A STUDY OF MIX DESIGN AND DURABILITY OF SELF COMPACTING CONCRETE

BY

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عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES


بسم الله الرحمن الرحيم

Dedicated to

DEAR and NEAR ONES

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THESIS ABSTRACT

Full Name	**MOHAMMED ABDUL HAMEED**
Title of Study	**A STUDY OF MIX DESIGN AND DURABILITY OF SELF COMPACTING CONCRETE**
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A self-compacting concrete (SCC) is the one that can be placed in the form and can go through obstructions by its own weight and without the need of vibration. Since its first development in Japan in 1988, SCC has gained wider acceptance in Japan, Europe and USA due to its inherent distinct advantages. Although there are visible signs of its gradual acceptance in the Middle East through its limited use in construction, Saudi Arabia has yet to explore the feasibility and applicability of SCC in new construction. The contributing factors to this reluctance appear to be lack of any supportive evidence of its suitability with local marginal aggregates and the harsh environmental conditions.

The primary aim of this study is to explore the feasibility of using SCC made with local marginal aggregates of Eastern Province of Saudi Arabia by examining its basic properties and durability characteristics.

This research consists of : (i) development of a suitable mix for SCC that would satisfy the requirements of the plastic state; (ii) casting of concrete samples and testing them for compressive strength, drying shrinkage, water permeability, and chloride permeability; and (iii) cyclic exposure tests involving wet-dry and heat-cool cycles to observe the degradation of the prepared SCC samples. Local aggregates, cement, admixtures and additives produced by the local suppliers were used by in this work.

The significance of this work lies in its attempt to provide some performance data of SCC made in the Eastern Province of Saudi Arabia so as to draw attention to the possible use of SCC.

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ARABIC ABSTRACT

ملخص الرسالة

الاسم الكامل: محمد عبد الحميد

عنوان الدراسة: دراسة تصميم الخلطة وديمومة الخرسانة ذاتية الرص.

الاختصاص: هندسة مدنية (إنشاءات)

تاريخ الرسالة: ديسمبر 2005

إن الخرسانة ذاتية الرص أو الدك (SCC) يمكن صبها في القالب ويمكنها من الانسياب تحت تأثير وزنها الذاتي بدون الحاجة إلى عملية الدك. تم تطويرها للمرة الأولى في اليابان عام 1988 ومنذ ذلك الحين حاز هذا النوع من الخرسانة على قبول كبير في اليابان وأوروبا والولايات المتحدة لما لها من مميزات خاصة بطبيعتها. على الرغم أن هناك مرئيات واضحة حول قبولها التدريجي في الشرق الأوسط من خلال محدودية استخدامها في أعمال الإنشاء فإن المملكة العربية السعودية حتى الآن لم تستكشف عن الجدوى وإمكانية استخدام هذا النوع من الخرسانة في أعمال الإنشاء الجديدة. إن العوامل التي ساهمت في هذا التردد تعود لنقص أي دليل مساعد لملائمتها مع حصويات الصخور الحدودية المحلية وبسبب الشروط البيئية القاسية.

إن الهدف الرئيسي من هذه الدراسة هو الكشف عن ملائمة استخدام الخرسانة ذاتية الرص باستخدام حصويات الصخور الحدودية المحلية في المنطقة الشرقية من المملكة من خلال اختبار خصائصها الأساسية ومميزات ديمومتها.

يحتوي هذا البحث على:

1. تطوير خلطة مناسبة للخرسانة ذاتية الرص والتي تتوافق مع متطلبات الحالة اللدنة.
2. صب عينات من الخرسانة وإجراء اختبارات المقاومة على الضغط والانكماش الجاف ونفاذية الماء ونفاذية الكلور.
3. اختبارات التعريض الدوري للعينات: ويشمل التعريض الدوري الرطب – الجاف والحار – البارد لملاحظة تآكل عينات الخرسانة ذاتية الدك.

يتم استخدام الحصويات المحلية والخلائط والمواد المضافة والمصنعة محلية في هذا العمل.

تقع ميزة هذا العمل في محاولة تقديم بعض المعلومات حول سلوك الخرسانة ذاتية الدك والمصنعة في المنطقة الشرقية من المملكة العربية السعودية لكسب الانتباه حول إمكانية استخدام هذا النوع من الخرسانة.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF SELF COMPACTING CONCRETE

Self compacting concrete (SCC) represents one of the most significant advances in concrete technology for decades. Inadequate homogeneity of the cast concrete due to poor compaction or segregation may drastically lower the performance of mature concrete in-situ. SCC has been developed to ensure adequate compaction and facilitate placement of concrete in structures with congested reinforcement and in restricted areas.

SCC was developed first in Japan in the late 1980s to be mainly used for highly congested reinforced structures in seismic regions (Bouzoubaa and Lachemi, 2001). As the durability of concrete structures became an important issue in Japan, an adequate compaction by skilled labors was required to obtain durable concrete structures. This requirement led to the development of SCC and its development was first reported in 1989 (Okamura and Ouchi, 1999).

SCC can be described as a high performance material which flows under its own weight without requiring vibrators to achieve consolidation by complete filling of formworks even when access is hindered by narrow gaps between reinforcement bars (Zhu et al., 2001). SCC can also be used in situations where it is difficult or impossible to use mechanical compaction for fresh concrete, such as underwater concreting, cast in-situ pile foundations, machine bases and columns or walls with congested reinforcement. The high flowability of SCC makes it possible to fill the formwork without vibration (Khayat et al., 2004). Since its inception, it has been widely used in large construction in Japan (Okamura and Ouchi, 2003). Recently, this concrete has gained wide use in many countries for different applications and structural configurations (Bouzoubaa and Lachemi, 2001).

It can also be regarded as "the most revolutionary development in concrete construction for several decades". Originally developed to offset a growing shortage of skilled labor, it is now taken up with enthusiasm across European countries for both site and precast concrete work. It has proved beneficial economically because of a number of factors as noted below (Krieg, 2003 and ENFARC, 2002):

i. Faster construction,
ii. Reduction in site manpower,
iii. Easier placing,
iv. Uniform and complete consolidation,
v. Better surface finishes,
vi. Improved durability,
vii. Increased bond strength,
viii. Greater freedom in design,
ix. Reduced noise levels, due to absence of vibration, and
x. Safe working environment.

The method for achieving self-compactability involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregate and mortar when the concrete flows through the confined zone of reinforcing bars (Okamura and Ouchi, 2003). Homogeneity of SCC is its ability to remain unsegregated during transport and placing. High flowability and high segregation resistance of SCC are obtained by:

1. A larger quantity of fine particles, i.e., a limited coarse aggregate content.
2. A low water/powder ratio, (powder is defined as cement plus the filler such as fly ash, silica fume etc.) and
3. The use of superplasticizer (Okamura and Ouchi, 2003 and Audenaert et al., 2002).

Because of the addition of a high quantity of fine particles, the internal material structure of SCC shows some resemblance with high performance concrete having self-compactibility in fresh stage, no initial defects in early stage and protection against external factors after hardening. Due to the lower content of coarse aggregate, however, there is some concern that: (1) SCC may have a lower modulus of elasticity, which may affect deformation characteristics of prestressed concrete members and (2) creep and shrinkage will be higher, affecting prestress loss and long-term deflection (Mata, 2004).

Self compacting concrete can be produced using standard cements and additives. It consists mainly of cement, coarse and fine aggregates, and a filler, such as fly ash or Super-pozz®, water, super plasticizer and stabilizer.

The composition of SCC is similar to that of normal concrete but to attain self flow ability admixtures, such as fly ash, glass filler, limestone powder, silica fume, Super-pozz®, etc; with some superplasticizer is mixed. Since Super-pozz® is a new emerging admixture and is a highly reactive alumino – silicate pozzolanic material, its fineness and spherical particle shape improves the workability of SCC. Thus, it can be used as a suitable admixture in SCC.

Three basic characteristics that are required to obtain SCC are: high deformability, restrained flowability and a high resistance to segregation (Khayat, et al., 2004). High deformability is related to the capacity of the concrete to deform and spread freely in order to fill all the space in the formwork. It is usually a function of the form, size, and quantity of the aggregates, and the friction between the solid particles, which can be reduced by adding a high range water-reducing admixture (HRWR) to the mixture. Restrained flowability represents how easily the concrete can flow around obstacles, such as reinforcement, and is related to the member geometry and the shape of the formwork. Segregation is usually related to the cohesiveness of the fresh concrete, which can be enhanced by adding a viscosity-modifying admixture (VMA) along with a HRWR, by reducing the free-water content, by increasing the volume of paste, or by some combination of these constituents. Two general types of SCC can be obtained: (1) one with a small reduction in the coarse aggregates, containing a VMA, and (2) one with a significant reduction in the coarse aggregates without any VMA.

To produce SCC, the major work involves designing an appropriate mix proportion and evaluating the properties of the concrete thus obtained. In practice, SCC in its fresh state shows high fluidity, self-compacting ability and segregation resistance, all of which contribute to reducing the risk of honey combing of concrete (Su et al., 2001). With these good properties, the SCC produced can greatly improve the reliability and durability of the reinforced concrete structures.

In addition, SCC shows good performance in compression and can fulfill other construction needs because its production has taken into consideration the requirements in the structural design.

1.2 NEED FOR THIS RESEARCH

Despite its advantages as described in previous section, SCC has not gained much local acceptance though it has been promoted in the Middle East for the last five years. The majority of applications thus far have been small niche pours into congested areas, domes, or thin wall sections. In UAE, specifically in Dubai, there are a few high-rise structures under construction using SCC and many more are expected in future (Kapoor et al., 2003).

Awareness of SCC has spread across the world, prompted by concerns with poor consolidation and durability in case of conventionally vibrated normal concrete.

However, the awareness in the Kingdom of Saudi Arabia regarding SCC is somewhat muted and this explains the lack of any commercial use of SCC in the Kingdom thus far.

The reluctance in utilizing the advantages of SCC, if any, in Saudi Arabia, stems from two contributing factors:

1. Lack of research or published data pertaining to locally produced SCC, and
2. The potential problems for the production of SCC, if any, with local marginal aggregates and the harsh environmental conditions prevailing in the region. Locally available aggregates are characterized as porous, absorptive, relatively soft, excessively dusty, and the coefficient of thermal expansion is much less than that of the hardened cement mortar. The climate of this region is characterized by high temperature and humidity with large fluctuations in the diurnal and seasonal temperature and humidity.

Therefore, there is a need to conduct studies on SCC using local aggregates.

1.3 SCOPE AND OBJECTIVES

The scope of this work was limited to the development of a suitable mix design to satisfy the requirements of SCC in the plastic stage using local aggregates and then to determine the strength and durability of such concrete exposed to thermal and moisture cycles.

The general objective of this study was to conduct an exploratory work towards the development of a suitable SCC mix design using local aggregates and to evaluate the performance of the selected SCC mix under thermal and moisture variations. The specific objectives were as follows:

1. To design a suitable SCC mix utilizing local aggregates, and
2. To assess the strength development and durability of SCC exposed to thermal and moisture variations.

1.4 WORK PLAN

The research work was conducted in the following five phases. A general overview of the phases involved is shown in Figure 1.1.

The first phase included a comprehensive literature survey and data collection in the following areas:

1. Basic requirements of SCC.
2. Properties of fresh SCC.
3. Durability properties of SCC.
4. Available techniques for computing durable properties of SCC.
5. Water permeability of SCC.

The second phase involved fabrication, upgrading and calibration of the equipment and molds. The equipments for V-funnel and U-tube tests were fabricated to evaluate the self-compactability of freshly prepared SCC. Molds were fabricated for casting different types of specimens required for assessing the properties of hardened SCC.

In the third phase, the mix design of a suitable SCC was carried out in an exploratory manner. A series of trials was conducted to develop a suitable mix design using local aggregates. Eight trials mixes were prepared by varying the superplasticizer content, Super-pozz® content and FA/CA ratio. Out of the eight trial mixes, a suitable mix design was adopted with self-compactability and compressive strength as the criteria for selection.

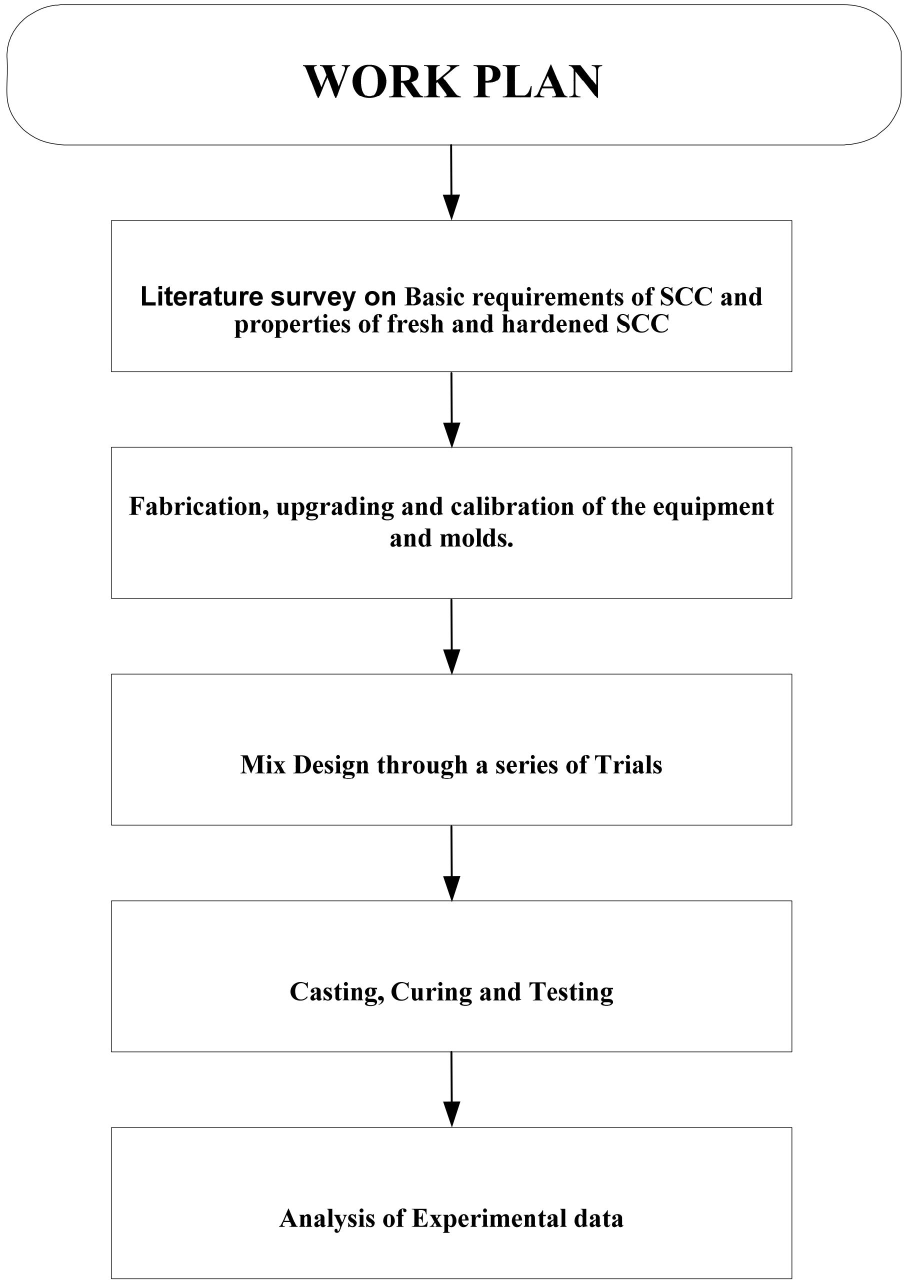

Figure 1.1: Phases of the Research

In the fourth phase, specimens were cast and cured for 28 days before and then exposed to moisture and thermal variations. The specimens were exposed to three different exposures, namely normal exposure at room temperature, thermal variations; heating the specimens at 40°C for two days and then cooling them at room temperature for two days, and moisture variations. In the moisture variations the specimens were dried for two days at room temperature and then submerged in water for two days. After the aforesaid exposure, the specimens were tested to determine compressive strength, depth of water penetration, rapid chloride permeability, water absorption, water permeability, and drying shrinkage.

The fifth phase, involved the analysis of experimental data.

CHAPTER 2

LITERATURE REVIEW

2.1 DEVELOPMENT OF SELF COMPACTING CONCRETE

The idea of a concrete mixture that can be cosolidated into every corner of a formwork, purely by means of its own weight and without the need for vibration, was first considered in 1983 in Japan, when concrete durability, constructability and productivity became a major topic of interest in the country. During this period, there was a shortage of number of skilled workers in Japan which directly affected the quality of the concrete.

In order to achieve acceptable concrete structures, proper consolidation is required to completely fill and equally distribute the mixture with minimum segregation. One solution to obtain acceptable concrete structures, independently of the quality of construction work, is the employment of SCC. The use of SCC can reduce labor requirements and noise pollution by eliminating the need of either internal or external vibration.

Okamura proposed the use of SCC in 1986. Studies to develop SCC, including a fundamental study on the workability of concrete, were carried out by Ozawa and Maekawa at the University of Tokyo, and by 1988 the first practical prototypes of SCC were produced. By the early 1990's Japan started to develop and use SCC and, as of 2000, the volume of SCC used for prefabricated products and ready-mixed concrete in Japan was over 520,000 yard3 (i.e. 400,000 m3) (Ouchi et al., 2003).

In 1996, several European countries formed the "Rational Production and Improved Working Environment through using SCC" project in order to explore the significance of published achievements in SCC and develop applications to take advantage of the potentials of SCC. Since then, SCC has been used successfully in a number of bridges, walls and tunnel linings in Europe (Ouchi et al., 2003).

During the last three years, interest in SCC has grown in the United States, particularly within the precast concrete industry. SCC has been used in several commercial projects (Ozyldirim, 2003; Ouchi et al., 2003). Numerous research studies (Khayat et al., 2001; Chan et al., 2003; Sonebi et al., 2003), have been conducted recently with the objective of developing raw material requirements, mixture proportions, material requirements and characteristics, and test methods necessary to produce and test SCC.

The latest studies related to SCC focused on improved reliability and prediction of properties, production of a dense and uniform surface texture, improved durability, and both high and early strength permitting faster construction and increased productivity (Khayat et al., 2004; Khayat et al., 2001; Khayat et al., 2002; Chan et al., 2003; Sonebi et al., 2003).

2.2 BASIC PRINCIPLES AND REQUIREMENTS OF SCC

With regard to its composition, SCC consists of the same components as conventionally vibrated normal concrete, which are cement, aggregates, water, additives and admixtures. However, high volume of superplasticizer for reduction of the liquid limit and for better workability, the high powder content as "lubricant" for the coarse aggregates, as well as the use of viscosity-agents to increase the viscosity of the concrete have to be taken into account (Dehn et al., 2000). Figure 2.1 shows the basic principles for the production of SCC

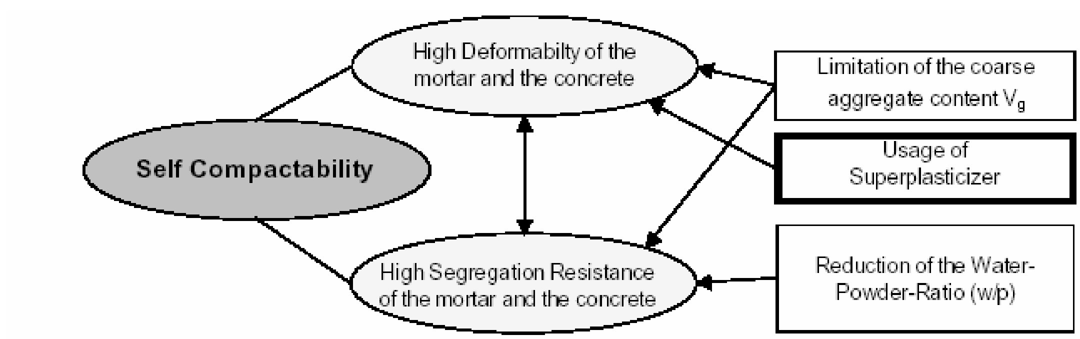

Figure 2.1 Basic principles for the production of SCC (Dehn et al., 2000).

Okamura and Ozawa (1995) have employed the following methods to achieve self-compactability of SCC:

1. Limited aggregate content (coarse aggregate □ 50% of the concrete volume and sand □ 40% of the mortar volume),
2. Low water/powder ratio, and
3. Use of higher dosage of superplastcizer.

A concrete mix can only be classified as SCC if the requirements for all the following three workability properties are fulfilled (EFNARC, 2002):

1. Filling ability,
2. Passing ability, and
3. Segregation resistance.

Filling ability: It is the ability of SCC to flow into all spaces within the formwork under its own weight. Tests, such as slump flow, V-funnel etc, are used to determine the filling ability of fresh concrete.

Passing ability: It is the ability of SCC to flow through tight openings, such as spaces between steel reinforcing bars, under its own weight. Passing ability can be determined by using U-box, L-box, Fill-box, and J-ring test methods.

Segregation resistance: The SCC must meet the filling ability and passing ability with uniform composition throughout the process of transport and placing.

The test methods to determine the workability properties of SCC are presented in Table 2.1.

Table 2.1: Test methods to evaluate the workability properties of SCC (EFNARC, 2002).

Property	Test methods	
	Laboratory (For mix design)	Field (For quality control)
Filling ability	Slump flow T_{50cm}slumpflow V-funnel Orimet	Slump flow T_{50cm}slumpflow V-funnel Orimet
Passing ability	L-box U-box Fill-box	J-ring
Segregation resistance	GTM test V-funnel at $T_{5minutes}$	GTM test V-funnel at $T_{5minutes}$

A simple apparatus and a rapid method for testing the segregation resistance of SCC have been recently developed by Bui et al. (2002). The developed apparatus and method are useful in rapidly assessing the segregation resistance of SCC in both vertical and horizontal directions. The proposed method can also distinguish between different CA/TA ratios, different water/binder ratios, and different materials. The self-compactibility tests commonly conducted on SCC mixes are briefly described below:

2.2.1 Slump Flow Test:

The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions. The test method is based on the conventional slump test. The diameter of the concrete circle is a measure for the filling ability of the concrete. It is the most commonly used test, and gives a good assessment of filling ability. It gives no indication of the ability of the concrete to pass between reinforcement without blocking, but may give some indication of resistance to segregation. The higher the slump flow value, the greater is its ability to fill formwork under its own weight. Acceptable range for SCC is from 650 to 800 mm (EFNARC, 2002).

2.2.2 V-funnel test:

This test is used to determine the filling ability (flowability) of the concrete with a maximum aggregate of 20 mm. The funnel is filled with about 12 liters of concrete and the time taken for it to flow through the apparatus is measured. The test measures the ease of flow of the concrete; shorter flow times indicate greater flowability. For SCC, a flow time in the range of 6 to 12 second is considered appropriate (EFNARC, 2002). The inverted cone shape restricts the flow, and prolonged flow times may give some indication of the susceptibility of the mix to blocking.

2.2.3 U-box test:

This test is used to measure the filling ability of SCC. The apparatus consists of a vessel that is divided by a middle wall into two compartments. It provides a good direct assessment of filling ability.

For conducting the U-box test, one of the compartments of the apparatus is filled with the concrete sample and filled concrete is left to stand for 1 minute. Then the sliding gate is lifted to allow the concrete to flow out into the other compartment. After the concrete comes to rest, the height of the concrete in the compartment that has been filled is measured in two places and the mean height (H1) is calculated. Also the height in the other compartment (H2) is measured. The filling height is then calculated as H1- H2. The whole test has to be performed within 5 minutes. If the concrete flows as freely as water, at rest it will be horizontal, so H1- H2 = 0. Therefore, the nearer this test value, i.e., the 'filling height', is zero, the better the flow and passing ability of SCC (EFNARC, 2002).

Typical acceptance criteria for SCC with a maximum aggregate size of up to 20 mm are presented in Table 2.2.

Table 2.2: Acceptance criteria for SCC (EFNARC, 2002).

Method	Unit	Typical range of values	
		Minimum	Maximum
1. Slump flow by Abram's cone	mm	650	800
2. T_{50cm}slumpflow	s	2	5
3. J-ring	mm	0	10
4. V-funnel	s	6	12
5. Time increase, V-funnel at $T_{5\ min}$	s	0	+3
6. L-box (h_2/h_1)	(h_2/h_1)	0.8	1.0
7. U-box (h_2-h_1)	mm	0	30
8. Fill-box	%	90	100
9. GTM Screen stability test	%	0	15
10. Orimet	s	0	5

In order to ensure that the SCC has not lost its uniformity during transport and placing due to its highly flowable and self leveling nature, it is suggested that the in-situ tests, such as rebound hammer, pull-out, etc. should be conducted. Non-variations in these near-surface properties may be considered as an indication of no loss of uniformity (Zhu et al., 2001).

In order to obtain adequate deformability, it is important to minimize the friction between the solid particles of the mixture. Reduction of the coarse aggregates and an increase in the paste volume is required to achieve the desired deformability (Khayat et al., 2004).

The size and quantity of coarse aggregates in a SCC mixture are directly related to the concrete passing ability. The passing ability requirements depend on the formwork geometry and the extent of congestion of the reinforcement. Risk of blockage is reduced by providing adequate viscosity.

Adequate cohesiveness can be obtained by incorporating a viscosity-modifying admixture (VMA) along with a high range water reducing admixture to control bleeding, segregation, and surface settlement (Khayat et al., 1997).

2.3 CONSTITUENT MATERIALS OF SCC

The constituent materials used for the production of SCC are the same as those for conventionally vibrated normal concrete except that SCC contains lesser aggregate and greater powder (cement and filler particles smaller than 0.125 mm). Fly ash, glass filler, limestone powder, silica fume, etc are used as the filler materials. To improve the self-compactibility, without segregation, a superplasticizer along with a stabilizer is added.

2.3.1 Powder (Mixture of Portland cement and Filler)

The term 'powder' used in SCC refers to a blended mix of cement and filler particles smaller than 0.125 mm. The filler increases the paste volume required to achieve the desirable workability of SCC. The addition of filler in an appropriate quantity enhances both workability and durability without sacrificing early strength (Mata, 2004).

CEMENT

Cement used for SCC should not contain C3A content higher than 10% to avoid the problems of poor workability retention (EFNARC, 2002). Selection of the type of cement depends on the overall requirements for concrete, such as strength and durability.

FILLER

Materials, such as fly ash, blast furnace slag, ground glass, limestone powder, silica fume, etc, are commonly used as filler for producing SCC. Savings in labor costs might offset the increased cost related to the use of more cement and superplasticizer, but the use of limestone powder (LSP) as a filler could increase the fluidity of the concrete, without any increase in the cost (Sonebi, 2004).

Natural pozzolan: The use of a natural pozzolan has been found to improve the fresh and hardened properties of SCC (Ramsburg and Neal, 2003).

Super-pozz®: Super-pozz® is a new emerging mineral admixture containing highly reactive alumino – silicate pozzolan, which adds strength to cementitious mixes whilst its fineness (more surface area) and spherical particle shape improves the workability a lot (Seedat and Dijkema, 2000). So, it can be used as a mineral filler for SCC.

The typical chemical composition and physical characteristics of Super-pozz® are given in Table 2.3 (Seedat and Dijkema, 2000).

Table 2.3: Chemical composition and Physical characteristics of Super-pozz® (Seedat and Dijkema, 2000).

Chemical Constituent	**%**	**Physical Properties**	
SiO_2	53.5	Relative Density	2.25
Al_2O_3	34.3	Surface Area	13000 cm^2/g
CaO	4.4	pH	11-12
Fe_2O_3	3.6	Color	Grey
K_2O	0.8	Particle Shape	Spherical
MgO	1.0	Particle Size, D90	11 µm
TiO_2	1.7	Particle size, D99	25 µm
Loss on ignition at 950 °C	0.4		

The effect of Super-pozz® on fresh concrete is to improve its viscosity, and its effect is the same as that of a viscosity agent. It does not decrease the flowability of fresh concrete. The SCC with Super-pozz® has higher mechanical properties, excellent impermeability and freez-thaw resistance, and lower drying shrinkage (Youjun et al., 2001).

Due to its particle shape and size, Super-pozz® provides a reduced water demand and/or a reduced admixture dosage for a given workability, even up to 20% replacement level. Due to its ability to reduce water and/or admixture, Super-pozz® can either be used as a high range water reducer to improve compressive strength or as a super workability aid to improve flow (Seedat and Dijkema, 2000).

Due to the fineness, spherical shape and the highly reactive nature of Super-pozz®, many technical benefits can be associated with its use. Super-pozz® can be ideally used in the following applications:

1. High Performance concrete,
2. Spray Concrete, i.e. shortcreting and guniting applications,
3. Repair Mortars,
4. Specialist grout mixes,
5. Cement modified Pre-Mixed base materials, and
6. Self Leveling Floor Screeds.

Due to lower water demand required, Super-pozz® can be ideally used to:

1. Decrease the water/binder ratio,
2. Reduce the high doses of superplasticizer normally required, and
3. Or a combination of the above.

Class F fly ash: Class F fly ash is a finely divided ash left after hard coal is burnt for power. If cement is replaced by fly ash, the paste volume of the concrete will increase, bleeding will decrease and, due to the increase of paste volume, the shrinkage may increase. Class F fly ash is generally used to replace Portland cement in the range of 15% to 25% of the total cementitious material in conventional mixtures. According to Khayat et al. (2003) a 40% Class F fly ash in a SCC mixture resulted in good workability, with acceptable strength development and frost durability.

Bouzoubaa and Lachemi (2001) have conducted a study on SCC incorporating high volumes of class F fly ash as filler in the range of 40 to 60% by mass of powder, the water/powder ratio in the range of 0.35 to 0.45, sulfonated naphthaleneformaldehyde superplasticizer in the range of 0 to 3.8 l/m3, and keeping the powder content constant at 400 kg/m3. They reported that it is possible to design a SCC incorporating high volumes of class F fly ash as a filler. They achieved a slump flow in the range of 500 to 700 mm, a flow time ranging from 3 to 7 s, a segregation index ranging from 1.9 to 14%, and compressive strengths from 15 to 31 MPa, and from 26 to 48 MPa, at 7 and 28 days, respectively.

Limestone: Bosiljkov (2003) has carried out a study on SCC with poorly graded aggregate and high volume of limestone as filler (in the range of 47 to 49% of the mass of powder), a high paste content of (in the range of 891 to 906 kg/m3 of mix, i.e. 41.3 to 42.8 % by the volume of mix) due to the poorly graded coarse aggregates, the lower water/powder ratio (in the range of 0.22 to 0.25 by mass), a constant optimum dosage of superplasticizer (0.6% by mass of powder), and a viscosity agent (30 to 35% by the mass of water). The results obtained indicated that finer and better-graded limestone dust significantly increases the deformability of the paste and it also appeared that the addition of filler improved the 28-day compressive strength of concrete mixes besides the required self-compacting properties.

Silica-fume: Silica-fume, also known as condensed silica fume or microsilica (ACI 116R), is a very fine, non-crystalline silica produced in electric arc furnaces as a by-product of the production of elemental silicon or silico-alloys. It is basically a “Super-pozzolan” with a very high durability and excellent strength, but creates a high water demand, thus requiring the use of HRWR. Silica-fume is generally used in quantities of 3% to 10% of the total cementitious materials in concretes with accelerated curing.

Slag: Slag is a by-product of the iron industry, generally used to replace Portland cement in the range of 40% to 60% of the total cementitious material in conventional concrete mixtures. According to Lachemi et al. (2003) a 50% to 70% slag, as cement replacement, with different viscosity modifying admixtures (VMA) for various SCC mixtures produced good results. Mixtures containing slag as a partial replacement of portland cement generally have lower early strengths and higher ultimate strengths than otherwise comparable mixtures containing only Portland cement.

2.3.2 Aggregates

The maximum size and grading of the aggregates depends on the particular application. Maximum size of aggregate is usually limited to 20 mm. The coarse aggregate content in SCC is kept either equal to or less than that of the fine aggregate content. Bui et al., (2002) proposed a rheological model for SCC relating the rheology of the paste to the average aggregate spacing and average aggregate diameter to consider the effect of most of the factors related to aggregate properties and content. According to Bui et al. (2002) and other researchers, a higher aggregate spacing requires a lower flow and higher viscosity of the paste to achieve satisfactory deformability and segregation resistance of SCC. Better results were also obtained with the same spacing and a smaller aggregate diameter. For SCC mixtures, a coarse aggregate size of 5 mm to 14 mm and quantities varying from 790 kg/m3 to 860 kg/m3 have been used with satisfactory results (Khayat et al., 2004).

The sand ratio (i.e. fine aggregate volume/total aggregate volume) is an important parameter for SCC and the rheological properties improved with an increase in the sand ratio (Su et al., 2002).

According to Okamura (1977), if the coarse aggregate content in a SCC mixture exceeds a certain limit, blockage would occur independently of the viscosity of the mortar. Superplasticizer and water content are then determined to ensure desired self-compacting characteristics. Yugi et al (1993) reported that reducing the volume of coarse aggregates in a SCC mixture is more effective than decreasing the sand-to-paste ratio to increase the passing ability through congested reinforcement.

The aggregate packing factor (i.e. the ratio of mass of aggregates of tightly packed state in SCC to that of loosely packed state in air) determines the aggregate content, and influences the strength, flowability and self-compacting ability (Su et al., 2001).

The moisture content of aggregates should be closely monitored and must be taken into account in order to produce SCC of constant quality (EFNARC, 2000).

The coarse aggregate should not contain clay seams that may produce excessive creep and shrinkage. Therefore, aggregates must be clean for incorporation in the mix (Gerwick, 1993).

2.3.3 Admixtures

Superplasticizer: Superplasticizer (SP) is an essential component of SCC to provide the necessary workability. The superplasticizer to be selected should have: (i) high dispersing effect for low water/powder ratio (less than 1 by volume), (ii) maintenance of the dispersing effect for at least two hours after mixing, and (iii) less sensitivity to temperature changes (Okamura and Ouchi, 2003; Ouchi et al., 2001).

The main purpose of using a super plasticizer is to produce flowing concrete with very high slump that is to be used in heavily reinforced structures and in places where adequate consolidation by vibration cannot be readily achieved. The other major application is the production of high-strength concrete at w/c's ranging from 0.3 to 0.4. The ability of a superplasticizer to increase the slump of concrete depends on such factors as the type, dosage, and time of addition, w/c and the nature or amount of cement. It has been found that for most types of cement, a superplasticizer improves the workability of concrete.

Some of the benefits/features of a super plasticizer are:

1. Specified strength can be achieved at high workability,
2. Faster placing with reduced labor and equipment costs, and
3. Low permeable concrete leading to enhanced durability.

Some of the benefits of a high-range water reducer are:

1. Higher strength can be achieved at "normal" workability without the need for additional cement,
2. Reduction in water content typically reduces bleeding,
3. Produces cohesive and workable concrete at high slump, and
4. Reduction in striking times.

Some of the applications of a superplasticizer are:

1. Incorporating the admixture during batching or on delivery at site increases workability to a flowing or self-leveling state,
2. Heavily reinforced sections,
3. Deep sections where normal consolidation is difficult,
4. High quality formwork finishes,
5. Pumped concrete (long pipelines), and
6. Compatible with all types of Portland cements, including sulfate-resisting cements and blends.

Stabilizer: Other types of admixtures may be incorporated as necessary, such as VMA for stability, air-entraining admixture (AEA) to improve freeze-thaw resistance, retarders for control of setting, etc. Lachemi et al. (2004) have carried out a study on the performance of new VMAs in enhancing the rheological properties and consistency of SCC. They found that the combined use of proper dosages of VMA and SP contribute to securing high-performance cement pastes that is highly fluid yet cohesive enough to reduce water dilution and enhance water retention.

2.3.4 Ranges of the quantities of the Constituent Materials for SCC

Typical ranges of proportions and quantities of the constituent materials for producing SCC are given below:

1. Water content: 170 to 176 kg/m^3 (Su et al., 2001). It should not exceed 200 kg/m^3 (EFNARC, 2002).
2. Cement content: 350 to 450 kg/m^3 (EFNARC, 2002),
3. Total powder content (i.e., cement + filler): 400 to 600 kg/m^3 (EFNARC, 2002),
4. Dosage of superplasticizer: 1.8% of the total powder content (by mass) (Su et al., 2001). However, the recommended dosage varies from product to product,
5. Water/powder ratio: 0.80 to 1.10 (by volume) (EFNARC, 2002). A water/powder ratio in the range of 0.30 to 0.38 (by mass) for tropical Middle East conditions (Munn, 2003; Kapoor et al., 2003),
6. Coarse aggregate content : 28 to 35% by volume of the mix, i.e., 700 to 900 kg/m^3 of concrete (EFNARC, 2002),
7. The sand content balances the volume of other constituents. The sand content should be greater than 50% of the total aggregate content (Munn, 2003; Kapoor et al., 2003). Sand ratio (i.e. volume ratio of fine aggregate to total aggregate) is an important parameter in SCC and the rheological properties increase with an increase in sand ratio. Sand ratio should be taken in the range of 50 to 57% (Su et al., 2001), and
8. The aggregate packing factor: 1.12 to 1.16 (Su et al., 2001).

2.4 MIX DESIGN FOR SCC

A flow-chart describing the procedure for design of SCC mix is shown in Figure 2.2 (EFNARC, 2002).

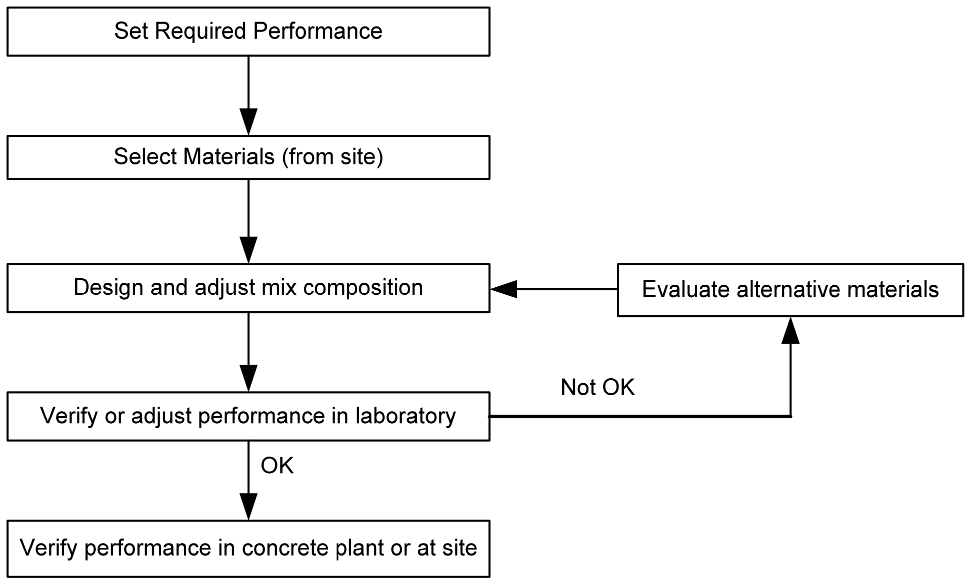

Figure 2.2: SCC mix design procedure (EFNARC, 2002).

Okamura and Ozawa (1995) have proposed a simple mix proportioning system for SCC. The coarse and fine aggregate contents are fixed so that self-compactibility can be achieved easily by adjusting the water/powder ratio and super plasticizer dosage only. The mix design procedure is as follows:

1. The coarse aggregate content (all particles larger than 4 mm and smaller than maximum size of aggregate) is fixed in the range of 50 to 60% of the solid volume or 28 to 35% of the concrete volume or 700 to 900 kg per cubic meter of concrete.
2. The fine aggregate content (all particles larger than 0.125 mm and smaller than 4 mm) is fixed in the range of 40 to 50% of the mortar volume.

3. The water/powder ratio is assumed in the range of 0.8 to 1.0 (by volume), depending on the properties of the powder (i.e. cement and filler having particles smaller than 0.125 mm).
4. The superplasticizer dosage and the final water/powder ratio are determined through trial mixes so as to ensure self-compactibility using U-flow, slump-flow and V-funnel tests. Target values are U-flow of 0 to 30 mm, slump-flow of 650 to 800 mm, and V-funnel time of 6 to 12 seconds.

A simple mix design method for SCC has been proposed by Su et al (2001). Compared with the method developed by the Japanese Ready-Mixed Concrete Association (JRMCA), this method is simple, easy for implementation and less time-consuming, requires a small quantity of binder and saves cost. This method consists of the following steps:

1. Determination of amounts of aggregates required using the other parameters, such as loosely piled densities of fine and coarse aggregates in SSD condition, volume ratio of fine aggregate to total aggregate and packing factor.
2. Determination of the cement content for a target design compressive strength.
3. Determination of the filler content and water content for the selected water/powder ratio and assumed air content, using the total absolute volume equation.
4. Determination of the dosage of superplasticizer based on the calculated total powder content.
5. Adjustment of the calculated water content for aggregate surface moisture or absorption, if any, and for water content in the superplasticizer.
6. Preparation of the trial mixes and carrying out tests for determining the properties of SCC.
7. Adjustment of mix proportions.

Patel et al. (2004) and Sonebi (2004a and 2004b) has derived statistical models relating the major SCC properties, such as slump flow, compressive strength, chloride permeability, etc, with the SCC mix parameters, such as water/powder ratio, total powder content, fly ash (filler) content, superplasticizer content, etc. These models can be used as economical tools for the optimum design of fly ash based SCC mixtures with desired properties in practical applications.

Nagamoto and Ozawa (1997) have proposed mixture proportions of self-compacting high performance concrete.

During production of SCC, tests on aggregate grading and moisture content should be carried out more frequently than usual, since SCC is more sensitive than normal concrete to variations in the properties of aggregates. Since the quality of freshly mixed concrete may fluctuate at the beginning of production, it is recommended that workability tests should be conducted until consistent and compliant results are obtained. SCC tends to dry faster than conventional concrete because there is little or no bleed water at the surface. Initial curing should therefore be commenced as soon as practicable after placing in order to minimize the risk of shrinkage cracking.

2.5 PROPERTIES OF HARDENED SCC

2.5.1 Compressive, Tensile, and Bond Strength

SCC with a compressive strength around 60 MPa can easily be achieved. The strength could be further improved by using fly ash as a filler (Kapoor et al., 2003). The characteristic compressive and tensile strengths have been reported to be around 60 MPa and 5 MPa, respectively (Brameshuber and Uebachs, 2002). Patel et al. (2004) reported 28-days compressive strength values ranging from 31 to 52 MPa. According to Nehdi et al. (2004) the 91-days compressive strength was in the range of 28 and 47 MPa. Xie et al. (2002) have reported a compressive strength of up to 80 MPa with a low permeability, good freeze-thaw resistance, and low drying shrinkage (Xie et al., 2002).

SCC mixes with a high volume of cement – limestone filler paste can develop higher or lower 28-day compressive strength, compared to those of vibrated concrete with the same water/cementitious material ratio and cement content, but without filler. It appears that the strength characteristics of the SCC are related to the fineness and grading of the limestone filler used (Bosiljkov, 2003).

SCC with water/cementitious material ratios ranging from 0.35 to 0.45, a mass proportion of fine and coarse aggregates of 50:50 with cement replacement of 40%, 50% and 60% by Class F fly ash and cementitious materials content of 400 kg/m3 being kept constant, obtained good results for compressive strength ranging from 26 to 48 MPa, which shows that an economical SCC could be successfully developed by incorporating high volumes of Class F fly ash (Bouzoubaa and Lachemi, 2001). According to Kumar et al., (2004) SCC containing more than 50% fly ash of the total powdered material produced compressive strengths ranging from 20 to 30 MPa at the ages of 3 and 7 days.

The bond behavior of SCC was found to be better than that of normally vibrated concrete (Dehn et al., 2000). The higher bond strength was attributed to the superior interlocking of aggregates due to the uniform distribution of aggregates over the full cross section and higher volume of cement-binder matrix (Kapoor et al., 2003).

2.5.2 Modulus Of Elasticity

Modulus of elasticity of SCC and that of a normally vibrated concrete, produced from the same raw materials, have been found to be almost identical. Although there is a higher paste matrix share in SCC, the elasticity remains unchanged due to the denser packing of the particles (Brameshuber and Uebachs, 2002).

The modulus of elasticity of concrete increases with an increase in the quantity of aggregate of high rigidity whereas it decreases with increasing cement paste content and porosity. A relatively small modulus of elasticity can be expected, because of the high content of ultra fines and additives as dominating factors and, accordingly, minor occurrence of coarse and stiff aggregates at SCC (Holschemacher and Klug, 2002). According to Holschemacher and Klug (2002), the modulus of elasticity of SCC can be up to 20% lower compared with normal vibrated concrete having same compressive strength and made of same aggregates. Leemann and Hoffmann (2005) reported an average modulus of elasticity of SCC to be 16% lower than that of normal vibrated conventional concrete for an identical compressive strength.

Results available indicate that the relationships between the static modulus of elasticity (E) and compressive strength (fc') were similar for SCC and normally vibrated concrete. A relationship in the form of E = k.fc0.5, where k is a constant, has been widely reported, and all values of this constant were close to the one recommended by ACI 318-02 for structural calculations for normal weight traditional vibrated concrete (Guidelines on SCC, 2000). Average 28-days modulus of elasticity of SCC has been reported to be 30 GPa corresponding to average 28-days cube strength of 55.41 MPa (Dehn et al., 2000).

2.5.3 Shrinkage And Creep

Shrinkage and creep of the SCC mixtures have not been found to be greater than those of traditional vibrated concrete (Guidelines on SCC, 2000; Persson and Terrasi, 2002). Ramsburg et al. (2003) have reported the shrinkage of SCC as follows: 0.03% for mixes with cement tested at 14 days, 0.03% to 0.04% for mixes with slag cement tested at 28 days, and 0.04 to 0.045% for mixes with calcined shale cement tested at 28 days. Shrinkage and creep of SCC coincided well with the corresponding properties of normal concrete when the strength was held constant (Persson, 2001). According to Kapoor et al (2003), the drying shrinkage of SCC is similar to that of conventional concrete.

The shrinkage and creep rates of SCC have been found to be approximately 30% higher at an identical compressive strength; this is because of the high amount of paste (Leemann and Hoffmann, 2005). Since SCC is rich in powder content and poor in the coarse aggregate fraction, addition of fiber will be effective in counteracting drying shrinkage (Corrinaldesi and Moriconi, 2004).

The 90 days drying shrinkage value as reported by Xie et al (2002) was 383 x 10-6 mm/mm. They suggested that SCC with UPFA (Ultra Pulverized Fly Ash) has higher mechanical properties, excellent impermeability and freezing resistance, and lower drying shrinkage.

In a study on SCC incorporating high volumes of class F fly ash, conducted by Bouzoubaa and Lachemi (2001), 112-days drying shrinkage was found in the range of 493 to 591 × 10-6 and 224-days drying shrinkage was in the range of 504 to 595 × 10-6 (Bouzoubaa and Lachemi, 2001).

In another study on SCC incorporating high volumes of class F fly ash, conducted by Patel et al (2004) 112-days drying shrinkage was found to be in the range of 330 to 667 × 10-6 (Patel et al., 2004).

2.5.4 Water Absorption and Initial Surface Absorption

Kapoor et al. (2003) have reported a water absorption value of 1% for SCC against 2% for normal vibrated concrete, obtained through the water absorption test conducted as per BS 1881: Part 122. An initial surface absorption value of 0.01 ml/m2/sec has been reported by Kapoor et al. (2003) for SCC against 0.02 ml/m2/sec for normal vibrated concrete, obtained through ISAT conducted as per BS 1881: Part 208.

2.5.5 Water Permeability

SCC with high strength and low permeability can easily be produced (Ouchi et al., 2001). Zhu and Bartos have found the permeability of SCC significantly lower as compared to that of normally vibrated concretes of the same strength grade. Kapoor et al. (2003) have reported a water permeability value of 5 mm for SCC against 10 mm for normal vibrated concrete, obtained through the water penetration test conducted as per DIN 1048.

The water permeability test, which is most commonly used to evaluate the permeability of concrete, is the one specified by DIN 1048. This test is useful in evaluating the relative performance of concrete made with varying mix proportions and incorporating admixtures. The Concrete Society (1987) provided some indication of typical and specified results for various concrete, as shown in Table 2.4.

Table 2.4: Assessment of Concrete Permeability according to Water Penetration Depth (The Concrete Society, 1987).

Depth of penetration, mm	Permeability
Less than 30	Low
30 to 60	Moderate
More than 60	High

It is known that most specifications control the durability of concrete almost exclusively by specifying certain requirements for concrete composition, strength and permeability. Hilsdorf (1995) stated that this approach frequently yields unsatisfactory results and there is a need to develop performance criteria that would allow more reliable estimates of the potential durability of a given concrete mix and of the probable durability of a concrete structure. It is generally accepted that the concrete's resistance to penetration of aggressive media governs concrete durability; therefore, a criterion that is based upon such resistance should be a more reliable approach (Hilsdorf, 1995).

Permeability tests, particularly those involving water penetration and chloride permeability, are increasingly used to test concrete to evaluate its conformance with the specifications, particularly for concrete exposed to aggressive conditions.

2.5.6 Rapid Chloride Permeability

Rapid chloride permeability of concrete is determined using a standard test method for electrical indication of concrete's ability to resist chloride ion penetration, covered by ASTM C 1202. The rapid chloride permeability test evaluates the performance of various cementitious materials based on the accelerated diffusion of chloride ions under the application of an external electric field. The chloride ion penetrability of different SCC mixes, as reported by Ramsburg et al, (2003) are as follows: 2,000 to 4,000 coulombs (categorized as "moderate") for mixes with cement, 1,000 to 2,000 coulombs (categorized as "low"); for mixes with slag cement, and 100 to 1,000 coulombs (categorized as "very low"); for mixes with calcined shale cement. Kapoor et al. (2003) have reported a rapid chloride permeability value of 620 coulombs for SCC against 1970 coulombs for normal vibrated concrete, obtained through the rapid chloride permeability test conducted as per ASTM C-1202-94.

According to Plante and Bilodean (1989), the incorporation of supplementary cementing materials in concrete contributes to the reduction in the porosity of the system, which, in turn, results into a reduction in the chloride ion permeability of concrete.

Patel et al. (2004) reported the rapid chloride permeability in the range of 772 and, 1379 Coulombs with percentage of fly ash in the range of 30% and 60%. According to Nehdi et al. (2004) the 91 days rapid chloride penetration value was in the range of 400 and 900 Coulombs. Table 2.5 shows guidelines to evaluate the chloride ion permeability based on the charge passed.

Table 2.5: Relationship between charge passed and chloride permeability (ASTM C-1202-94).

Charge Passed (Coulombs)	**Chloride Ion Penetrability**
More than 4,000	High
2,000 to 4,000	Moderate
1,000 to 2,000	Low
100 to 1,000	Very Low
Less than 100	Negligible

2.6 ECONOMICS OF SCC

Savings in labor costs might offset the increased cost related to the use of more cement and superplasticizer, and the mineral admixtures, such as pulverized fuel ash (PFA), ground granulated blast furnace slag (GGBS) or lime stone powder (LSP), could increase the fluidity of the concrete, without any increase in the cost. These supplementary cementing materials also enhance the rheological parameters and reduce the risk of cracking due to the decreased heat of hydration, and therefore, improve the durability (Sonebi, 2004b).

2.7 LITERATURE SUMMARY

A brief literature review on SCC, as presented above, indicates that the SCC has several advantages over the traditional vibrated concrete, mainly the ease and precision in placement and lack of vibration. SCC can be produced using the same raw materials and has either similar or better strength and durability properties compared to the traditional vibrated concrete. Some information pertaining to the production and performance of SCC is available in literature in context to the UAE. However, no published information is available on the study of SCC in the Eastern Saudi Arabia. As mentioned earlier, the aggregate available in this region is of marginal quality. A study on SCC produced with local aggregates is therefore needed to promote interest in SCC.

CHAPTER 3

DESIGN OF A SUITABLE SCC MIX

3.1 INTRODUCTION

In this chapter, details of selecting a suitable SCC mix for evaluating its performance in terms of strength and durability are described. For selecting a suitable mix using local aggregates, eight trial mixes were considered by varying the mix parameters, such as quantity of filler and superplasticizer and fine aggregate/coarse aggregate ratio, while keeping the water/powder ratio constant. Proportioning of the trial mixes was carried out using the absolute volume method. Each mix was tested for self-compactibility and compressive strength. Finally, a suitable mix was selected based on the self-compactibility and strength test results.

3.2 CONCRETE CONSTITUENTS FOR TRIAL MIXES

The following materials were utilized in the trial mixes.

3.2.1 Cement

ASTM C 150 Type I Portland cement which is extensively used in Saudi Arabia, was used in this study. The specific gravity of cement used was taken as 3.15.

3.2.2 Coarse aggregates

The coarse aggregates used in this study were crushed limestone processed from the local quarries in Abu Hadriah. The maximum aggregate size was 20 mm. Grading of coarse aggregates is shown in Table 3.1. The average values of specific gravity and absorption of the coarse aggregates, determined in accordance with ASTM C 127, were 2.5 and 1.5 %, respectively.

Table 3.1: Grading of coarse aggregates.

Sieve opening	Percent passing
¾ in.	100
½ in.	90
3/8 in.	45
3/16 in.	0

3.2.3 Fine Aggregates

Dune sand was used as fine aggregate. The specific gravity and absorption of the fine aggregates are typically 2.6 and 0.57%, respectively. The grading of the fine aggregate is presented in Table 3.2.

Table 3.2: Grading of fine aggregates

Sieve	Percent passing
#4	100
#8	100
#16	100
#30	76
#50	10
#100	4

3.2.4 Filler

A highly pulverized fly ash commercially known as Super-pozz® was used as a filler. The specific gravity of Super-pozz® used in this study was 2.15.

Admixtures:

Superplasticizer by the trade name of "Structuro 220" from Fosam Company limited, was used as superplasticizer. The specific gravity of the superplasticizer as given by the supplier is 1.08 and the pH is 6.5 with chloride content of less than 0.1%. Structuro 220 is developed for use in high performance concrete where increased early and ultimate compressive strength is required. The level of fluidity is governed chiefly by the dosing of the superplasticizer. However, overdosing may lead to the risk of segregation and blockage.

A high performance cohesion agent named "Structuro 420" from Fosam Company limited, specially designed to ensure a good consistency and stability in concrete with very high fluidity, was used as a stabilizer. The specific gravity of stabilizer "Structuro 420" as specified by the supplier is 1.01 with chloride content of less than 0.1%.

3.3 TRIAL MIXES

Eight trial mixes were prepared by varying the Super-pozz® content, fine to coarse aggregate ratio, and superplasticizer content. Two levels of the Super-pozz®: 100 and 125 kg/m3, two levels of fine to coarse aggregate ratio: 1 and 1.1 (by mass), and two levels of superplasticizer (Structuro 220) : 0.8 and 1.0% (by mass of powder) were used for preparing and testing eight trial mixes. For each trial mix, a constant water/powder ratio of 0.38 (by mass) and a constant amount of stabilizer (Structuro 420) 3.03 kg/m3 of concrete were taken. Proportions of the trial mixes, determined using the absolute volume method, are presented in Table 3.3.

Table 3.3: Weights of constituents in trial mixes

Trial Mix #	Mix variables			Quantities of mix ingredients (kg/m^3)							
	FA/CA ratio	Filler content (kg/m^3)	Structo 220 (%)	Water	Powder		FA	CA	Str. 220	Str. 420	Density
					Filler	Cement					
TM1	1	100	0.80	190.0	100	350	846	846	3.6	3.03	2339
TM2	1	100	1.00	189.6	100	350	846	846	4.5	3.03	2339
TM3	1	125	0.80	198.7	125	350	819	819	3.8	3.03	2318
TM4	1	125	1.00	198.1	125	350	819	819	4.7	3.03	2318
TM5	1.1	100	0.80	189.4	100	350	888	807	3.6	3.03	2341
TM6	1.1	100	1.00	188.9	100	350	888	807	4.5	3.03	2341
TM7	1.1	125	0.80	198.0	125	350	859	781	3.8	3.03	2319
TM8	1.1	125	1.00	197.4	125	350	859	781	4.7	3.03	2320

3.4 SELF-COMPACTABILITY TESTS ON TRIAL MIXES

Batching of trial mixes was carried out according to their respective proportions, presented in Table 3.3. The concrete ingredients were mixed in a revolving drum type mixer for about three to five minutes to attain uniform consistency. The self-compactibility of the trial mixes was evaluated using slump flow test, V-funnel test, and U-box test.

3.4.1 Slump Flow Test

The slump flow test was carried out according to ASTM C 143. Figure 3.1 shows the accessories used for the slump flow test. The dimensions of the frustum of cone used in this test are same as that used for slump test (i.e. 200 mm bottom diameter, 100 mm top diameter and 300 mm height). The diameter of the concrete after allowing its full flow, as shown in Figure 3.2, was taken as slump flow value

Figure 3.1: Accessories for slump flow test.

Figure 3.2: Measurement of slump flow.

3.4.2 V-Funnel Test

V-funnel test was used to determine the filling ability (i.e. flowability) of SCC. The dimensions of V-funnel, similar to that used by Khayat et al. (2004) were adopted, shown in Figure 3.3.

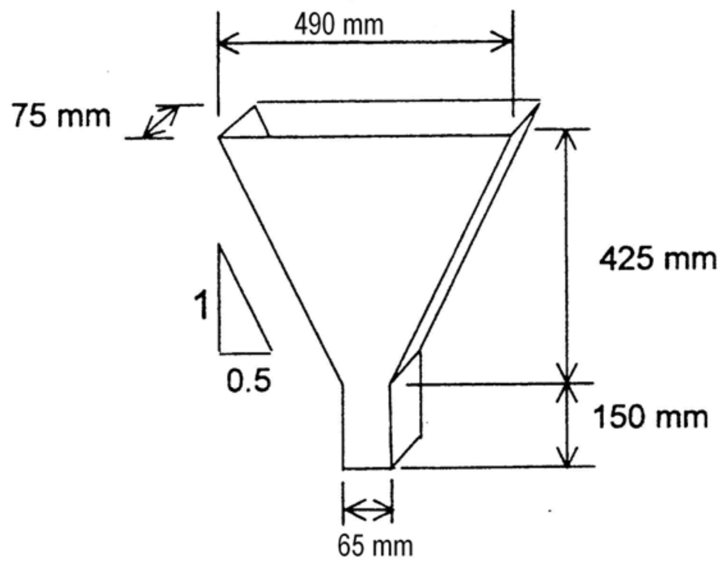

Figure 3.3: Schematic diagram of V-funnel (Khayat et al., 2004).

A V-funnel using the dimensions of Figure 3.3 was fabricated in the laboratory for this study. A view of the V-funnel is shown in Figure 3.4.

Figure 3.4: Locally fabricated V-Funnel utilized to evaluate the segregation resistance of SCC.

Procedure for conducting the V-funnel test includes the following steps:

1. The V-funnel is kept firm on the ground and the inside surfaces of the funnel are moistened and the trap door is kept open to allow any surplus water to drain.
2. About 12 liters of concrete is poured into V-funnel to fill it completely without compacting or tamping, while keeping the trap door closed and a bucket placed underneath.
3. After filling the V-funnel, concrete level is simply struck off with the top with a trowel.
4. After 10 sec of filling, the trap door is opened to allow concrete to flow out under gravity. The stopwatch is started when the trap door is opened, and the time taken for complete discharge of concrete from funnel is recorded as 'flow time'. As recommended, the whole test is to be performed within 5 minutes.

3.4.3 U-Box Test

The U-box test was used to measure the filling ability of the mixes. The apparatus used was similar to that used by Khayat et al. (2004), which consists of a vessel that is divided by a middle wall into two compartments, as shown in Figure 3.5.

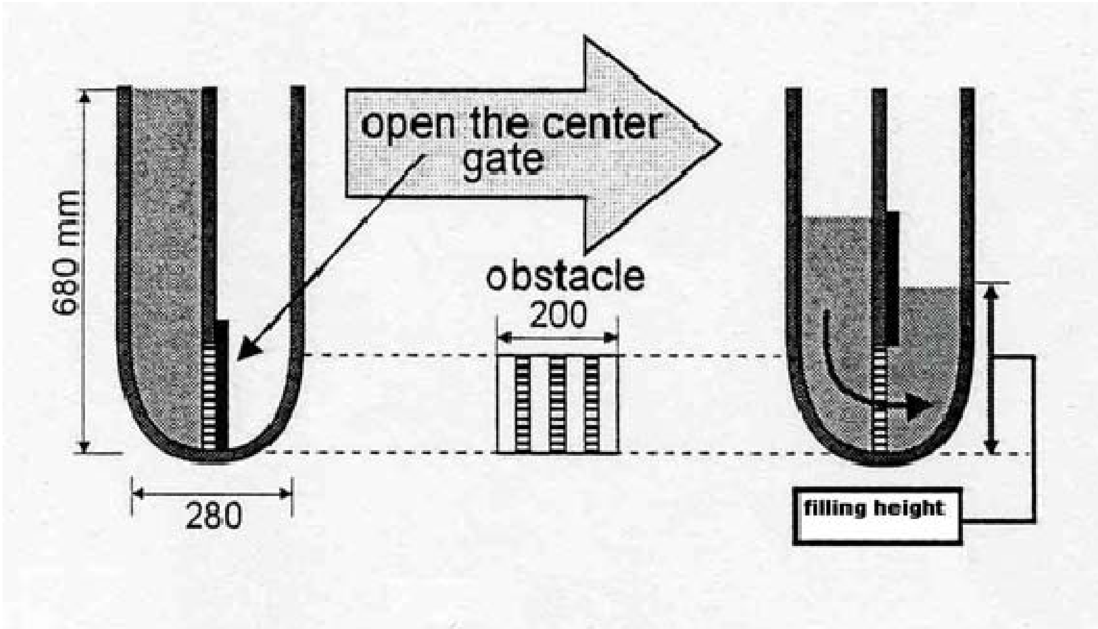

Figure 3.5: Schematic representation of U-Tube (Khayat et al., 2004).

As shown in Figure 3.5, an opening with a sliding gate is fitted between the two sections. Reinforcing bars with normal diameters of 13 mm are installed at the gate with centre-to-centre spacing of 50 mm. This creates a clear spacing of 35 mm between the bars. Concrete filled in the left hand box is allowed to pass through this obstacle and to fill the right hand box. More will be the height of filling in the right hand box more will be the filling ability of the SCC mix.

A U-box apparatus was built in the laboratory using the dimensions suggested in EFNARC (2000). A view of the built apparatus is shown in Figure 3.6.

Procedure for conducting the U-box test includes the following steps:

1. The apparatus is set on firm ground, ensuring that the sliding gate can open freely and then be closed.
2. The inside surfaces of the apparatus are moistened, any surplus water is removed.
3. The left hand compartment of the apparatus is filled with about 20 liters of concrete.
4. After allowing concrete filled in the left hand compartment to stand for 1 minute, the sliding gate is then opened by lifting it up and concrete is allowed to flow upwards into the right hand compartment
5. After the concrete has come to rest, the height of the concrete is measured in both compartments at two places and the mean heights (say H1 as mean height in the left compartment and H2 as mean height in the right compartment) are calculated.
6. The 'filling height' is then calculated as H1- H2. Like the V-funnel test, the whole U-box test is also performed within 5 minutes.

Figure 3.6: Locally fabricated U-box to evaluate passing ability of concrete.

3.5 CASTING AND CURING OF TRIAL SPECIMENS

From each trial mix, a total of 12 cylindrical concrete specimens, 75 mm in diameter and 150 mm high, were cast for determining the compressive strength after 3, 7, 14, and 28 days of water curing. The moulds were oiled properly for easy demolding. The moulds were filled with concrete in three layers. Since this is a Self Compacting concrete, the concrete will flow under its own weight, therefore, the molds were not vibrated. After casting and finishing, the specimens were covered with plastic sheet to avoid loss of water due to evaporation. The specimens were demolded after 24 hours of casting and then they were transferred to a curing tank placed at the laboratory temperature of 18 to 20□C. The specimens were cured in the water tank for 28 days.

3.6 COMPRESSIVE STRENGTH OF TRIAL MIXES

The specimens were capped with a sulfur compound to obtain a horizontal surface. Prior to capping, the diameter and height of the specimens were measured. The capped specimens were then placed in a compression testing machine of 700 kN capacities. The compressive strength was determined according to ASTM C 39. Compressive strength was calculated by dividing the failure load by the average cross sectional area of the specimen. The compressive strength testing of cylinders is shown in the Figure 3.7.

Figure 3.7: A Cylindrical Concrete Specimen being tested to evaluate the compressive strength.

3.7 SELECTION OF A SUITABLE MIX

Results of the self-compactibility and strength tests conducted on eight trial mixes are presented in Table 3.4.

Table 3.4: Self-compactibility and compressive strength of trial mixes.

Trial Mix #	Self-Compactibility properties			Strength (MPa)			
	Flow table* (mm)	V-Funnel** (sec)	U-tube*** (mm)	3 Days	7 Days	14 Days	28 Days
TM1	650	10	19	25.90	27.87	32.45	33.19
TM2	690	6	5	25.50	29.56	33.07	39.70
TM3	740	8	29	23.97	28.03	30.97	31.96
TM4	750	8	28	27.42	30.03	33.59	39.39
TM5	680	8	36	21.75	26.83	30.48	34.68
TM6	720	10	5	26.98	30.67	33.64	41.52
TM7	770	7	6	26.49	29.45	33.38	39.28
TM8	760	6	6	26.36	29.91	32.44	38.69

*Flow table value should be in the range of 650 to 800 mm (EFNARC, 2002).

** V-funnel value should be in the range of 6 to 12 sec (EFNARC, 2002).

*** U-box value should be in the range of 0 to 30 mm (EFNARC, 2002).

The values of compressive strengths of each trial mix at different curing ages, as presented in Table 3.4, were plotted as shown in Figure 3.8 to show the evolution of compressive strength with curing period. Like traditionally consolidated concrete, SCC also continues to gain strength with curing time. The 28-day compressive strength is approximately 20-30% higher than the 7-day strength.

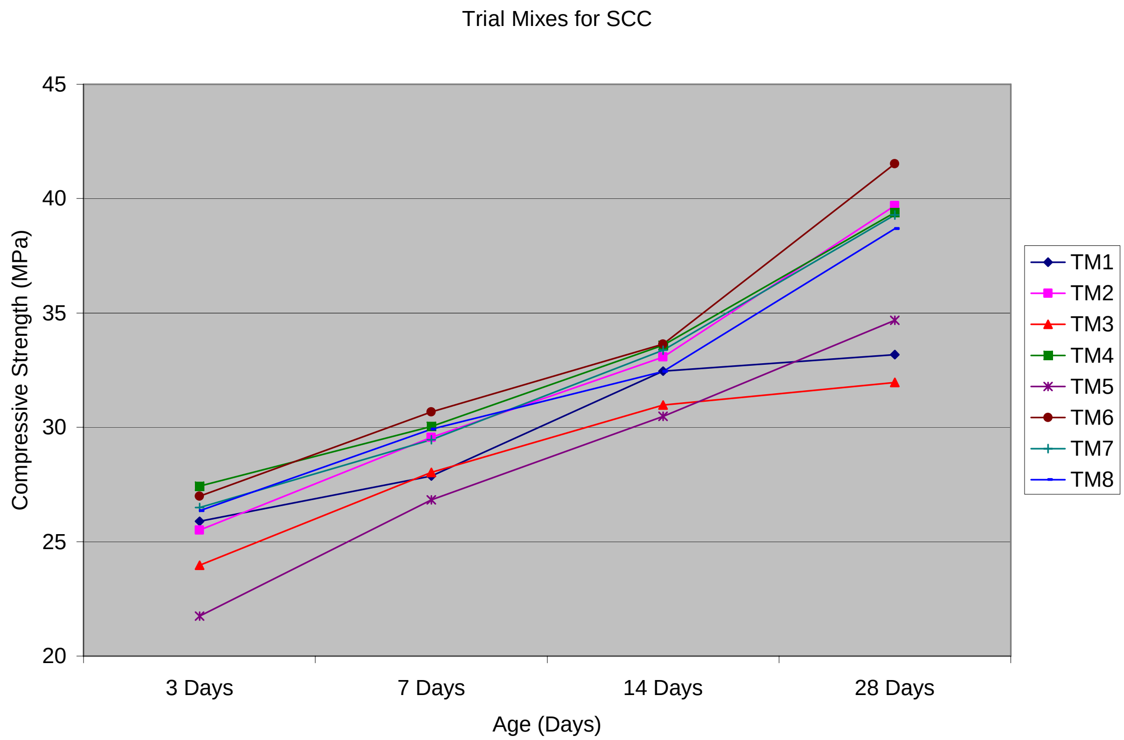

Figure 3.8: Variation of compressive strength of trial mixes with curing age.

As observed from Table 3.4, all the trial mixes satisfied the self-compactibility criteria, except mix TM5, in which the filling height was more than the permissible limit. The highest 28-day compressive strength of 41.5 MPa was achieved in mix TM6 and the lowest value of 32 MPa was noted in mix TM3. Interdependency of the mix ingredients on self-compactibility property and strength makes it difficult to identify the effect of one ingredient. Mixes TM2, TM4, TM6, TM7, and TM8 are all suitable mixes, as they show superior compressive strength and similar self-compactability. Out of these, trial mix # TM6 was considered for further investigation.

CHAPTER 4

EVALUATION OF HARDENED PROPERTIES OF SELECTED SCC MIX

4.1 INTRODUCTION

In this chapter, the details of casting and testing of the selected SCC mix for evaluating its hardened properties are presented. After curing, the concrete specimens were exposed to normal, heat-cool and wet-dry exposures for a period of four months and then they were tested for compressive strength and durability properties. Durability tests on concrete specimens included:

1. Rapid chloride permeability,
2. Water absorption,
3. Water permeability by DIN 1048
4. Water permeability by Darcy's test, and
5. Drying shrinkage.

4.2 SPECIMENS

Specimens required for the determination of compressive strength and durability properties are presented in Table 4.1.

Table 4.1: Specimens prepared for determining the properties of hardened concrete.

Test	Test Standard	Specimen
Compressive strength	ASTM C 39	150 x 300 mm cylinder
Drying shrinkage	ASTM C 426	100 x 100 x 400 mm prism
Water absorption	BS 1881:Part 122	75 x 150 mm cylinder
Depth of water penetration	DIN 1048	150 mm cube
Water permeability	Darcy's principle	100 mm long, 100 mm outer diameter and 25 mm thick hollow cylinder
Chloride permeability	ASTM C 1202	75 x 150 mm cylinder

4.3 SELECTED SCC MIX PROPORTIONS

Trial mix # TM6 was selected as a suitable mix which satisfies self-compactibility criteria and has highest 28-days compressive strength of 41.52 MPa as described in Chapter 3. The following proportions were used for this mix:

Water-powder ratio:	0.38
Water content:	188.9 kg/m^3
Cement content:	350 kg/m^3
Fine aggregate content:	888 kg/m^3

Coarse aggregate content: $807\ kg/m^3$

Super Pozz content: $100\ kg/m^3$

Super Plasticizer (Structuro 220): $4.5\ kg/m^3$

Stabilizer (Structuro 420): $3.03\ kg/m^3$

4.4 CASTING AND CURING OF SPECIMENS

The specimens were cast and cured in the similar manner as that of the specimens for the trial mixes, described in the previous chapter.

4.5 EXPOSURES OF SPECIMENS

After 28 days of water curing, the specimens were divided into three groups and exposed to conditions detailed in Table 4.2.

Table 4.2: Details of Exposure conditions.

Exposure	**Duration**
Control (lab environment)	Four months
Heat-cool (Heating at 40ºC for 2 days and then cooling at room temperature for 2 days)	Four months
Wet-dry (Wetting for 2 days and then drying at 30ºC for 2 days)	Four months

4.6 TESTS

4.6.1 Compressive Strength

The concrete specimens were tested for compressive strength after seven and 28 days of water curing and after four months of exposures to normal, heat-cool and wet-dry conditions. The testing procedure was similar to that for the specimens for the trial mixes, described in the previous chapter.

4.6.2 Drying Shrinkage

Prismatic concrete specimens measuring 100 x 100 x 300 mm were cast to determine the drying shrinkage of SCC. In order to measure the shrinkage, strain gauges were embedded in the specimens prior to casting of concrete. These specimens were cured for 28 days. A data logger was used for measuring the gauge readings for about 3 months. Strains were recorded every day till the end of the testing period. This was done to generate enough points to plot the shrinkage strain evolution curves. Figure 4.1 shows the specimens used for shrinkage measurements and Figure 4.2 shows the complete set-up for measuring the drying shrinkage.

Figure 4.1: Specimens utilized for Drying Shrinkage measurements.

Figure 4.2: Set up utilized for drying shrinkage measurements.

4.6.3 Water Absorption

The water absorption of the concrete cylindrical specimens was determined according to ASTM C 642. Figure 4.3 shows concrete cylinders soaked in water bath determining water absorption.

Figure 4.3: Specimens for determining Water Absorption.

The 75 x 150 mm cylindrical concrete specimens were dried in an oven (shown in Figure 4.4) at a temperature of 100 to 1100 C for not less than 24 hours. They were allowed to cool to room temperature and weighed (W1). Then they were immersed in a water bath at approximately 250 C for not less than 48 hours. After removing from the water bath, the cylinders were surface-dried and weighed (W2). Water absorption was determined using the following relationship:

Absorption % = (W2-W1) / W1 x 100.

Figure 4.4: Concrete specimens placed in the oven.

4.6.4 Water Permeability

The water permeability of self compacting concrete specimens was evaluated by conducting DIN 1048 and also by Darcy's principle.

WATER PENETRATION TEST

The depth of water penetration was determined according to DIN 1048. Figures 4.5 and 4.6 show the experimental test set-up to determine the depth of water penetration. The depth of water penetration was determined after four months of exposure to laboratory, heat-cool and wet-dry conditions.

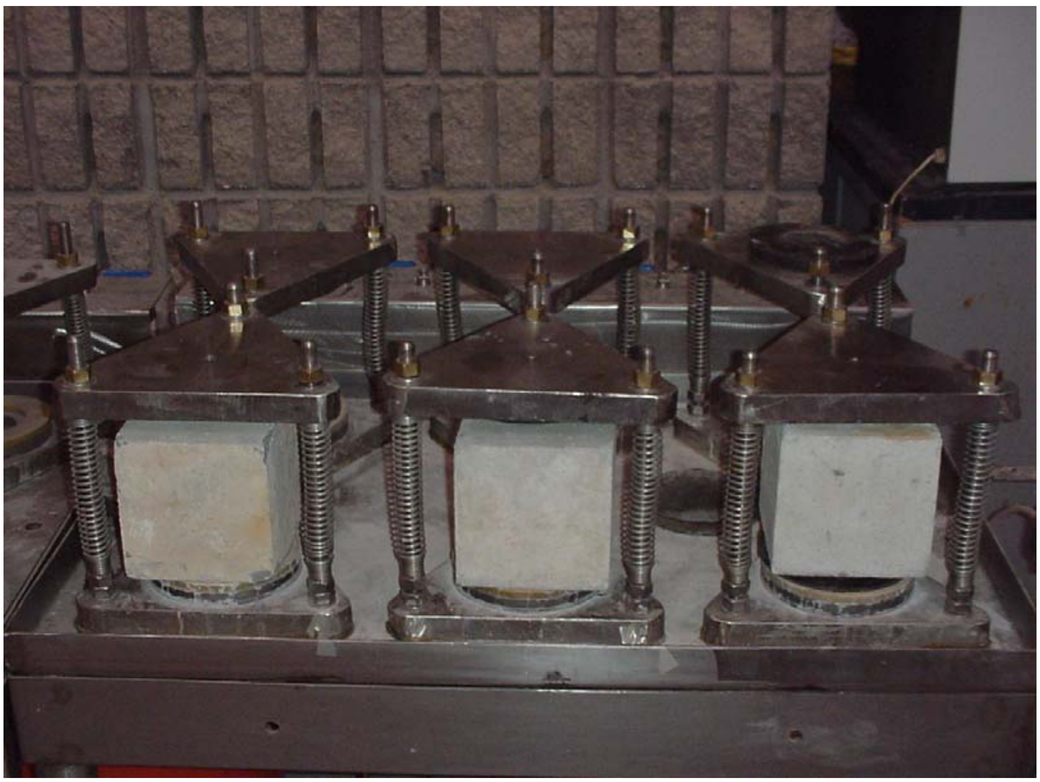

Figure 4.5: Specimens placed in water penetration cell.

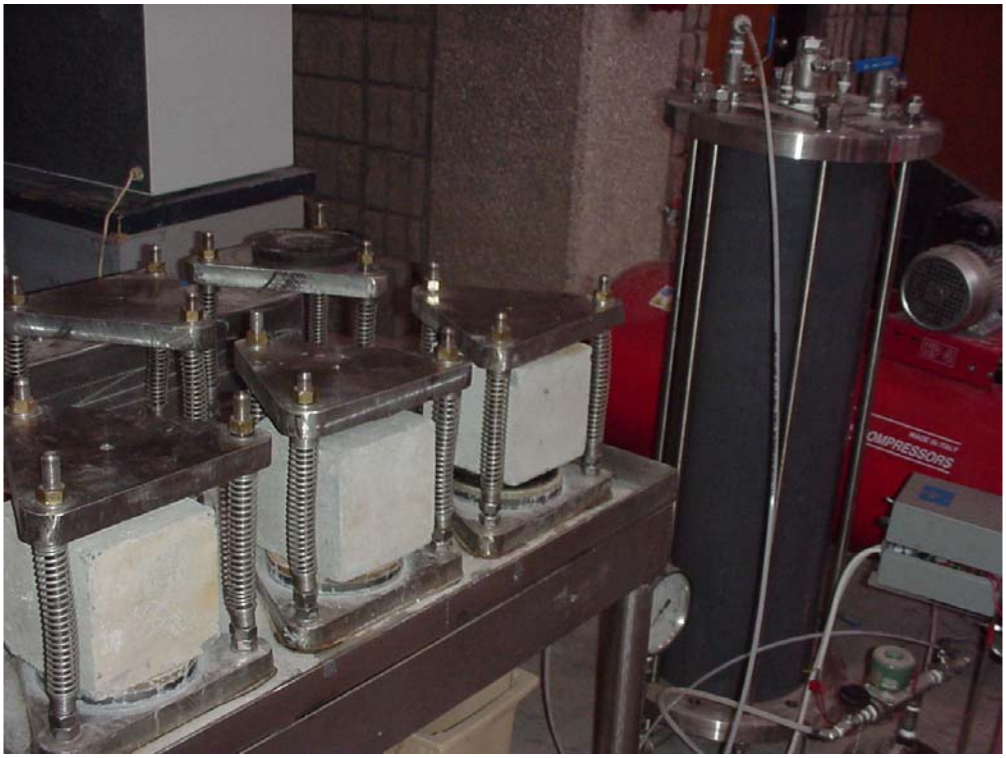

Figure 4.6: Water penetration test set-up

The concrete specimens were exposed to a water pressure of 0.5 N/mm^2 which is equivalent to a pressure of five bars. This pressure was maintained invariant for a period of 72 hours. Immediately, after the completion of the test, the specimens were taken out and split open into two halves with the face which was exposed to water facing down. Figure 4.7 shows the split permeability specimen showing depth of water penetration. The water penetration profile on the concrete surface was then marked and the maximum depth of water penetration in three specimens was recorded and average values are reported.

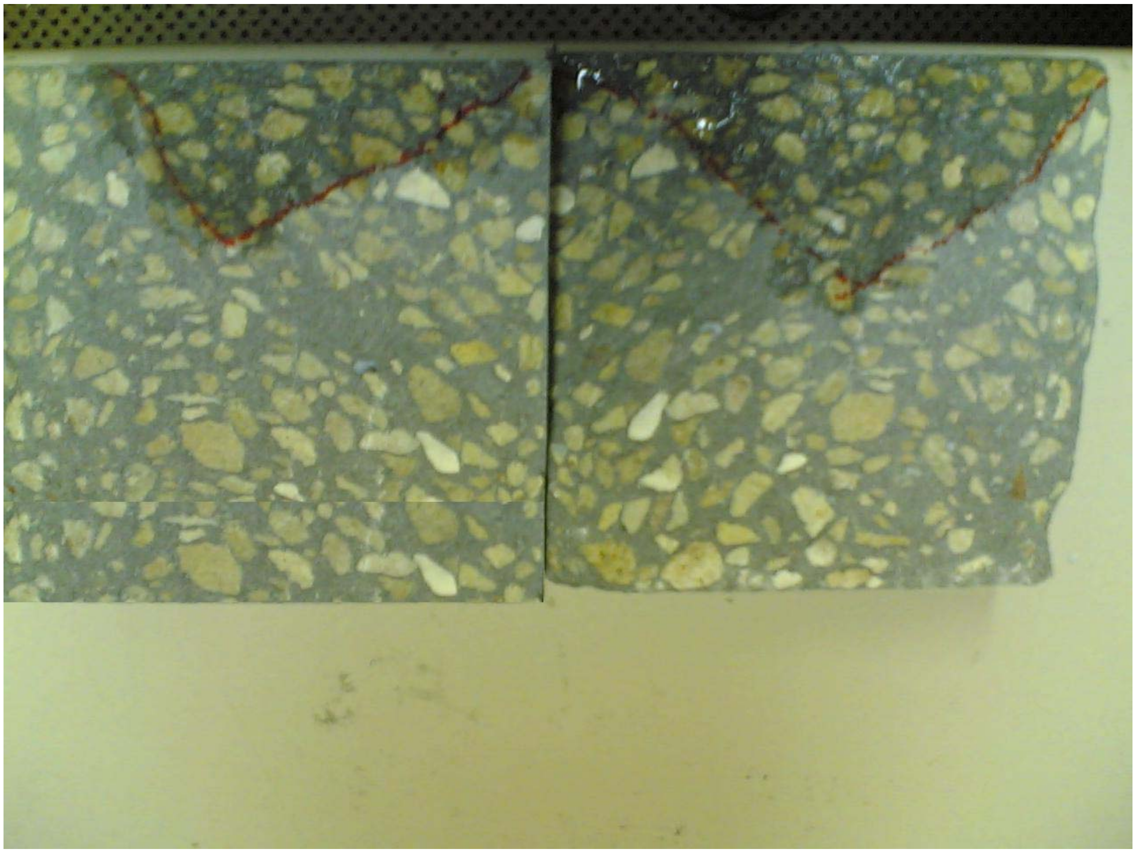

Figure 4.7: Concrete specimen showing Depth of Water Penetration.

WATER PERMEABILITY TEST (DARCY'S PRINCIPLE)

The water permeability of concrete was also evaluated using Darcy's principle. A 100 mm long, hollow cylindrical concrete specimen with 100 mm outer diameter and 50 mm thick internal diameter (Figure 4.8) were used to evaluate water permeability by Darcy's principle of constant head method. In this test 50 psi pressure was applied.

In the absence of a readily available test apparatus, it was necessary to develop an in-house apparatus for the measurement of permeability. A test setup based on the principle of the test of water penetration depth, recently proposed by Li and Chau (2000), was developed to measure permeability using hollow cylindrical concrete specimens shown in Figure 4.8. The proposed water permeability test setup can be claimed to be a valid means of characterizing concrete permeability with high efficiency accompanied by excellent reproducibility.

Figure 4.8: Hollow cylindrical concrete specimen used for determining Water Permeability according to Darcy's principle.

Figure 4.9 shows the schematic representation of the water permeability test setup. The equipment and accessories required for developing the test setup for permeability measurement were purchased and fitted, as shown in Figure 4.10, according to the recommendations by Li and Chau (2000). It essentially consists of a water-tight cell that houses another cell containing the hollow specimen. The specimen is sealed water tight at top and bottom using rubber gaskets. It is then subjected to a water pressure and the flow of water through the thickness of the hollow specimen is measured for the calculation of permeability.

The test procedure is briefly discussed below:

1. The specimen is placed in the chamber with top and bottom lids with rubber pads. The lids are fully tightened to prevent any leak.
2. Air bubbles from the water pressure cylinder are removed and then nitrogen gas is applied at a pressure of 50 psi (0.344 MPa) through the pressure cylinder (Figure 4.9) to push the piston.
3. A patriot extensometer is connected to the piston head and is calibrated with respect to the movement of the piston under pressure to measure the seeping volume of water into the cylinder.
4. The piston pushes the water head in water pressure cylinder forcing the water to apply pressure against the hollow cylindrical specimen.
5. The volume of water entering through the hollow specimen is recorded automatically on a data logger, as the movement of the piston head defines the volume of water displaced.
6. The amount of water flow is recorded over time and then from the steady-state water flow, the flow rate Q is calculated.

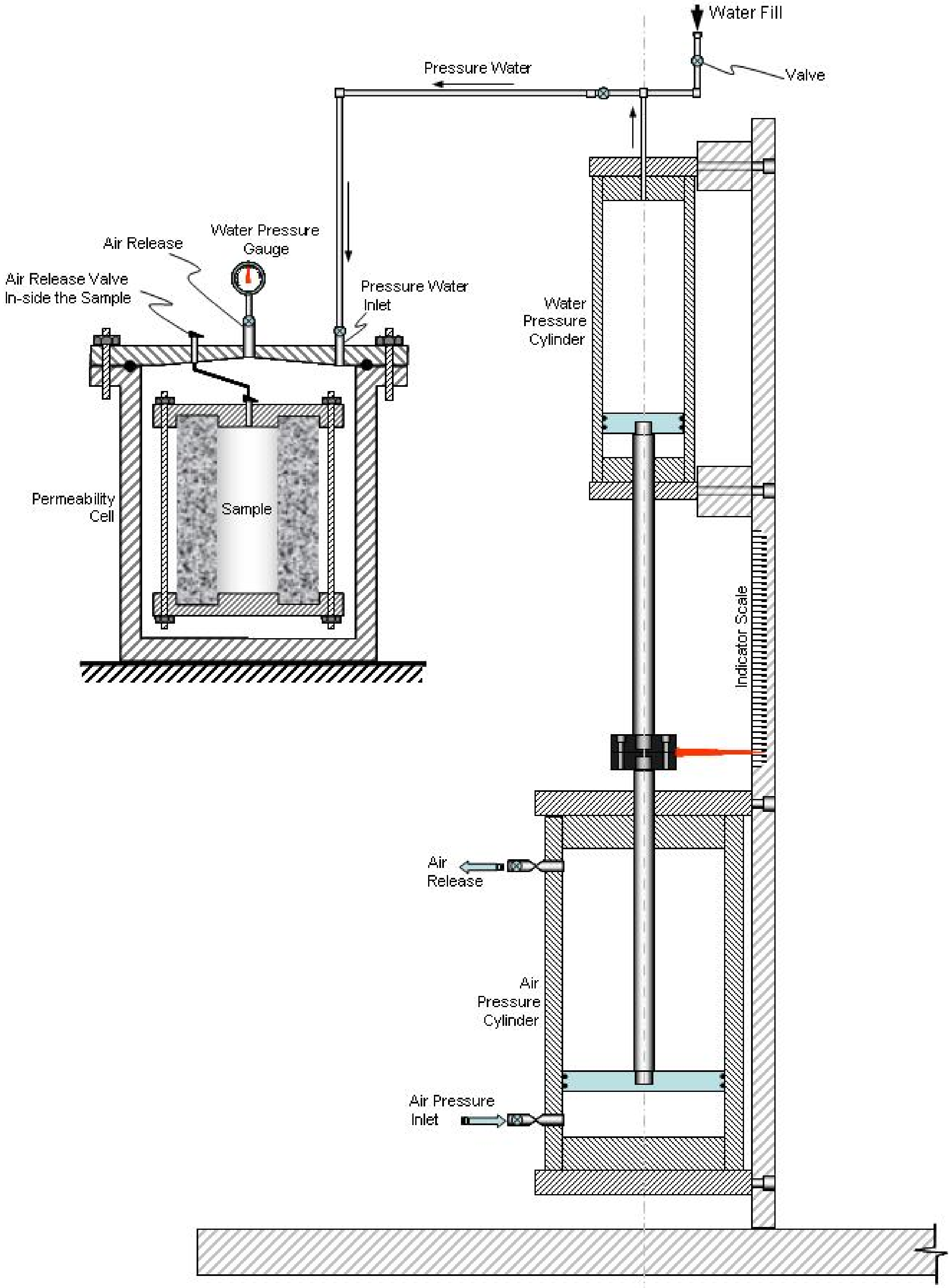

Figure 4.9: Schematic diagram for permeability measurement.

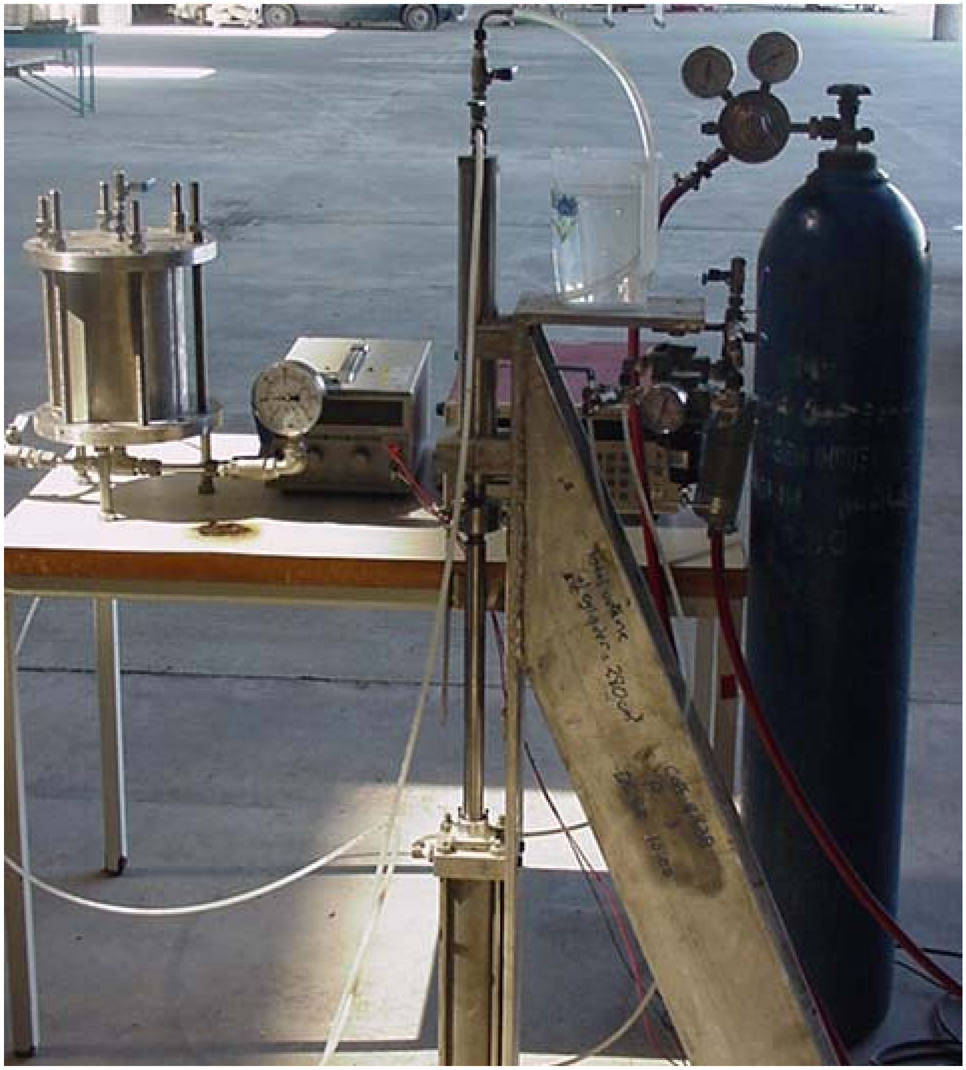

Figure 4.10: Test Setup for permeability measurement.

The following Darcy's formula was used to determine the coefficient of permeability using the measured steady-state water flow rate through specimen under a constant pressure.

$$K = \frac{QL}{HA} \tag{4.1}$$

where:

K = coefficient of permeability, cm/s

L = water travel length = thickness of the hollow concrete specimen (25.4 mm)

A = area through which water flows (32429 mm^2)

H = constant pressure applied = 50 psi (0.344 MPa)

Q = measured steady-state water flow rate

The steady-state Q-values were determined using the flow rate (Q) versus time (t) plots obtained from the actual measurements. A typical plot is shown in Figure 4.11.

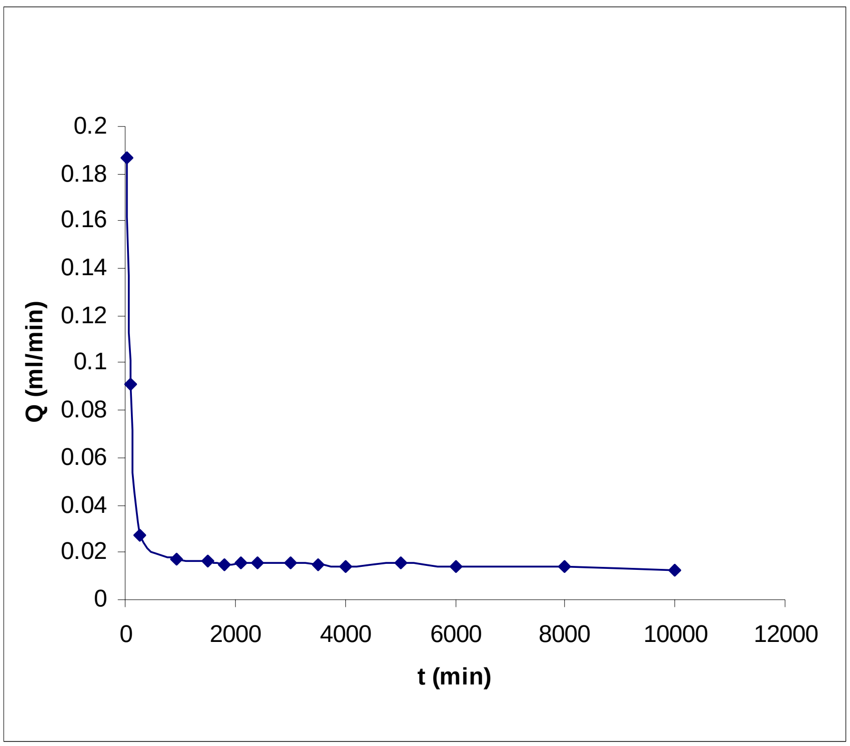

Figure 4.11: Flow rate (Q) versus time (t) plot.

4.6.5 Rapid Chloride Permeability

The rapid chloride permeability of concrete specimens was determined according to ASTM C 1202. This method determines the electrical conductance of concrete. From the 75 x 150 mm cylinders, a 50 mm thick disk was cut from the center of the specimen. The curved surface of the disk was coated with an epoxy coating to avoid evaporation of moisture during testing. The disk specimens were saturated with water under vacuum and kept saturated for about 24 hours.

In this test, the disk specimen was clamped between two cells and a potential difference of 60 V DC was maintained across them. The upstream cell was filled with 3% sodium chloride (NaCl) solution, and the downstream cell was filled with 0.3 M sodium hydroxide (NaOH) solution. A resistor is built into the circuit and the current is recorded at periodic intervals by connecting the resistor to a data logging system. The total charge passed, in coulombs is recorded over a six hour period. The whole test has to be performed at room temperature of 20 to 250C. Typical chloride permeability cells and specimens are shown in Figures 4.12 and 4.13, respectively.

Figure 4.12: Rapid Chloride Permeability Test Cell.

Figure 4.13: Specimens utilized for determining Rapid Chloride Permeability.

Since a 75 mm nominal diameter specimen was used, the test results were adjusted, i.e. a correction factor was applied using the following relationship:

$$Q_s = Q_x * (95 / x)^2 \qquad (4.2)$$

Where: Qs is the charge passed through the 95 mm diameter specimen, Qx is the charge passed through the specimen of x mm diameter. Figure 4.14 shows the chloride permeability test set up.

Figure 4.14: Experimental set up to determine the Rapid Chloride Permeability.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 COMPRESSIVE STRENGTH

The compressive strength of SCC specimens is summarized in Table 5.1. The average compressive strength values for all the specimens (7 days cured specimens, 28 days cured specimens, specimens subjected to normal, heat-cool and wet-dry exposures after 28 days curing) are plotted in Figure 5.1. The Compressive strength values compared to 28-days values are presented in Table 5.2.

The compressive strength of the mix after 7 and 28 days of water curing are close to the respective values obtained for the same mix during the trial test (Table 3.4). The 7-days compressive strength was about 75% of the 28-days compressive strength. A 28-days average compressive strength of around 40 MPa, of the selected SCC mix, is quite satisfactory for the intended use of concrete in the local conditions. Al-Kutti (2005) reported that the 28 days compressive strength of conventional concrete prepared with 20% fly ash at a water/cementitious material ratio of 0.35 and total cementitious material content of 400 kg/m3 to be in the range of 35 to 40 MPa. This indicates that the strength of the selected SCC mix is almost similar to that of the conventional concrete. Further, the value of the compressive strength of the selected SCC mix is well within the range of

28-days compressive strength of SCC, as recently reported by various researchers (Patel et al., 2004; Zhu and Bartos, 2003; Bouzoubaa and Lachemi, 2001).

Table 5.1: Compressive Strength of SCC specimens.

Sample #	**Compressive strength (MPa)**				
	7 Days water curing	28 Days water curing	4 Months Normal Exposure	4 Months Wet-Dry Exposure	4 Months Heat-Cool Exposure
1	32.27	43.64	45.77	45.29	56.20
2	28.40	37.78	49.35	52.28	49.43
3	29.06	38.90	44.48	50.49	53.03
Average	**29.91**	**40.11**	**46.53**	**49.36**	**52.89**

From Table 5.2 it can be noted that the compressive strengths of the specimens exposed to all the three exposures was more than the 28-days compressive strength. Compared to the 28-days compressive strength, the compressive strengths of specimens exposed to normal, wet-dry, and heat-cool exposures are higher by about 17%, 24%, and 32%, respectively. Further, compared to the compressive strength of concrete specimens exposed to normal conditions, the compressive strengths of specimens exposed to wet-dry and heat-cool conditions are higher by about 7% and 15%, respectively.

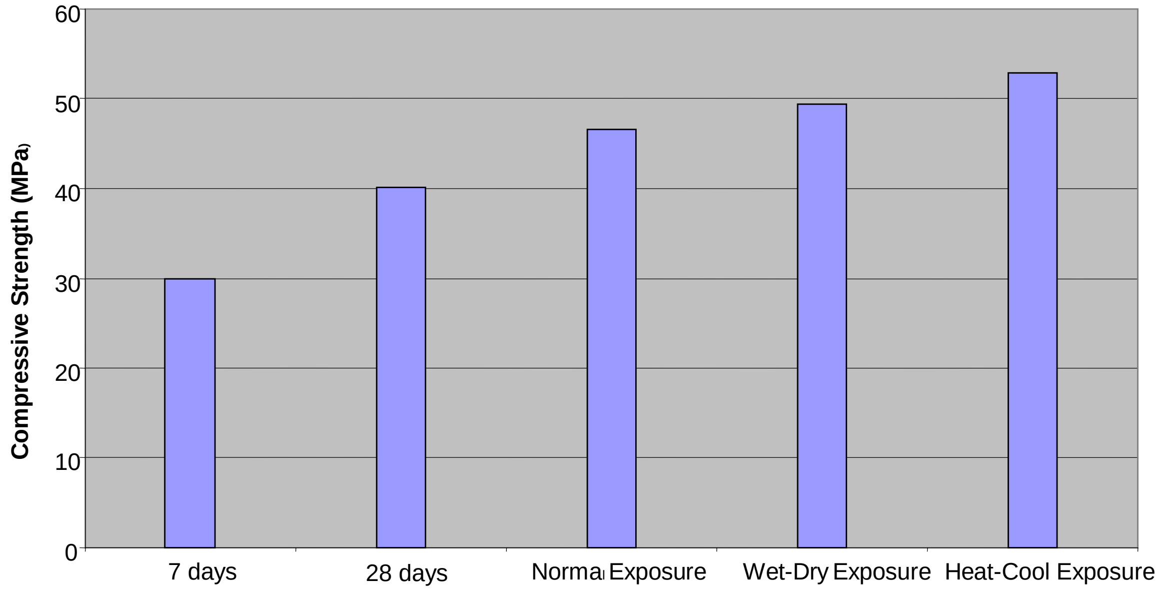

Figure 5.1: Average Compressive strength of SCC specimens exposed to various exposures.

Table 5.2: A comparison of Compressive strengths of SCC specimens.

Sample #	Percentage of 28-day Compressive strength				
	7 Days Water Curing	28 Days Water Curing	4 Months Normal Exposure	4 Months Wet-Dry Exposure	4 Months Heat-Cool Exposure
1	73.94	100.00	104.88	103.79	128.78
2	75.17	100.00	130.62	138.38	130.83
3	74.70	100.00	114.34	129.79	136.32
Average	**74.60**	**100.00**	**116.61**	**123.98**	**131.97**

The higher value of compressive strength of SCC specimens exposed to wet-dry conditions compared to those exposed to normal conditions may be attributed to increased hydration of cement and Super-pozz®. Similarly, the higher compressive strength of specimens exposed to heat-cool conditions compared to those exposed to normal conditions may be attributed to the accelerated hydration due to an increase in the temperature. However, a decrease in the compressive strength due to wet-dry and heat-cool exposures may be expected after a long period of exposure. The effect of aggressive exposures on the compressive strengths seen within the duration of this study, i.e., four months, is not detrimental.

5.2 WATER ABSORPTION

The water absorption of the SCC specimens exposed to three conditions is summarized in Tables 5.3 through 5.5.

Table 5.3: Water absorption of SCC specimens exposed to normal conditions.

Sample #	Actual weight,g	W_1, g (After drying)	W_2,g (after 48 hr of water soaking)	Absorption (%) $= \left[\frac{W_2 - W_1}{W_1}\right]100$
1	1624.9	1591.7	1646.6	3.45
2	1665.3	1631.9	1692.6	3.72
3	1675.8	1644.1	1699.2	3.35
Average				**3.51**

Table 5.4: Water absorption of SCC specimens exposed to wet-dry conditions.

Sample #	Actual weight, g	W_1, g (After drying)	W_2, g (after 48 hr of water soaking)	Absorption (%) $= \left[\frac{W_2 - W_1}{W_1}\right]100$
1	1672.4	1617.88	1666.97	3.03
2	1669.2	1610.32	1663.79	3.32
3	1648	1592.05	1642.89	3.19
Average				**3.18**

Table 5.5: Water absorption of SCC specimens exposed to heat-cool conditions.

Sample #	Actual weight, g	W_1, g (at 100 °C)	W_2, g (after 48 hr of water soaking)	Absorption (%) $= \left[\frac{W_2 - W_1}{W_1}\right]100$
1	1668	1645.69	1718.38	4.42
2	1664.5	1640.34	1711.53	4.34
3	1652.7	1628.84	1703.11	4.56
Average				**4.44**

The average water absorption in the SCC specimens, exposed to all the three conditions is lower than that of conventional concrete. The average water absorption of conventional concrete produced using the dune sand as fine aggregate and Abu-Hadriyah aggregate as coarse aggregate is reported to be 4.9% (Research Project Report, 2000). The lower water absorption exhibited by SCC specimens is an indication of lower porosity of SCC compared to the conventional concrete.

Figure 5.2 depicts the average values of water absorption in the SCC specimens exposed to the three conditions investigated in this study. The water absorption in the specimens exposed to wet-dry condition was less than that in the specimens exposed to normal conditions by about 9%.

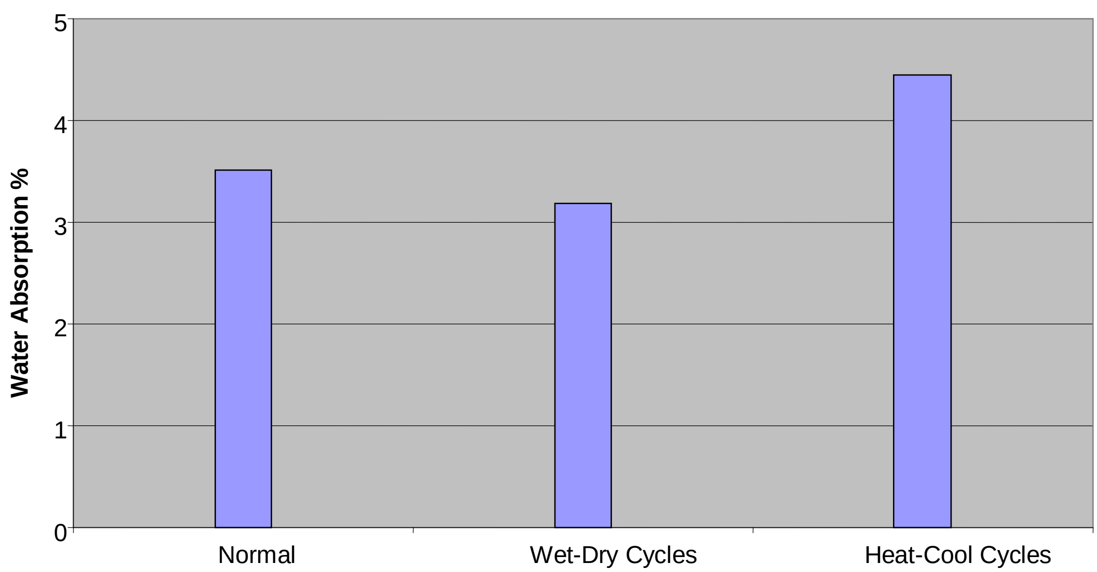

Figure 5.2: Average Water absorption of SCC under various exposures.

The water absorption in the SCC specimens exposed to heat-cool conditions was more than that of specimens exposed to normal conditions, by about 26%. Reduction in the water absorption in the specimens exposed to wet-dry conditions may be attributed to intermittent curing during the entire period of exposure. It seems that the heat-cool exposure has resulted in an increase in the porosity of concrete.

5.3 DEPTH OF WATER PENETRATION

The depth of water penetration in the SCC specimens exposed to all the three conditions is shown in Table 5.6. The average values of depth of water penetration are plotted in Figure 5.3.

Table 5.6: Depth of water penetration in the SCC specimens.

Specimen#	Normal (mm)	Wet-Dry (mm)	Heat-Cool (mm)
1	35	23.3	42.2
2	35.5	24.7	39
3	40.7	24.3	40.2
Average	**37.1** **(Moderate Permeability)**	**24.1** **(Low Permeability)**	**40.5** **(Moderate Permeability)**

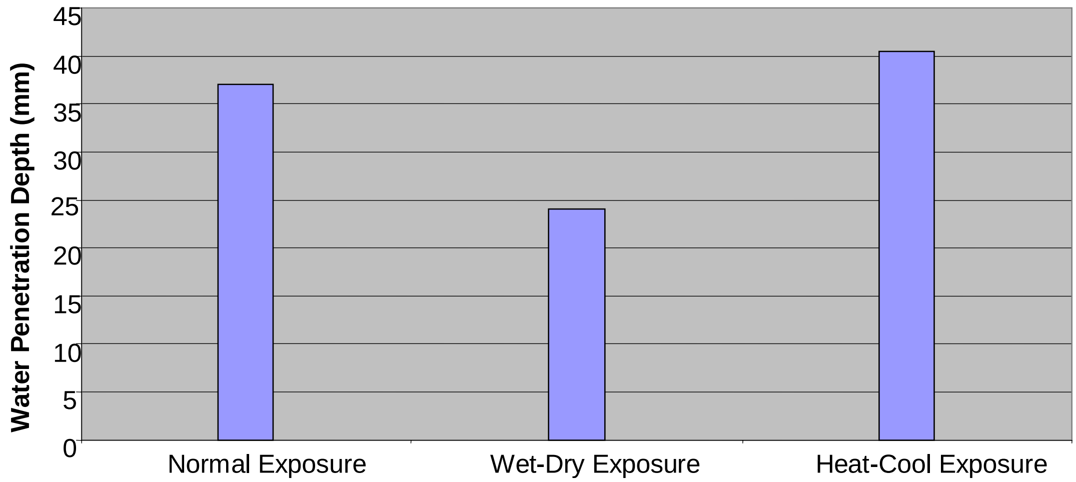

Figure 5.3: Average depth of water penetration in the SCC specimens.

As indicated in Table 5.6, the depth of water penetration in the specimens exposed to wet-dry conditions corresponds to the "low permeability" and that for specimens exposed to normal and heat-cool conditions it correspond to "moderate permeability", according to the criteria set by the Concrete Society, (1987). According to Al-Kutti (2005) the 28-days depth of water penetration in the conventional concrete prepared with 20% fly ash, water/cementitious material ratio of 0.35, and total cementitious material content of 400 kg/m3 to be in the range of 22 to 35 mm.

The depth of water penetration in the specimens exposed to wet-dry conditions is 35% less than that in the specimens exposed to normal conditions, while the values in the specimens exposed to normal and heat-cool conditions are almost similar to each other. The reduction in the depth of water penetration in the specimens exposed to wet-dry conditions may be attributed to the effect of intermittent curing.

Limited wet-dry cycles seem to improve water-tightness of SCC specimens, confirming further the results observed in absorption tests. Heat-cool cycles have shown the trend of increasing the depth of water penetration. A prolonged cycle will have more adverse effect.

5.4 WATER PERMEABILITY

The coefficient of water permeability for specimens exposed to all the three conditions investigated in this study is presented in Table 5.7.

Table 5.7: Average water permeability of SCC.

Exposure	Average coefficient of water permeability (m/s)
Normal	13.1×10^{-12}
Wet-dry	6.3×10^{-12}
Heat-cool	12.7×10^{-12}

The average coefficient of water permeability for specimens exposed to normal lab conditions was 13.1 × 10-12 m/s. This is less than the maximum permissible value of the water permeability coefficient (15 × 10-12 m/s) for a conventional concrete, recommended by ACI 301-89.

Similar to the depth of water penetration, the coefficient of water permeability for the specimens exposed to wet-dry conditions was around 50% less than that for specimens exposed to normal conditions. The coefficient of water permeability for specimens exposed to normal and heat-cool conditions was almost similar. The decrease in the coefficient of water permeability in the SCC specimens exposed to wet-dry conditions may be attributed to the effect of intermittent curing.

5.5 RAPID CHLORIDE PERMEABILITY

The chloride permeability for SCC specimens exposed to all three types of conditions is presented in Table 5.8. The average chloride permeability values are plotted in Figure 5.4.

Table 5.8: Chloride permeability of SCC concrete specimens.

Specimen#	Chloride Permeability, coulombs		
	Normal Exposure	Wet-Dry Exposure	Heat-Cool Exposure
1	414	670	540
2	456	833	512
3	444	843	515
Average	**438** ***"Very Low chloride permeability"***	**782** ***"Very low chloride permeability"***	**522** ***"Very low chloride permeability"***

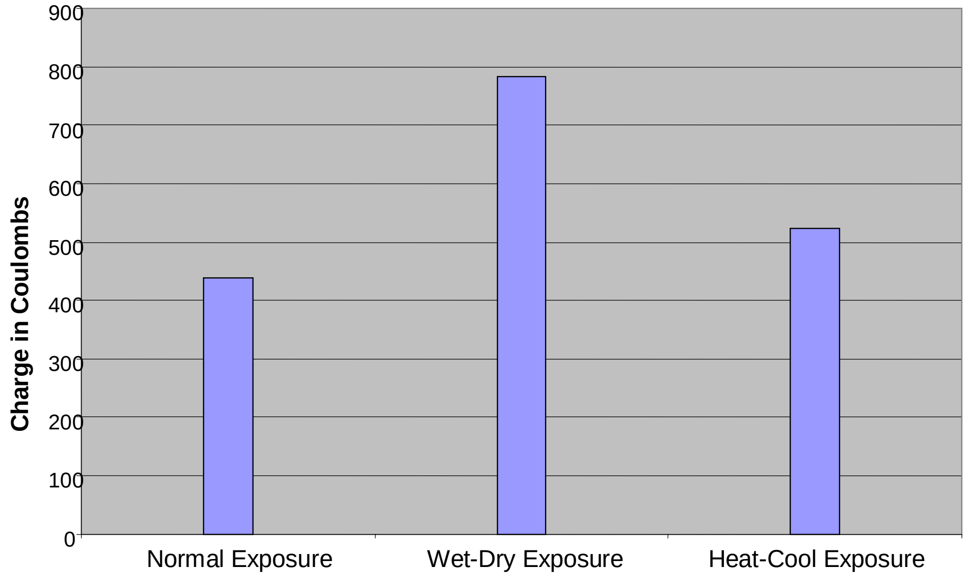

Figure 5.4: Average chloride permeability of SCC specimens.

The chloride permeability for all the specimens was "very low", according to ASTM C 1202 criteria. Al-Kutti (2005) reported that the 28-days chloride permeability of conventional concrete prepared with 20% fly ash, water/cementitious material ratio of 0.35 and the total cementitious material content of 400 kg/m3 was in the range of 1380 to 1574 Coulombs, which corresponds to the "low chloride permeability". The chloride permeability values obtained for all three exposures fall well within the range of rapid chloride permeability value of SCC reported recently in literature (Nehdi et al., 2004; Patel et al., 2004).

5.6 DRYING SHRINKAGE

The drying shrinkage measurements recorded continuously for about 90 days are presented in Table 5.9. A plot of time versus average shrinkage strain is shown in Figure 5.5.

The shrinkage strain (Table 5.9) was in the range of 486 to 608 μm. As expected the drying strain increased with the time of exposure. The values of drying shrinkage strains for SCC obtained in this study are in agreement with the results reported by other researchers (Bouzoubaa and Lachemi, 2001; Xie et al., 2002). Bouzoubaa and Lachemi (2001) reported that the maximum drying shrinkage strain for SCC was 600 μm after 224 days and no difference was noticed between the drying shrinkage of the normal concrete and that of the SCC. The drying shrinkage values ranged between 493 and 591 μm after 112 days for SCC with water to binder ratio in the range of 0.35 to 0.5 (Bouzoubaa and Lachemi, 2001). Xie et al. (2002) have reported that the 90 days drying shrinkage of SCC was 383 μm, which is less than the values obtained under the present study. This is because of differences in the mix proportions, admixture type and dosage, and specimen size.

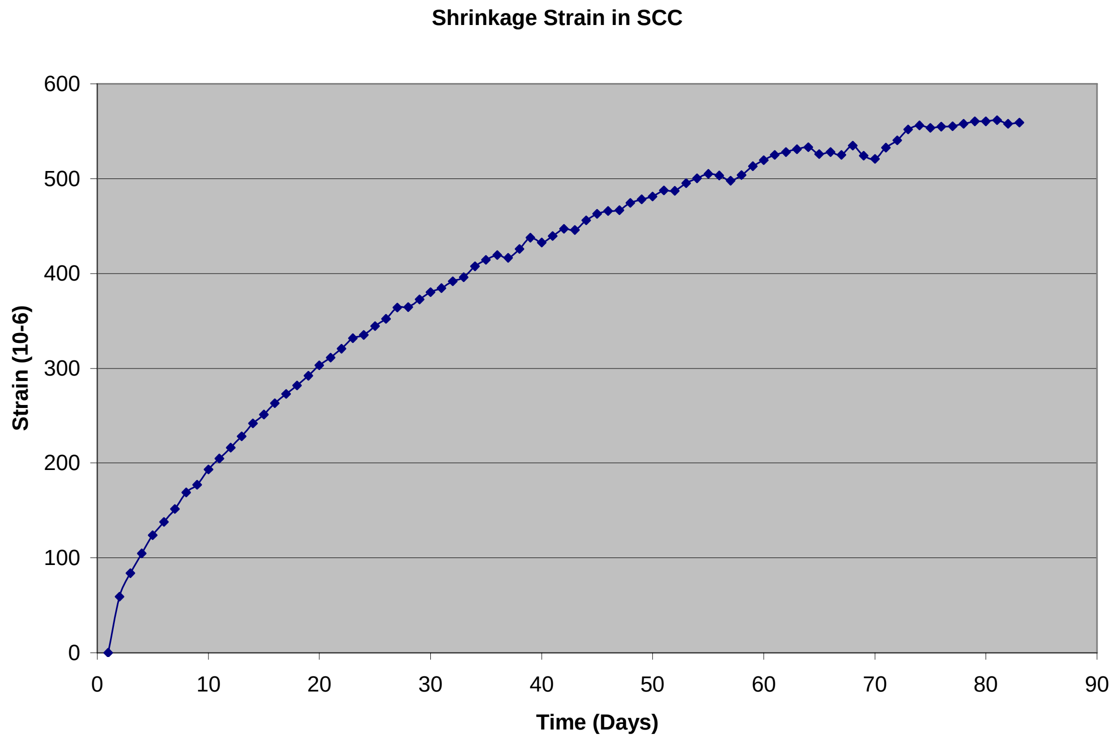

Figure 5.5: Average shrinkage strain variation with time in SCC specimens.

Table 5.9: Drying shrinkage strain in SCC specimens.

Days	Strains (x10^{-6})				Days	Strains (x10^{-6})			
	Sample #			Average		Sample #			Average
	1	2	3			1	2	3	
1	0	0	0	**0.00**	**42**	466	468	407	**447.00**
2	61	56	61	**59.33**	**43**	466	468	403	**445.67**
3	83	83	86	**84.00**	**44**	475	479	414	**456.00**
4	104	104	106	**104.67**	**45**	482	486	421	**463.00**
5	124	124	124	**124.00**	**46**	486	491	421	**466.00**
6	137	137	140	**138.00**	**47**	486	493	421	**466.67**
7	153	151	151	**151.67**	**48**	493	502	428	**474.33**
8	169	169	169	**169.00**	**49**	497	506	432	**478.33**
9	182	173	176	**177.00**	**50**	502	509	432	**481.00**
10	198	191	191	**193.33**	**51**	506	518	439	**487.67**
11	212	200	203	**205.00**	**52**	504	518	439	**487.00**
12	225	212	212	**216.33**	**53**	513	527	446	**495.33**
13	239	223	223	**228.33**	**54**	520	531	450	**500.33**
14	252	239	234	**241.67**	**55**	524	536	455	**505.00**
15	263	248	243	**251.33**	**56**	524	536	450	**503.33**
16	277	259	254	**263.33**	**57**	522	531	441	**498.00**
17	286	270	263	**273.00**	**58**	527	538	446	**503.67**
18	295	279	272	**282.00**	**59**	536	549	455	**513.33**
19	306	290	281	**292.33**	**60**	542	556	461	**519.67**
20	317	304	288	**303.00**	**61**	549	560	466	**525.00**
21	326	311	297	**311.33**	**62**	551	565	468	**528.00**
22	338	320	304	**320.67**	**63**	556	567	470	**531.00**
23	349	333	313	**331.67**	**64**	558	569	473	**533.33**
24	353	335	317	**335.00**	**65**	549	565	464	**526.00**
25	362	347	324	**344.33**	**66**	551	567	466	**528.00**
26	369	356	331	**352.00**	**67**	551	563	461	**525.00**
27	383	369	340	**364.00**	**68**	560	576	468	**534.67**
28	385	369	340	**364.67**	**69**	551	563	459	**524.33**
29	389	380	349	**372.67**	**70**	547	560	455	**520.67**
30	398	387	356	**380.33**	**71**	558	574	466	**532.67**
31	401	394	358	**384.33**	**72**	565	583	473	**540.33**
32	410	403	362	**391.67**	**73**	578	596	482	**552.00**
33	414	407	367	**396.00**	**74**	583	601	484	**556.00**
34	425	419	378	**407.33**	**75**	578	599	484	**553.67**
35	432	428	383	**414.33**	**76**	581	601	482	**554.67**
36	439	432	387	**419.33**	**77**	581	601	484	**555.33**
37	434	432	383	**416.33**	**78**	585	605	484	**558.00**
38	443	443	392	**426.00**	**79**	587	608	486	**560.33**
39	455	455	403	**437.67**	**80**	585	610	486	**560.33**
40	452	452	394	**432.67**	**81**	585	612	488	**561.67**
41	459	459	401	**439.67**	**82**	581	608	484	**557.67**
42	466	468	407	**447.00**	**83**	583	608	486	**559.00**

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The primary aim of this research was to design a suitable SCC mix with local aggregates and thereafter determine its durability due to exposure to moisture and thermal variations. The main conclusions drawn from the results are summarized below:

1. From eight trial mixes, a mix with FA/CA ratio of 1.1, a filler content of 100 kg/m3 and 1.00% superplasticizer, was found to meet the compactibility criteria and possessed maximum compressive strength.
2. The compressive strength of SCC specimens increased with the time of curing. A considerable increase in the compressive strength of concrete specimens exposed to thermal variations was noted compared to specimens exposed to wet-dry and normal exposures. Further, compared to the compressive strength of specimens under normal exposure, the compressive strengths of specimens under wet-dry was higher.
3. The SCC specimens displayed better performances with regard to water absorption. The water absorption of specimens exposed to normal laboratory conditions was 3.51%, while that of specimens exposed to heat-cool and wet-dry exposure it was 4.44 and 3.18%, respectively.

4. Water penetration depth value found in case of wet-dry exposure corresponds to the "low permeability" whereas the same in cases of normal and heat-cool exposures correspond to the "moderate permeability".
5. Average water permeability coefficient for the SCC specimens under normal exposure was found to be 13.1 × 10-12 m/s, which is lower than the maximum permissible value of the water permeability coefficient (15 × 10-12 m/s), recommended by ACI 301-89. Value of the water permeability coefficient in case of wet-dry exposure is less than that for normal exposure, whereas values of the water permeability coefficient for normal and heat-cool exposures are almost similar to each other.
6. The chloride permeability of SCC was very low (less than 1000 coulombs) for all the specimens exposed to all the conditions investigated in this study. The chloride permeability values obtained in this study are in agreement with those reported in the literature.
7. After three months of normal curing at room temperature, the drying shrinkage strains of SCC prisms (100 mm x 100 mm x 300 mm) ranged between 486 and 608 µm. The drying shrinkage strains for SCC obtained in this study are in agreement with the results reported by other researchers.

6.2 RECOMMENDATIONS

Following parameters are recommended for producing SCC using local aggregates:

1. FA/CA : 1.1
2. Filler content : 100 kg/m^3
3. Super plasticizer : 1%
4. W/Powder ratio : 0.38
5. Cement : 350 kg/m^3
6. Stabilizer : 3.03 kg/m^3

6.3 SUGGESTIONS FOR FUTURE RESEARCH

Following are some suggestions for future research.

1. The durability properties of SCC can be evaluated by varying mix proportions, like aggregate content, cement content, superplasticizer content, maximum aggregate size and the use of different types and quantity of filler.
2. Comparative study related to normal conventional vibrated concrete can be studied using the mix design adopted in this research.
3. Long-term study on durability of SCC considering rebar corrosion monitoring in addition to other durable properties of concrete.

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