 1 day, 6.8 ksi at 3 days, and 7.5 ksi at 7 days) and a high compressive strength of 9 ksi at 28 days, which corresponds to an increase of 100% when compared to the designed and tested conventional concrete. Properties associated to the compressive strength, such as the tensile splitting strength, the modulus of rupture and the modulus of elasticity, also exhibit considerable increases ranging from 30% to 45% when compared to conventional concrete.

The freeze-thaw resistance of the developed self-consolidating concrete was also investigated. All three designed mixes demonstrate an excellent freeze-and-thaw resistance since their durability factor after 300 cycles ranges from 87% to 98%. The tests were pursued until 640 cycles and the samples' durability factors were still ranging from 84% to 95%. Even though the air-content of the formulated concrete was rather low (2.5%), the obtained concrete was compact enough to ensure an excellent frost resistance in severe weather environment.

Since the segregation is a very important issue, a special attention was paid to carefully examine it. There are a few methods to assess the segregation. It can be determined by observing the slump spread or by longitudinal or transverse cut sections. Even though these methods do not guarantee that the segregation will not occur during construction, as reinforcement may stimulate some segregation, they are a good indication whether or not the concrete is prone to the segregation. Figures 34 and 35 show the cut sections through the samples cast with the developed mix. As seen, the coarse aggregates are distributed homogeneously, and they do not form any local clusters.

Figure 34 Longitudinal Cut Through SCC Samples

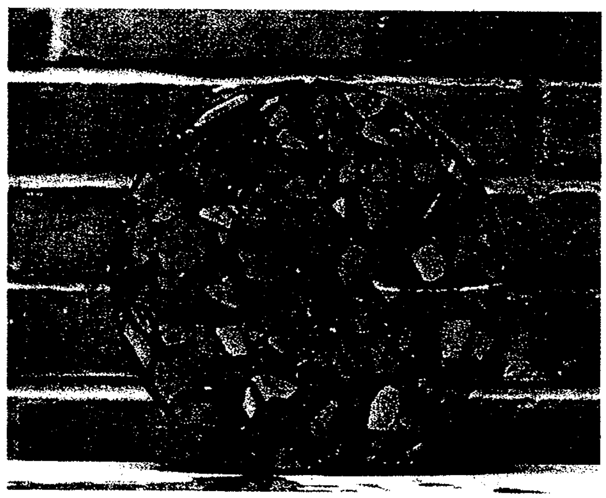

Figure 35 Transverse Cut Through SCC Sample

The obtained self-consolidating concrete mixes were compared to conventional concrete to determine the advantages and disadvantages of such a material. A material cost comparison was done and it appears that the designed SCC is significantly more expensive than a conventional concrete. However, increased mechanical properties can lead to thinner sections, therefore reduce the material quantity required. Last but not least, self-consolidating concrete does not require any vibration because the viscosity of this particular concrete allows it to flow freely between rebars, and to occupy all the space in the formworks, hence removing any need of intensive, dangerous, and costly labor. The increase in cost of material can be largely covered by the reduction of labor, and so makes this material very attractive.

Based on mix proportions parameters, the materials used, and other factors associated with this work, the following conclusions can be made:

- SCC flows into formwork (through reinforcement) under the influence of its own weight; thus no external vibration is needed,
- SCC has very high compressive strength compare to the conventional concrete,
- SCC can be produced with locally available materials even though the mix is very sensitive to proportioning,
- SCC has a tendency toward segregation if too much superplasticizer is used or the water to cement ratio is too high, so quality control is of utmost importance,
- SCC demonstrates a very good resistance to frost damage even with a low air content,
- SCC can be particularly useful to bridge repair projects, during new constructions, and whenever dense reinforcement exists because of its good workability,

The advantages and disadvantages of the self-consolidating concrete are summarized in Table 29.

Table 29 Advantages and Disadvantages of SCC

Advantages of SCC	Disadvantages of SCC
No noise (better working environment, increased productivity, reduced health and safety risks),	**Higher unit cost** (SCC can be 40-60% more expensive compare to the conventional concrete),
No vibration (less wear and tear of formwork),	**Sensitive mix** (even small changes in proportioning may change the properties of freshly mixed concrete),
Reduction in site manpower (additional cost of SCC paid for by the ability to fill complex molds efficiently),	**Segregation** (when occurs, it may lead to undesirable performance),
Better surface finish,	**Control of workability is critical,**
Faster placing time (increased productivity),	**Quality control** (more skillful labor required),
Savings in labor and equipment (lower project cost),	**Lack of industry guidance, standards and specifications,**
Feasibility of otherwise impossible project requirements,	

10 REFERENCES

AASHTO Standard Specifications for Highway Bridges, Sixteen Edition, 1996

Abou-Zeid, M. N., and Roushdy, M. S., "Performance and Uniformity of Self-Compacting Concrete", *TRB 2005 Annual Meeting CD-ROM*, Washington, 2005

ASTM C136, 2004, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C33, 2004, "Standard Specifications for Concrete Aggregates", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C127, 2004, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregates", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C128, 2004, "Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregates", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C29, 2004, "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C127, 2004, "Standard Test Method for Density, Relative Density (specific Gravity), and Absorption of Coarse Aggregate", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C138, 2004, "Standard Test Method for Density (Unit Weight), Yield, Air Content (Gravimetric) of Concrete", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C173, 2004, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C192, 2004, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C215, 2004, "Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C231, 2004, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C293, 2004, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C469, 2004, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C496, 2004, "Standard Test Method for Splitting tensile Strength", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C597, 2004, "Standard Test Method for Pulse Velocity Through Concrete", ASTM Annual Book of Standards, Vol. 04-02.

ASTM C666, 2004, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing", ASTM Annual Book of Standards, Vol. 04-02.

Billberg, P., "Self-compacting Concrete for Civil Engineering Structures – the Swedish Experience", *Swedish Cement and Concrete Research Institute*, SE-100 44, Stockholm, CBI Report 2:99

Bui, V.K., Shah, S.P., Akkaya, Y., A new Approach in Mix Design of Self-Consolidating Concrete, Proceedings of First North American Conference on the Design and Use of Self-Consolidating Concrete, 2003, pp 71-76

Hodgson, D., et al., "The Feasibility of Using Self-Consolidating Concrete (SCC) in Drilled Shaft Applications", *TRB 2004 Annual Meeting CD-ROM*, Washington, 2004

Holschemacher K., Klug Y., "A database for the evaluation of hardened properties of SCC", Leipzig Annual Civil Engineering Report No. 7, 2002, pp. 123-134.

Johasen K., Hammer T. A., "Drying shrinkage of 'Norwegian' self-compacting concrete", Nordic Concrete Research, No.27, pp. 1-7.

Jin, J., Domone, P.L., Relationships between the fresh properties of SCC and its mortar component. Conference Proceedings of First North American Conference on the Design and Use of Self-Consolidating Concrete, 2003, pp 33-38

Kaszyńska M – Application of Self-Consolidating Concrete for the Repair of Concrete Structures, The Second International Workshop on Structural Composites for Infrastructure Applications, Cairo, Egypt, December, 2003

Kaszyńska M. - "Early age properties of high-strength/high performance concrete" - CEMENT AND CONCRETE COMPOSITES, Elsevier Science Ltd, London – (24) 2002, pp.253-261.

Kaszyńska M. – "The Properties of Early Age HPC" – 5-th International Symposium Utilization of High Strength/High Performance Concrete – Sandefjord, Norway, 1999.

Kaszyńska M. Nowak A.S. – Effect of Mixing tolerances on Performance of Self-Consolidating Concrete (SCC) – 3rd PCI/FHWA International Symposium on High Performance Concrete – Orlando, Florida, October 2003

König G., Holschemacher K., Dehn F., Weiße D., "Self-Compacting Concrete - Time Development of Material Properties and Bond Behaviour", Proceedings of the Second International Symposium on Self-Compacting Concrete, Tokyo, (2001), pp. 507 - 516.

Khayat K. H., Manai K., Trudel A., "In Situ Mechanical Properties of Wall Elements Cast Using Self-Consolidating Concrete". ACI Materials Journal 96, No. 2, (March-April 1997), pp. 491 - 500.

Mindess S., Young J. F., Darwin D., 2003, "Concrete", second edition, Prentice Hall, New Jersey, 2003

Nawy, E. G., "Reinforced Concrete, A Fundamental Approach", fifth edition, Prentice Hall, New Jersey, 2003

Okamura, H. and Ozawa, K., " Mix-design for Self-compacting Concrete", *Concrete Library of JSCE*, No. 25, 1995, pp. 107-120

Okamura, H., Ozawa, K., Self-Compacting High Performance Concrete, Structural Engineering International 4/96

Ozawa, K., Maekawa, K. and Okamura, H., "Development of High Performance Concrete", *Journal of the Faculty of Engineering*, The University of Tokyo, Vol. XLI, No. 3, 1992, pp. 381-439

Ozyildirim, C., and Lane, D., S., "Investigation of Self-Consolidating Concrete", *TRB 2003 Annual Meeting CD-ROM*, Washington, 2003

Ozyildirim, C., "The Virginia Department of Transportation's Early Experience with Self-Consolidating Concrete", *TRB 2005 Annual Meeting CD-ROM*, Washington, 2005

Persson B., "A comparison between mechanical properties of self-compacting concrete and the corresponding properties of normal concrete", Cement and concrete research, Vol. 31, 2001, pp. 193-198.

Proceedings of the International Workshop on Self-Compacting Concrete, *Concrete Engineering Series 30*, (Kochi University of Technology, Japan), 1998

Recommendation for Self-Compacting Concrete, *Concrete Engineering Series 31*, Japan Society of Civil Engineers (ed. Taketo Uomoto and Kazumasa Ozawa), 1999

Recommended Practice for Evaluation of Strength Test Results of Concrete (ACI 214-77) (Reapproved 1997)

Skarendahl A., Petersson Ö., "Self-Compacting Concrete. State-of-the-Art", report of RILEM Technical Committee 174. RILEM-Report No. 23, Ca-chan Cedex/France, (2000).

Specification and Guidelines for Self-Compacting Concrete, EFNARC, 2002.

Takada, K., Pelova, G. and Walraven, J., " Self-compacting Concrete Produced by Japanese Method with Dutch Materials", submitted to the *Congress of European Ready Mixed Concrete Organization*, ERMCO98, Lisbon, 1998

Takada, K., Pelova, G. and Walraven, J., "Influence of Microfillers on Proportioning of Mortar in Self-compacting Concrete", Proceedings of the *1st International RILEM Symposium on Self-Compacting Concrete,* Stockholm, Sweden, 1999, pp. 537-548

Walraven, J. and Takada K., "Selbtverdichtender Beton", *Betoninnovationen, Verkehrsprojekte, Architektur*, 1/99, pp. 23-27

Walraven, J., "The Development of Self-Compacting Concrete in the Netherlands", Proceedings of *International Workshop on Self-Compacting Concrete*, Kochi University of Technology, Kochi, Japan, 1998, pp.87-96

Walraven J., Self-Compacting Concrete in the Netherlands, Conference Proceedings of First North American Conference on the Design and Use of Self-Consolidating Concrete, 2003, pp 399-405.