IMPLEMENTATION OF SELF-CONSOLIDATING CONCRETE FOR PRESTRESSED CONCRETE GIRDERS

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16. Abstract

This report documents the first experience of using self-consolidating concrete for pretressed concrete bridge girders in North Carolina. Under construction in eastern North Carolina was a multi-span bridge which used one hundred thirty AASHTO Type III girders, each 54.8 ft (16.7 m) long. To demonstrate the full-scale field production of self-consolidating concrete, and for comparative purposes, three girders from one production line of five girders were selected for the experimentation. Two of the girders were cast with self-consolidating concrete and one with normal concrete as control.

The plastic and hardened properties of both the self-consolidating concrete and the normal concrete were monitored and measured. The plastic properties of self-consolidating concrete included unit weight, air content, slump flow, visual stability index (VSI), and passing ability measured by J-ring and L-box. Hardened properties of the two concretes included temperature development during curing, compressive strength, elastic modulus, and flexural tensile strength, creep and shrinkage. The prestressing force was monitored by load cells. The transfer lengths of prestressing strands were determined by embedded strain gauges, and from the measured strand end-slips. Finally, the three girders were tested in flexure up to the design service load to determine and compare their load-deformation characteristics. Based on the satisfactory results of this study, the two prestressed SCC girders were installed in the bridge for service as other normal concrete girders.

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SUMMARY

This report documents the first experience of using self-consolidating concrete for pretressed concrete bridge girders in North Carolina. Under construction in eastern North Carolina was a multi-span bridge which used one hundred thirty AASHTO Type III girders, each 54.8 ft (16.7 m) long. To demonstrate the full-scale field production of self-consolidating concrete, and for comparative purposes, three girders from one production line of five girders were selected for the experimentation. Two of the girders were cast with self-consolidating concrete and one with normal concrete as control.

The plastic and hardened properties of both the self-consolidating concrete and the normal concrete were monitored and measured. The plastic properties of self-consolidating concrete included unit weight, air content, slump flow, visual stability index (VSI), and passing ability measured by J-ring and L-box. Hardened properties of the two concretes included temperature development during curing, compressive strength, elastic modulus, and flexural tensile strength, creep and shrinkage. The prestressing force was monitored by load cells. The transfer lengths of prestressing strands were determined by embedded strain gauges, and from the measured strand end-slips. Finally, the three girders were tested in flexure up to the design service load to determine and compare their load-deformation characteristics. Based on the satisfactory results of this study, the two prestressed SCC girders were installed in the bridge for service as other normal concrete girders.

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1. INTRODUCTION

1.1 Background

Self-consolidating concrete (SCC) is a special class of high-performance concrete. It has very high workability and consolidates under its own weight without vibration. It is also known as self-compacting concrete or self-leveling concrete. Motivated by the concerns over shortage of skilled workers in construction, causing durability problems of concrete structures, and coupled with the vision of construction automation, Okamura and his colleagues in Japan developed SCC in 1988, nearly two decades ago (Okamura and Ozawa 1994; Okamura 1997). It has been considered as one of the most significant developments of concrete technology in several decades.

Despite its 17 years of history, it was not until the late 1990's that the U. S. precast concrete industry applied the technology to architectural and structural building elements. Only in the past few years, the state transportation agencies in the United States began to consider the use of SCC for bridge structures.

In June 2003, the North Carolina Department of Transportation (NCDOT), North Carolina State University (NCSU), and Georgia/Carolinas PCI jointly sponsored a workshop on SCC. The workshop attracted over 100 participants including more than 60 NCDOT design, materials, and construction engineers. During the workshop, the participants reviewed the results of recent advances of SCC and witnessed successful demonstrations of the impressive performance of the material.

Motivated by the success of the workshop, the NCDOT decided to explore the use of this high performance material to take advantage of its potential benefits. A research and implementation program was then developed jointly with NCSU and S & G Prestress

Company in Wilmington, N. C. The latter was under contract to produce 130 prestressed concrete girders for a 13-span bridge over Upper Broad Creek in Craven/Pamlico Counties in eastern North Carolina (NCDOT Project 8.1170903).

Since SCC is a specially designed concrete, its performance depends highly on the characteristics of its ingredient materials. In general, the behavior of SCC is fairly similar to that of normal concrete such as compressive strength, flexural modulus, and shrinkage. However, SCC may have lower modulus of elasticity because it contains more fine particles (fine aggregates, supplementary cementitious materials, and other inert powders). This may affect the short-term and long-term deformation characteristics of prestressed concrete members. In addition, there is a shortage of research data on the bond strength between SCC and the prestressing strands. Therefore, it is necessary to examine the potential impact of these properties of SCC on the behavior and design of prestressed concrete girders. Furthermore, there is a need to demonstrate the proper placing procedure for SCC in full-scale production of large-sized and long-span prestressed concrete girders.

1.2 Objectives and Scope

The objectives of this research and implementation project were three-fold: (1) Monitor and document the actual production of two prestressed concrete girders using SCC. (2) Determine and document the various properties of SCC used in the production of the two prestressed SCC girders. (3) Conduct static load tests of two SCC girders and one normal concrete girder for comparison. The girders would be tested to full design service load condition to validate their design and performance. If the performance is satisfactory, and subject to the NCDOT approval, the producer would have the option of installing the SCC girders in the bridge for service as other normal concrete girders.

2. REVIEW OF LITERATURE

2.1 Development of Self-Consolidating Concrete

The idea of a concrete mixture that can be placed into every corner of a formwork, purely by means of its own weight and without vibration, was first considered in 1983 in Japan, when concrete durability, constructability and productivity became a major concern. During that time, Japan was suffering a shortage of skilled workers in the construction industry which affected the quality of the concrete construction.

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 (Ozawa et at. 1989). By the early 1990's, Japan started to develop and use SCC and, as of 2000, the amount of SCC used for prefabricated products and ready-mixed concrete in Japan was over 520,000 CY (400,000 m^3) (Ouchi et al. 2003).

In 1996, several European countries organized a project called "Rational Production and Improved Working Environment through using Self-compacting Concrete" to explore the significance of published achievements in SCC and develop applications to take advantage of its potentials. Since then, SCC has been used successfully in a number of bridges, walls and tunnel linings in several locations in Europe (Campion and Jost 2000; Ouchi et al. 2003).

In the last five years, interest in SCC has also grown steadily in the United States, particularly within the precast concrete industry. SCC has been used in several commercial projects (Ouchi et al. 2003; Ozyldirim and Lane 2003). Research studies (Khayat et al. 1999, 2000; Chan et al. 2003; Sonebi et al. 2003), have been conducted with the objective of developing raw material requirements, mixture proportions, material characteristics, and test methods necessary to routinely implement SCC.

By 2003, the Precast/Prestressed Concrete Institute (PCI), the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM) had developed similar definitions for SCC:

> "A highly workable concrete that can flow through densely reinforced or complex structural elements under its own weight and adequately fill voids without segregation or excessive bleeding without the need for vibration" (PCI Fast Team 2003)
>
> "Highly flowable, non-segregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation" (Szecsy 2004)
>
> "Concrete that can flow around reinforcement and consolidate within formwork under its own weight without additional effort, while retaining its homogeneity" (Szecsy 2004)

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

2.2 Properties of Self-Consolidating Concrete

For hardened concrete, research by Attiogbe et al. (2003) showed that engineering properties of stable SCC (slump flow of 26 to 27 in. or 660 to 686 mm) such as compressive and tensile strengths, modulus of elasticity, Poisson's ratio, drying shrinkage, creep, porosity, chloride diffusivity, and bond to reinforcement were virtually comparable to similar properties of conventional flowable (8 to 9 in. or 203 or 229 mm) concrete mixtures. Their study also demonstrated that the use of a viscosity modifying admixture (VMA) would enhance the production of stable SCC mixtures at normal levels of sand/aggregate (s/a = 0.48

and 0.39), with the additional benefit of lower shrinkage compared with SCC mixtures that are produced with higher than normal levels of s/a = 0.58.

Turcry et al. (2002) conducted an experimental program to investigate the various shrinkage and basic mechanical properties of two SCC and compared the results with those of regular concrete. They found that the total shrinkage was almost the same for SCC and regular concrete. The same was true for the modulus of rupture. However, with same compressive strength, the modulus of elasticity was slightly lower for SCC than regular concrete.

A study conducted by Raghavan et al. (2002) on creep, shrinkage, and chloride permeability properties of SCC revealed that with similar compressive strength, SCC performed better than regular concrete in all the tests. Although the initial elastic strain was more for SCC, the final strain induced by creep was less than regular concrete. The drying shrinkage of SCC was 25% lower than that of regular concrete which had less powder and higher water-powder ratio for the same water content. For SCC, with lower water-powder ratio and more dense structure, it was found more durable than regular concrete in terms of chloride permeability.

For plastic concrete, Kaszynska and Nowak (2003) and Khayat et al. (2004) indicated that SCC should be produced to meet three basic characteristics: (1) high deformability, (2) high passing ability and (3) high resistance to segregation.

<u>Deformability</u> – Deformability of concrete is defined as the ability of the concrete to undergo a change in shape under its own weight. It is also referred to as filling ability or flowability. High deformability is required so that the concrete can spread uniformly into the formwork. In order to obtain adequate deformability, it is important to minimize the friction

between the solid particles of the mixture. Reduction of the coarse aggregate and an increase in the paste volume is required to achieve the desired deformability (Okamura and Ozawa 1994, Okamura 1997). Another approach to reduce inter-particle friction is to incorporate continuously graded fillers, such as limestone filler, and to minimize the use of gap-graded or uniformly-graded aggregates.

The deformability of the concrete is directly related to the deformability of the paste. To increase the deformability of the paste and reduce the internal friction of solid particles, a high range water reducing admixture (HRWR) is commonly used in SCC mixtures. A HRWR can be used to maintain a relatively low water cementitious materials ratio (w/cm) while increasing fluidity. The deformability of the paste is increased by reducing the viscosity. A highly flowable concrete can be obtained without a significant reduction in cohesiveness, improving the resistance to segregation (Khayat et al. 2004).

<u>Passing Ability</u> – Blockage is caused by the collision and contact between the solid particles near an opening. Therefore the size and content of the coarse aggregate in a SCC mixture have a significant effect on the concrete passing ability. The passing ability requirements depend on the formwork geometry and the extent of congestion of the reinforcement. Providing adequate viscosity to the mixture reduces the risk of blockage.

If a SCC mixture is highly deformable, but has insufficient cohesiveness, the concrete may not distribute itself uniformly throughout the formwork. A mixture with low deformability can result in segregation which can also lead to blockage when the concrete attempts to pass the reinforcement.

<u>Segregation Resistance</u> – SCC must have sufficiently high resistance to segregation to ensure a homogenous distribution within the form. Adequate cohesiveness can be obtained

by incorporating a viscosity-modifying admixture (VMA) along with HRWR to control bleeding, segregation, and surface settlement (Khayat and Guizani 1997).

Another approach to secure adequate cohesiveness is to reduce the free water content and to increase the volume of sand and cement paste. Supplementary cementitious materials and fillers with a large surface area can adsorb considerably more water than the same mass of cement particles, thereby reducing the free water content of the mixture (Miura et al.1993; Trudel 1996).

2.3 Materials for Self-Consolidating Concrete

Cementitious Materials – To achieve a properly proportioned SCC mixture, an increased paste volume is required to obtain the necessary deformability. For SCC mixtures, cement contents from 650 pcy to 840 pcy (385 kg/m^3 to 500 kg/m^3) have been used with satisfactory results (Assaad et al. 2004). For precast operations, Type III cement is often used instead of Type I cement in order to achieve the necessary early strength.

Silica fume, fly ash, and ground granulated blast furnace slag (GGBFS) are often used to partially replace portland cement and to provide more fine particles in the paste. These materials can also reduce permeability and improve the chemical durability of moist cured concrete. If the mixture contains an excessive amount of cementitious materials, it may generate very high heat of hydration. In such a case, inert limestone powder can be used as partial replacement of the cementitious materials (Okamura 1997).

Silica fume is basically a "super-pozzolan" with a very high durability and excellent strength, but it is expensive and creates a high water demand, thus requiring the use of HRWR. Silica fume is generally used in quantities of 3% to 6% of the total cementitious materials in concretes with accelerated curing.

While Class F fly ash is generally used in the range of 15% to 25% of total cementitious material in conventional mixtures, Khayat et al. (2004) reported that using 30% Class F in a SCC mixture resulted in good workability, with acceptable strength development and frost durability.

Slag is generally used in the range of 40% to 60% of total cementitious material in conventional concrete mixtures. However, Lachemi et al. (2003) obtained effective results incorporating 50% to 70% slag as cement replacement with different Viscosity Modifier Admixtures (VMA) for various SCC mixtures.

Aggregates – Okamura (1997) reported that if the coarse aggregate content of a SCC concrete 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-consolidating characteristics. Yurugi et al. (1993) reported that reducing the volume of coarse aggregate in a SCC mixture is more effective than decreasing the sand-to-paste ratio to increase the passing ability through congested reinforcement.

The size, shape and, to a certain extent, the gradation of the aggregate in a SCC mixture are important to minimize the collision and contact between the solid particles near an opening, which affects the concrete passing ability. Bui et al. (2002) proposed a rheological model for SCC that relates the rheology of the paste to the average aggregate spacing D_{SS} and average aggregate diameter D_{av}. The model considers the effect of most of the factors related to aggregate properties and content. They reported that 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 0.2 to 0.55 in (5 mm to 14 mm) and quantities varying from 1,335 pcy to 1454 pcy (790 kg/m^3 to 860 kg/m^3) have been used with satisfactory results (Khayat et al. 2004).

High Range Water Reducers (HRWR) – Since a large amount of fine particles is necessary for the SCC mixture, the use of HRWR (or superplasticizer) is indispensable. It helps increase the paste flowability with a slight decrease of viscosity (Khayat 1999). In using the superplasticizer, the problems of non-compatibility between the cement and superplasticizer may be more critical with SCC than conventional mixtures (Kaszynska and Nowak 2003).

With the new HRWR of the polycarboxylate technology, the production of SCC can benefit from faster strength development in addition to meeting the requirements of plastic properties. In precast operations, this means reduced curing time, early strength development, savings in energy cost for curing, and increase in productivity (Daczko and Martin 2003).

2.4 SCC Mixture Design

There is no standard mix design method for SCC. Each SCC mixture must be designed to meet the demands of a given project. Generally speaking, for SCC, the amount of paste is increased as well as the relative proportion of the fine to coarse aggregate, in order to improve the overall flowability of the concrete. The maximum size of the coarse aggregate is selected according to the project requirement. For example, a maximum size of 1.6 in. (40 mm) may be used for mass concrete, but a smaller size of 0.4 in. (10 mm) would be used for castings with narrow forms and congested reinforcement. Also, a slightly larger size can be specified with smooth and rounded aggregate, whereas the size would be reduced for more angular and elongated aggregate. Normally, the maximum aggregate size is limited to 0.8 in.

Fly ash, ground granulated blast furnace slag, silica fume, and limestone powder are often used to provide more fine particles in the paste. This would often require more mixing water. However, too much water and paste may cause aggregate segregation and blocking. Therefore, it is critical to limit the water-cementitious materials ratio (w/cm) to no more than 0.45 by weight. Most times this ratio should be less than 0.40. With lower w/cm, the use of superplasticizer is essential to improve the flowability of the paste. Additionally, viscosity-modifying admixtures are very useful to compensate for small variations of the sand grading and the moisture content of the aggregates. These chemical admixtures will help improve segregation resistance. Other admixtures such as set retarder and air-entraining agent can also be used.

Okamura (1997) has proposed a simple approach to mix proportioning for SCC in the following steps:

1. Fix the coarse aggregate content at 50 percent of the solid volume.
2. Fix the fine aggregate content at 40 percent of the mortar volume.
3. Select a water-cement ratio by volume of 0.9 to 1.0 depending on the properties of the cement.
4. Determine the superplasticizer dosage and the final w/c so as to ensure the self-compactibility properties.

A European guideline (EFNARC 2002) has recommended similar ranges of proportions and quantities of the constituent materials:

1. Select total powder content at 160 to 240 liters (400 to 600 kg) per cubic meter.
2. Select water/powder ratio by volume of 0.80 to 1.10.
3. Select water/cement ratio based on strength requirements, typically water content should not be more than 200 liters per cubic meter.
4. Select coarse aggregate content normally at 28 to 35 percent by volume of the mix.
5. Select sand content for the remaining volume of the mix.

As an illustration, Table 2.1 shows three different SCC mixes that have been used in Japan, Canada, and the U. S. The Japanese SCC mix was used for a massive caisson foundation of a bridge (Ouchi, et al. 2003), the Canadian SCC mix was used for repair of a parking structure (Khayat and Aitcin 1998), and the SCC mix identified with the United States is for the casting of jail cells by a precast concrete producer (data obtained through private communication). Notice the differences in w/cm for the three different applications and the fairly equal proportions between the coarse and fine aggregates.

2.5 Test Methods

There are many test methods that have been developed to measure the characteristics of SCC. Detailed descriptions and requirements of these methods can be found in guidelines developed by EFNARC (2002) and PCI Fast Team (2003) and in the papers by Vachon (2002) and Zia (2005). None of these test methods has been standardized nationally or internationally, although they are being carefully considered by different standardization organizations. Three of these test methods – Slump Flow Test, J-Ring Test, and L-Box Test – have been widely used in the laboratory and/or in the field, and they will be described more fully in Section 4.3.

Table 2.1 Examples of SCC Mixes

Ingredients per m^3 (per yd^3)	Japan	Canada	United States
Water, kg (lbs)	165 (280)	218 (370)	221.1 (375)
Cement, kg (lbs)	220 (373)	400 (678)	470 (797)*
Fly Ash, kg (lbs)		115 (195)	
GGBFS, kg (lbs)	220 (373)		
Silica Fume, kg (lbs)		17 (28.8)	
Fine Aggregate, kg (lbs)	870 (1,475)	667 (1,131)	764.8 (1,297)
Coarse Aggregate, kg (lbs)	825 (1,399)	785 (1,332)	765.4 (1,298)
HRWR, kg (lbs)	4.4 (7.5)	1.9 (3.22)	1.53 (2.6)
VMA, kg (lbs)	4.1 (6.95)	4.5 (7.63)	
Water Reducer/Retarder, L (oz)		0.5 (13)	
Air-Entraining Agent, L (oz)		0.45 (11.7)	0.23 (6)
w/cm	0.38	0.41	0.47

* Type III cement

2.6 Applications of SCC

During the last decade, SCC has been increasingly used in a variety of applications such as bridges, high-rise buildings, caissons, tunnels, and architectural castings. In general, SCC has been used effectively and economically where large amounts of concrete are placed in a tight schedule, or concrete placement is in a confined space, or concrete is placed in thin sections with congested reinforcement, or a special appearance and finish of the concrete surface is required. Many interesting projects have been described in conference proceedings (Ozawa and Ouchi 1999; Shah et al. 2003). Three projects with unique features are described below to illustrate the advantages of using SCC and its versatility.

Akashi Straits Bridge, Japan – SCC was used in the two massive anchorages of this world's longest suspension bridge (Okamura and Ozawa 1994; Okamura 1997). The amount of concrete used including the foundation was 676,000 CY (520,000 m^3) for one anchorage and 325,000 CY (250,000 m^3) for another. Embedded in the anchorage was the cable anchor frame weighing 8,820 kips (4,000 tons). The concrete had to be placed in the anchorage at the rate of 2,470 CY (1,900 m^3) per day. To improve the placeability, SCC with maximum aggregate size of 1.6 in. (40 mm) was developed and used. The concrete was mixed at a batch plant near the site, and pumped out of the plant to the site for 656 ft (200 m) through 6 trains of 8 in. (200 mm) pipes. At the site, the pipes were arranged in rows of 10 to 16 ft (3 to 5 m) apart. The concrete was cast from gate valves located at 16 ft (5 m) intervals. The valves were automatically controlled so as to maintain a level surface of the cast concrete. The concrete had a maximum drop of 10 ft (3 m) without causing any segregation in spite of the large size coarse aggregate. The use of SCC reduced the construction time for the anchorages by 20 percent from 2.5 years to 2 years.

Repair of a Parking Garage, Canada – A 6.5 m (21 ft) long beam located under an expansion joint at the entrance to the Webster parking garage was damaged due to advanced corrosion. The repair included longitudinal reinforcing bars and stirrups anchored into the existing concrete which greatly restricted the spread of normal fresh concrete. The concrete cover to the outer steel was limited to 40 to 75 mm (1.6 to 3 in.). Such section would typically be repaired by using shotcrete or cast-in-place concrete. Instead, SCC was successfully used for the repair. It was placed through two 100 mm (4 in.) diameter holes drilled from the upper deck of the beam along the outer length of the beam between the existing concrete and formwork. Smaller holes were provided on the opposite side of the beam to allow air to bleed off of the watertight formwork. The highly flowable SCC was able to spread readily through the narrow space between the formwork and the existing concrete. It had to flow under its own weight along the highly restricted section and around the vertical side to fill the opposite side of the formwork, and still adhere well to the base concrete. The SCC mixture design is given in Table 2.1.

Precast Modular Jail Cell Unit, U. S. – In the United States, the precast and prestressed concrete industry has made rapid advances in the use of SCC in the past five years. SCC is increasingly used in architectural and structural products due to the need for special quality surface finish and ease of placement in thin sections with reinforcement congestion. An example is the precast modular jail cell from a plant of N. C. Products, an Oldcastle Precast company, near Raleigh, N. C.

The company built a new plant in 2001, using SCC exclusively for its precast products including manholes up to 2.44 m (8 ft) in diameter, box culverts up to 3.66 m (12 ft) in size, O-bridge sections and modular jail cell units. On the average, the plant uses 31 m^3 (40 yd^3) of SCC per day excluding the modular jail cell units. The typical SCC mix is shown in Table 2.1. The target slump flow is 700 mm (28 in.). The forms are usually stripped in one day and the products are left in the plant for air cure. The compressive strength of the SCC ranges from 16.6 MPa (2,400 psi) to 21 MPa (3,000 psi) in one day, and reaches over 49 MPa (7,000 psi) at 28 days.

The modular jail cell unit is basically a rectangular four-cell box structure of 2.44 x 3.66 x 9.14 m (8 x 12 x 30 ft) as shown in Figure 2.1. It has congested wall form for concrete placement and the vertical surfaces require practically an architectural finish. Thus SCC provides an ideal solution for this product. Using the precast scheme, the speed of construction is increased and the quality of the product is excellent.

Figure 2.1 Precast modular jail cell unit

2.7 Economic Impact of Self-Consolidating Concrete in Precast Applications

The economic impact of SCC in precast/prestress applications, as compared with the normal concrete, can be assessed in three categories: concrete mixture proportions and raw materials, production costs, and finished product improvements.

SCC uses larger quantities of portland cement or supplementary cementitious materials, the cost of the raw materials is usually greater. In addition to cement, the cost of admixtures, such as HRWR and possibly a Viscosity Modified Admixture (VMA), will also increase the cost of SCC. Typically, precast concrete producers will pay an additional 8-12% on average for raw materials in a SCC mixture relative to the raw materials cost of normal concrete mixtures (Martin 2002).

Chemical admixtures can increase the cost of the SCC mixture, but are necessary to achieve the desired concrete properties. Such is the case with VMAs which are added to improve the stability and help prevent segregation during placement. The extra cost would be around 2% of the cost of the mixture, but can yield savings by minimizing the need to increase the cement content in the SCC mixture, allow a broader variety of aggregates to be used and minimize the impact of moisture content in the aggregates (Martin 2002).

The SCC mixture cost can also be reduced by the use of pozzolanic materials such as fly ash, which is typically one-third to one-half the cost of cement. Fly ash can also help improve the flowability and stability of the SCC mixture (Lachemi et al. 2003).

The extra cost of the SCC mixture is compensated by production cost efficiencies such as reduction in placing time, vibrator use and maintenance, form maintenance, and improvement worker safety. Improved productivity by reducing time, labor or equipment may easily compensate for additional material costs. A case study for tracking the time required for placing double-tee beds in a precast plant reported a reduction of 20% compared to a conventional mixture, with a 32% reduction of labor involved in the process (Martin 2002). Regardless of the applications, an average reduction in labor during the placing process is estimated to be about 30% using SCC (Schlagbaum 2002).

The service life of vibration equipment and forms will increase with the use of SCC. A reduction in vibration operations will not only reduce maintenance and investment cost, but also improves the operating conditions at the plant by reducing noise levels. Reducing the exposure of workers and eliminating requirements for hearing protection may reduce insurance and safety costs. Due to the elimination of vibration to consolidate the mixtures, the forms use in the precast operations will receive less wear and tear, decreasing the regular maintenance costs and the costs of investing in new forms.

Patching operations and finished product improvements may be critical for certain precast concrete producers, especially for architectural panels. Many state transportation agencies require all the products to have a smooth finish with minimal "bug holes" for both sides of the girders. Properly proportioned SCC has been proven to reduce the number of "bug holes", honeycombing and other surface imperfection on the finished concrete surface. In many examples of structural, architectural, and utility products, producers in the United States have reported a decreased patching labor cost from 25-75% (Martin 2000).

3. SURVEY OF TRANSPORTATION AGENCIES AND PRESTRESSED CONCRETE PRODUCERS

In an effort to determine the current status of SCC utilization and production, survey questionnaires were sent to transportation agencies and the producer members of the Precast/Prestressed Concrete Institute (PCI). The transportation agencies included the 50 state departments of transportation, the transportation departments in the District of Columbia and Puerto Rico, the Federal Highway Administration (FHWA), and Ontario Ministry of Transportation, Canada. The results of the surveys are summarized below.

3.1 Survey of Transportation Agencies

The questionnaire shown in Appendix A was distributed to 54 transportation agencies and responses were received from 41 agencies, representing 76 percent returns.

Q1. Have you ever used self-consolidating concrete (SCC) for any of your transportation projects? If your answer is "yes", please continue. If your answer is "no", please go to Questions 6 and 7.

Of the 41 responding agencies, this question is not applicable to FHWA. Among the remaining 40 agencies, 19 agencies indicated that they have not used SCC although they are generally quite aware of the technology. Five of these agencies (Alabama, Georgia, Iowa, South Carolina, and Texas) are currently sponsoring research on behavior of SCC mixtures, and its applications in prestressed girders, pavement, and drilled shaft.

The other 21 agencies have all used SCC. Four agencies (Illinois, Michigan, North Carolina, and Virginia) have also been conducting research aimed at using SCC for prestressed bridge girders.

Q2. When did you first use SCC and for how many projects have you used SCC?

The 21 agencies have used SCC mostly within the past 2 to 3 years and the usage has been quite modest or minimal. Three states (Maine, Utah, and Virginia) seem to have used

SCC more extensively than others. Virginia started using SCC 4 years ago. Utah reported having used SCC in 25 projects and Maine has used SCC for 10 projects.

Q3. What are the types of projects for which you have used SCC, such as bridge girders, culverts, drilled shafts, etc.?

The 21 agencies have used SCC mostly in precast and cast-in-place elements, without prestressing. The most common precast products are drainage structures. Other precast products include median barriers, precast curbs, bridge abutments, and sound barrier walls. A precast 30 ft (9 m) single span arch bridge constructed in Virginia is a unique application of SCC. (Ozyildirim 2003). Cast-in-place applications of SCC include pier rehabilitation, bridge columns, bridge railings, retaining walls, and massive foundations (solid or box footings). These cast-in-place applications often involve reinforcement congestions. For prestressed SCC members, 10 agencies (Arizona, Illinois, Maine, Michigan, Mississippi, Nebraska, North Carolina, New Hampshire, Pennsylvania, and Virginia) have used box beams or AASHTO girders in limited number of bridges, or have tested experimental girders.

Q4. Are you satisfied with your experience in terms of cost, quality control, quality of construction and product, etc.?

One half of the 21 agencies who have used SCC responded to this question with an unreserved "yes". The remaining agencies seemed to be satisfied with the quality of the construction and products but expressed questions and reservations with respect to cost effectiveness, quality control, and some durability issues such as air void system.

Q5. Do you have special provisions for design, materials, and construction when you specify SCC for your project? If so, please send a copy with your response.

About one half of the 21 agencies who have used SCC did not have special provisions but allowed the use of SCC as an alternate. In such cases, the producers and suppliers of SCC would submit required documentations for review and approval.

The remaining agencies (California, Florida, Illinois, Kentucky, Maine, Michigan, New Hampshire, North Carolina, Ohio, Pennsylvania, Utah, and Virginia) have either developed or were developing special provisions. No information was received from five states (Michigan, New Hampshire, Ohio, Pennsylvania, and Utah). The provisions developed by California, Florida, Illinois, and Kentucky limit the use of SCC for non-prestressed precast products. Only Maine, North Carolina, and Virginia have developed special provisions applicable to prestressed concrete applications. A comparison of the various requirements of these different provisions is shown in Table 3.1.

Q6. If you have not used SCC, please check any of the applicable reasons listed below:

a. Higher cost of the materials_____
b. Lack of standard specifications_____
c. Lack of standard test methods_____
d. No producers of SCC in our area_____
e. Lack of technical knowledge_____
f. Need for increased quality control_____
g. Don't have prior experience_____
h. Others (please specify) _____

A great majority of the respondents cited the lack of standards, lack of standard test methods, and lack of technical knowledge and/or prior experience as the main reasons for not having used SCC. Other reasons cited by a few of the respondents are the need for increased quality control (especially segregation), no interest from producers, and no available producers and suppliers in their area. One respondent indicated that the need to use SCC was still being evaluated.

Table 3.1 Comparison of Requirements of Special Provisions

States	Maine	North Carolina	Virginia
Mixture Design Requirements			
Person performing mixture Design	Contractor's Option	Contractor's Option	Qualified SCC Technologist
Cement	Unspecified	Min. 639 pcy Max. 715 pcy	Unspecified
Fly Ash	Unspecified	Recommended Replace 20% of Cement	Permitted
Slag	Unspecified	Permitted	Permitted
Silica Fume	Unspecified	Permitted	Unspecified
Limestone Powder	Unspecified	Permitted	Unspecified
Maximum Aggregate Size	Unspecified	Unspecified	Meet Project Requirement
Fine Aggregate/Total Aggregate	Unspecified	50% to 55 %	Unspecified
Water-Cement. Material Ratio	Unspecified	Max. 0.42	Max. 0.40
Air Entraining Admixture	Unspecified	5% +/- 1.5%	5.5% +/- 1.5%
HRWR	Unspecified	Unspecified	ASTM C494 Type F or G or ASTM C1017
Viscosity Modifying Admixture	Unspecified	Recommended	Approved by Engineer
Water Reducing, Retarding, Accelerating Admixtures	Unspecified	Unspecified	ASTM C494
Test Requirements			
Slump Flow Test	24 to 32 in.	24 to 30 in.	23 to 28 in.
Visual Stability Index (VSI)	1 as Max.	Report	Unspecified
J-Ring Test Value	Not Required	< 0.5 in.	< 0.5 in.
L-Box Test (H2/H1)	Not Required	0.8 to 1.0	Not Required
Shrinkage Test	Not Required	Max. 0.04% at 28 days	Max. 0.04% at 28 days
Permeability Test	Not Required	Not Required	Max. 1500 coulombs at 28 days
Freeze-thaw Test	Max. 3% mass loss or 20% change in E (dynamic)	Not Required	Not Required
Hardened Air Void Analysis	Required	Not Required	Not Required
Compressive Strength Test	Unspecified	Required at 3, 7, 14, 28 days	Required at 28 days
Modulus of Elasticity Test	Unspecified	Required at 3 and 28 days	Unspecified
Placement Requirements			
Location of Placement	Unspecified	Unspecified	Placed from one side to other or pumped from bottom upward
Placement between lifts	Unspecified	Unspecified	Concrete not allowed to lose flow and unable to combine with next lift
Vibration	External vibrator allowed with delay in lifts and loss of slump	Not allowed without Engineer's permission	Not permitted
Finish	Unspecified	Unspecified	Smooth finish without holes larger than 3/8"

3.2 Survey of Precast/ Prestressed Concrete Industry

The questionnaire shown in Appendix B was distributed to 194 PCI producer members and only 26 responses were received. This seemingly represents a rather small percentage of returns. However, it is believed that most of the major precast/prestressed concrete producers in the United Stated participated in the survey.

Q1. Have you ever used self-consolidating concrete (SCC) for your precast and prestressed concrete products? If your answer is "yes", please continue. If your answer is "no", please go to Questions 6 and 7.

Of the 26 producers who responded, only 5 producers indicated that they have not used SCC. Twenty one producers have had experience with SCC to different degrees.

Q2. When did you first start using SCC for some or all of your products?

Most of the producers started using some SCC within the past 2 to 3 years. A very few have used SCC 4 or 5 years ago.

Q3. What are the types of products (architectural and/or structural) that you have used SCC, such as AASHTO girders, wall panels, double tees, beams, columns, piles, culverts, housing modules, pipes, etc.?

All but one producer use SCC for producing most of their precast and/or prestressed architectural and structural building elements. The most common products are double tees, beams, columns, and wall panels. Some also make slabs, spandrel beams, standard risers, and parking structures.

One unique and special case is that a new plant was constructed by a producer such that only SCC is used in the plant to produce precast products including prison modules, box culverts, Omega precast bridge elements, steam vaults, drainage vaults, and manholes. Another producer manufactures precast water tanks.

Three producers have used SCC in large (7 ft deep x 60 ft long) girders and girders in 36 ft to 46 ft range as a standard, box beams, small bridge deck panels, double tee bridge units and regular bridge beams. However, these products have been used only for private work or municipal projects.

Q4. Based on your experience, what are the benefits and shortcomings of using SCC for your products?

The benefits cited by most producers are reduced "bug holes" and improved finish, essential for placing concrete in areas with congested reinforcement, faster concrete placement with less manpower, reduction in labor cost, less wear and tear of formwork, noise reduction and improved plant environment.

The shortcomings cited most often are higher materials cost (although it is partially offset by reduced labor cost), need for more quality control to maintain the mix consistency, the material is less forgiving and sensitive to moisture variation, some design issues such as shrinkage and bond, some forming issues such as ledges and haunches and higher pressure on form, and lack of standards and technical knowledge.

Q5. Were you provided any special provisions or other specifications pertaining to design, materials, and construction for using SCC in your products? If so, please send a copy with your response.

Most of the producers were not provided with any special provisions or other specifications for using SCC in their products. Several producers relied on the advice and technical assistance of the admixture suppliers. Two producers use PCI Interim Guidelines. The producer for prison modules was provided with specifications by the North Carolina Department of Correction.

Q6. If you have not used SCC, please check any of the applicable reasons listed below:

- **a. Higher cost of the materials_____**
- **b. Lack of standard specifications_____**
- **c. Lack of standard test methods_____**
- **d. No suppliers of SCC admixtures in our area_____**
- **e. Lack of technical knowledge_____**
- **f. Need for increased quality control_____**
- **g. Don't have prior experience_____**
- **h. Others (please specify) _____**

Of the 5 producers who are not currently using SCC, one checked all the above reasons other than line "h". One cited higher cost and difficult quality control as the main reasons for not using SCC. One indicated that by using "flowing" concrete, similar results were achieved with minimal vibration. The remaining two producers cited that their respective state DOT has not approved the use of SCC.

4. EXPERIMENTAL PROGRAM

4.1 Test Girders

Three standard AASHTO Type III girders were selected for this investigation. Each girder was 54.8 ft (16.7 m) long, prestressed with 18 straight ½ in. (12.7 mm) Grade 270 low relaxation strands as shown in Figure 4.1. Each strand has a cross-sectional area of 0.153 in.^{2} (98.7 mm^2). Five girders were cast on a single production line. Of the five girders, three were cast with normal concrete and two were cast with SCC. One of the girders cast with the normal concrete was used as control for comparison with the girders cast with the SCC.

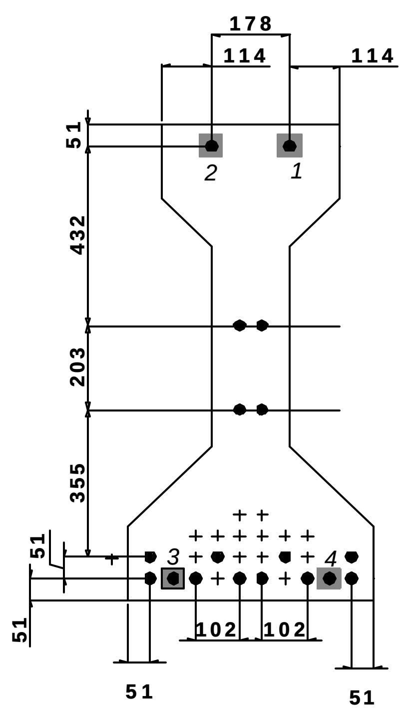


Figure 4.1 Cross-section of AASHTO Type III girder showing locations of load cells (*1, 2, 3, 4*). Dimensions are shown in mm (1 in. = 25.4 mm).

The sectional properties of the girder are: Cross-sectional Area A = 560 in.^{2} (3,613 cm^2); Moment of Inertia I = 125,390 in^4 (5,219,126 cm^4); Distance from Top Fiber to

Centroid y_t = 24.73 in. (628 mm); Distance from Bottom Fiber to Centroid y_b = 20.27 in. (515 mm); Eccentricity of Prestressing Force = 8.83 in. (224 mm).

The girder design called for each strand to be pretensioned to 30,980 lbs (137.8 kN). The specified concrete strength was 5,000 psi (34.5 MPa) at 28 days and 4,000 psi (27.6 MPa) at prestress release. The mixture proportions for the normal concrete and the SCC are shown in Table 4.1. The normal concrete was a standard 6,000 psi (41.4 MPa) concrete mixture developed by the producer for its normal production. The mixture proportion of the SCC was developed by the producer, with the assistance of the high-range water reducer manufacturer, over the course of several months involving three mock-up castings, each consisting of two or three 10 ft (3 m) long sections of Type III girders.

Table 4.1 Mixture Proportions of Normal Concrete and SCC

Materials per yd^3 (per m^3)	**Normal Concrete**	**SCC**
Cement – Type III	680 lbs (403 kg)	810 lbs (481 kg)
C. Aggregate – Granite*	1,700 lbs (1,009 kg)	1,330 lbs (789 kg)
F. Aggregate – 2MS**	1,295 lbs (768 kg)	1,300 lbs (771 kg)
Water	283.6 lbs (168.3 kg)	341.9 lbs (202.8 kg)
W/C	0.42	0.42
AEA – Darex II^{++}	0.3 oz/cwt (78.9 mL)	0.3 oz/cwt (94 mL)
Corrosion Inhibitor – DCIS	3 gal. (14.85 L)	3 gal. (14.85 L)
Retarder – Daratard 17	4.0 oz/cwt (1,052 mL)	4.0 oz/cwt (1,253 mL)
Superplasticizer – ADVA Flow^{+}	5.0 oz/cwt (1,315 mL)	N/A
Superplasticizer – ADVA 170^{+}	N/A	10.0 oz/cwt (3,133 mL)

* #67 for normal concrete and #78 for SCC **Class 2 manufactured sand from crushed marine marl limestone according to the NCDOT designation $^{+}$Polycarboxylate
$^{++}$Tall oil-based

4.2 Fabrication of Test Girders

Prestressing – The girders were cast on a 350 ft (106.7 m) long casting bed, oriented in the north-south direction, in the prestressing plant. The prestressing end is at the south and the dead (anchor) end is at the north. Prior to prestressing the strands, load cells were installed at the dead end on four of the 18 strands as indicated in Figure 4.1. The strands were tensioned individually and the prestressing force in each of the four selected strands was measured by the load cell. The load cell readings were taken again in the two succeeding mornings and just before detensioning, to determine any variations of the forces in the strands. The load cell readings are summarized in Table 4.2.

Table 4.2 Load Cell Readings

Load Cell	**Load Cell Reading in lbs (kN)**			
	5/5/04 1:50 PM*	5/6/04 9:00 AM	5/7/04 8:45 AM	5/7/04 1:00 PM**
#1	29,600 (131.7)	29,700 (132.1)	28,800 (128.1)	28,900 (128.5)
#2	29,800 (132.6)	29,600 (131.7)	28,800 (128.1)	28,800 (128.1)
#3	30,200 (134.3)	30,100 (133.9)	29,700 (132.1)	30,100 (133.9)
#4	30,770 (136.9)	30,770 (136.9)	30,570 (136.0)	30,770 (136.9)
Average	30,090 (133.8)	30,040 (133.6)	29,470 (131.1)	29,640 (131.8)

* Initial tension   ** Just before detensioning

Based on the average of the load cell readings, the initial tension was taken as 30,090 lbs (133.8 kN) per strand, which is well within the 5% tolerance permitted by the specifications. Just before detensioning, the average of the load cell readings was 29,640 lbs (131.8 kN) per strand, slightly less than the initial tension due to strand relaxation. Therefore, the initial prestressing force applied to the girders was taken as 29,640 lbs (131.8 kN) per strand.

After the 18 strands were tensioned and all necessary stirrups installed, two 3/8 in. (9.5 mm) steel bars instrumented with strain gages were installed at the south end of each of the three test girders. The bars served as strain transducers to measure the transfer length of the strands. One bar was located at the level of the two top prestressing strands, and one bar was located at the level of second row of strands at the bottom. A typical view of the strain transducer bar is shown in Figure 4.2. In order to monitor the concrete temperature during the curing period, thermocouples were installed at the midspan of each of the three test girders.

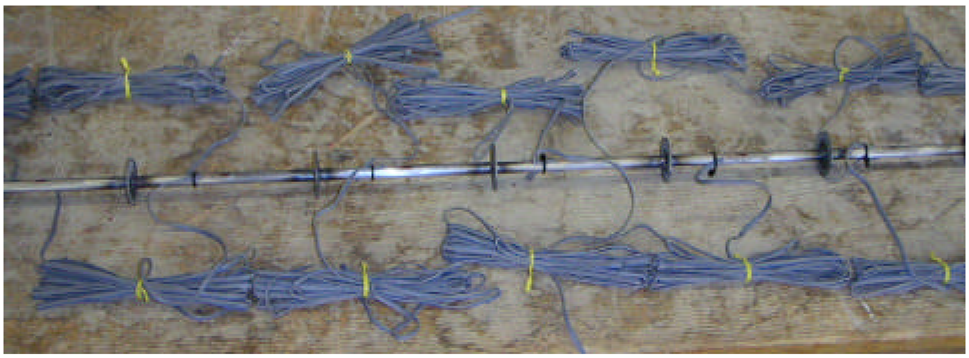


Figure 4.2   Typical view of a strain transducer bar

Concrete Placement – After the forms were set up, casting of concrete began from the north end. The first, second, and fifth girders were cast with the normal concrete, and the second girder was chosen as the control identified as test girder C.   The third and fourth girders were cast with the SCC and they were identified as test girders SCC1 and SCC2 respectively.

Concrete placement began at 1:30 p.m. with the first girder at the north end, and followed through the five-girder sequence to the south end. A ready-mix truck was used to transport the concrete from a central batching plant. The concrete was batched in a 3-yd^3 (2.29-m^3) pan mixer. For each normal concrete girder, one batch of 1 yd^3 (0.76 m^3), three batches of 2 yd^3 (1.53 m^3) each, and one batch of 1.5 yd^3 (1.15 m^3) were loaded into the truck for a total of 8.5 yd^3 (6.50 m^3). For each SCC girder, one batch of 1 yd^3 (0.76 m^3), and four batches of 2 yd^3 (1.53 m^3) each were loaded into the truck, making a total of 9 yd^3 (6.88 m^3).

The normal concrete was placed according to the standard plant procedures. After the truck was positioned alongside of the casting bed at the north end, concrete was discharged through a chute from the truck into the form, filling the form gradually from the north end to the south end. In the first lift, the form was filled with concrete up to 3 to 4 in. (75 to 100 mm) below the top flange of the girder. Two internal needle vibrators spaced about 5 to 6 ft (1.53 to 1.83 m) apart were used to consolidate the concrete as the concrete was discharged into the form. After the truck reached the south end of the girder, it returned to the north end and continued to fill the form to its top in the second lift. Again the concrete was consolidated with two vibrators as with the first lift. Figure 4.3 shows a view of casting test girder C.

The casting of the first girder was completed in about 30 minutes. However, the casting of the second girder (test girder C) was delayed near the end of the concrete placement when the concrete became very stiff in the truck under the hot summer sun with ambient temperature in the upper 90 F (32 C). Water was added by the producer to compensate for an expected variation of moisture content of the sand that was not accounted for at batching. The casting of the second girder was completed in about 45 minutes due to the unexpected delay. Later, the casting of the fifth girder with the normal concrete was completed as the first girder without any interruption.

Figure 4.3   Casting of test girder C as control

The placement procedure used for test girder SCC1 differed from that used for test girder SCC2. In casting SCC1, the concrete was discharged from the chute gradually and distributed from the north end to the south end in the first pass, filling the bottom of the form for about 6 in. (152 mm). Then the filling moved from the south end to the north end in the second pass, bringing the concrete level up to about 6 in. (152 mm) below the top flange. Finally, in the third pass from the north end to the south end, concrete level was brought to the top of the form. No vibration was used. The placement was completed in about 20 minutes. Figure 4.4 shows the casting of SCC1.

When SCC2 was cast, the concrete was discharged from the chute at about 6 ft (1.83 m) from the north end and the concrete flowed (spread) in both forward and backward directions under its own mass and momentum. When the peak level of the concrete reached the top of the girder web, the discharge point was moved about 12 ft (3.66 m) toward the south end, and the filling was continued until the peak level of the concrete again reached the top of the girder web. This process was repeated three times. Then the discharge point was moved continuously from the south end to the north end, to bring the concrete level to the top of girder form. Vibration was not used, and the placement was completed also in about 20 minutes.

Figure 4.4 Casting of test girder SCC1

Curing – Since the ambient temperature was above 90 F (32 C) in the day-time and in the low 70 F (21 C) at night, the five girders were cured without using heat. About one hour after the castings were complete, a soaker hose was place along the top of the five girders to provide moisture, and the entire line of castings was covered with heavy-duty tarpaulins. The curing began at about 6 p.m. The soaker hose was shut off at 4 a.m. the next morning. However, the tarpaulins remained in place until 10 a.m. for a total of 16 hours.

4.3 Tests for Fresh Concrete

Prior to casting the test girders, standard ASTM tests for unit weight, concrete temperature, and air content were conducted on both the normal concrete and SCC. In addition, the filling ability, the passing ability, and the flowability of the SCC were measured respectively by slump flow test, J-Ring test, and L-Box test (EFNARC 2002, PCI FAST Team 2003, Vachon 2002, Zia 2005). Though none of these tests has been standardized by national or international organizations, they have been commonly used in the laboratory and/or in the field.

Slump Flow Test – Slump flow test is the most commonly used method to assess filling ability. As shown in Fig. 4.5, a regular slump cone is placed at the center of a large square base plate with non-absorbent smooth surface, either in upright or inverted position. The plate should be stiff and in level position. A circle marking the central location for the slump cone is drawn on the plate. More concentric circles are often drawn on the plate, varying from 20 in. (500 mm) diameter to 28 in. (700 mm) diameter with 2 in. (50 mm) increments.

Figure 4.5 Slump flow test

Before the test begins, first moisten the base plate and inside of slump cone. Fill the cone with the SCC in one lift and do not use tamping. Strike off the concrete level with the top of the cone with a trowel. After removing the surplus concrete from around the base of the cone, it is raised vertically to allow the concrete to flow out freely.

Simultaneously, start the stopwatch and record the time taken for the concrete to reach the 20 in. (500 mm) circle. The measured time is T_{50cm}. The final diameter of the slump flow of the concrete is measured in two perpendicular directions. The average of the two measurements is the slump flow value of the concrete. If the difference between the two measurements is more than 2 in. (50 mm), the test is considered invalid and should be repeated. A minimum flow of 20 in. (500 mm) is required for concrete to be considered as SCC.

Depending on the applications, acceptable slump flow may vary between 23 in. (575 mm) to 30 in. (750 mm), although Khayat et al. (2004) suggested values from 24 to 29 in. (600 to 730 mm). Normally the desirable slump flow value is from 26 in. (650 mm) to 28 in. (700 mm). The time T_{50cm} is a secondary indication of flow. A lower time indicates greater flowability. In general, the desirable time is from 2 to 5 seconds.

If there is severe segregation, more coarse aggregates will remain at the center of the pool of concrete. More mortar and paste will flow to the edge of the slump spread. Visual inspection of the condition of the slump spread establishes the visual stability index (VSI) rating from 0 to 4 in 0.5 increments, according to a list of four descriptions. A rating of 0 indicates no segregation and a rating of 4 represents significant segregation with more than 3/8 in. (10 mm) mortar halo at the edge of slump spread. This evaluation is obviously quite subjective.

J-Ring Test – Figure 4.6 shows a J-ring test. This test is used to measure the passing ability of the SCC (Bartos 1998). It is used generally in conjunction with the slump flow test.

The size and spacing of the 4 in. (100 mm) long reinforcing bars attached to the 12 in. (300 mm) open steel circular ring can be varied according to the maximum nominal size of the aggregate. The bars are used as an obstacle to the flow of the concrete. Normally it is appropriate to use three times the maximum aggregate size as the spacing of the bars.

First, the J-Ring is placed on the base plate concentrically with the slump cone. Then the slump cone is filled with the SCC as in the case of slump flow test. Lift the slump cone vertically to allow the SCC to flow out freely. Measure the final diameter of the SCC in two perpendicular directions and obtain the average of the two measurements. This value represents the slump flow of the SCC with J-Ring. If the slump flow with J-Ring approaches the slump flow without J-Ring, it is an indication that the passing ability of the SCC is very good. Brameshuber and Uebachs (2001) proposed that the difference between the slump flow with and without the J-Ring should not exceed 2 in. (50 mm), but EFNARC reduced the value to 0.4 in. (10 mm) according to Khayat et al. (2004).

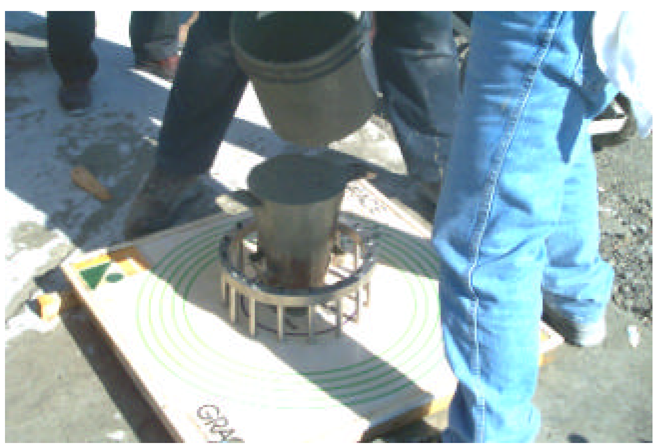


Figure 4.6 J-Ring test

The difference in height between the concrete just inside and outside the bars is also an indication of how much is the effect of aggregate blocking, and represents a measure of the passing ability. The difference should be measured at four locations and the average of the four difference values be calculated. If this average value is within 1/2 in. (13 mm), the passing ability would be acceptable.

L-Box Test – The L-Box test is shown in Fig. 4.7. This test evaluates the flowability of the SCC, and also the blocking effect of the reinforcement. The test apparatus is in the shape of an "L" box with a rectangular cross-section of 4 x 8 in. (100 x 200 mm). The vertical leg is 24 in. (600 mm) tall and separated by a movable gate from the horizontal leg which is 28 in. (700 mm) long. Placed in front of the gate are several vertical reinforcing bars to serve as an obstacle.

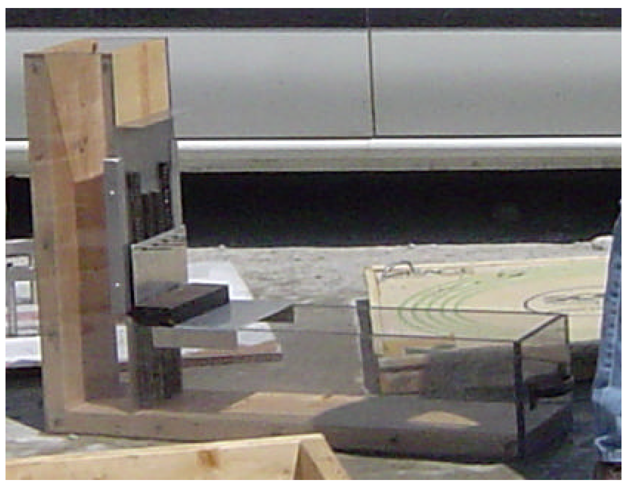


Figure 4.7 L-Box test

The vertical leg of the L-Box is filled with the SCC and then the gate is lifted to allow the SCC to flow through the vertical reinforcing bars into the horizontal leg of the L-Box. Simultaneously, start the stopwatch and record the times T_{20cm} and T_{40cm} for the SCC to reach the 8 in. (200 mm) mark and 16 in. (400 mm) mark from the gate, respectively. When the SCC stops flowing, measure the height of the SCC at the toe (H2) and at the gate (H1). The blocking ratio is then calculated as H2/H1. The whole test should be performed within 5 minutes.

If the SCC flows freely as water, then its surface should be horizontal, so H2/H1=1. Therefore, the closer the blocking ratio H2/H1 is to one, the less is the blocking and the better is the flow of the SCC. Any blocking of coarse aggregates behind the reinforcing bars can be detected visually. An acceptable value for the blocking ratio H2/H1 as proposed by Skarendahl (1999) was between 0.8 and 0.85. However, EFNARC guideline recommended the limit to be between 0.8 and 1.0 (Khayat et al. 2004).

The T_{20cm} and T_{40cm} values (in seconds) provide a measure of the rate of flow of the SCC. Longer time indicates an increase in viscosity. These values can be used for comparative purposes between different SCC mixtures. There are no recommended acceptable values for these time measurements at the present time.

4.4 Tests for Hardened Concrete

During the casting of the test girders, test specimens for compressive strength, flexural modulus, modulus of elasticity, shrinkage, and creep were prepared. These test specimens were cured overnight with the girders. The specimens were placed on the horizontal web stiffeners of the steel girder form except that the beam specimens for flexural modulus were left on the casting bed but next to the girders. Therefore the test specimens were under the same tarpaulin cover and subjected to similar environment as the girders. However, it should be noted that the test specimens received less moisture from the soaker hose since the hose was placed on top of the girders.

After the test specimens were brought to the laboratory at end of the 2nd day after casting, their molds were removed on the 4th or 5th day after casting. The specimens were then left in the open air outside the laboratory without moist curing until testing – except the creep test specimens and their companion shrinkage specimens – to simulate the condition of the test girders in the casting plant. The seasonal climatic condition outside the laboratory was similar to that at the casting plant where the test girders were kept.

The creep test specimens and their companion shrinkage specimens were kept and tested inside the laboratory under virtually constant temperature of 70 F (21 C) and an average humidity of 40 %.

4.5 Air Permeability Test and Air Void Analysis

As a measure of durability, test for air permeability and air void analysis were performed on samples of the normal concrete and SCC. These tests are briefly described below.

Air Permeability Test – Air permeability test was applied to three slab specimens by using the Zia-Guth test device that was developed at NC State University (Guth and Zia 2000, Guth and Zia 2001, Hassan and Zia 2005). The test device uses a surface airflow technique to determine the air permeability of the concrete. As shown in Figure 4.8, the device consists of two concentric cylinders that form an inner and outer chamber. When placed on the concrete surface, the chamber area is comprised of an inner circle and an outer ring.

To achieve a quick and airtight seal, a strip of rope caulking is placed on the bottom edge of each chamber. After pressing the test device on the test surface, a 2 in. (50 mm) wide strip of duct tape is used to cover the concrete surface around the outer chamber to prevent air from flowing through that area. With the valves of both chambers being open, a vacuum pump is connected to the test device to vacuum both chambers simultaneously, see Figure 4.8(a). Once the pressure reading inside the inner chamber reaches a value of 0.05 to 0.07 psi, both valves are closed and the vacuum pump is disconnected.

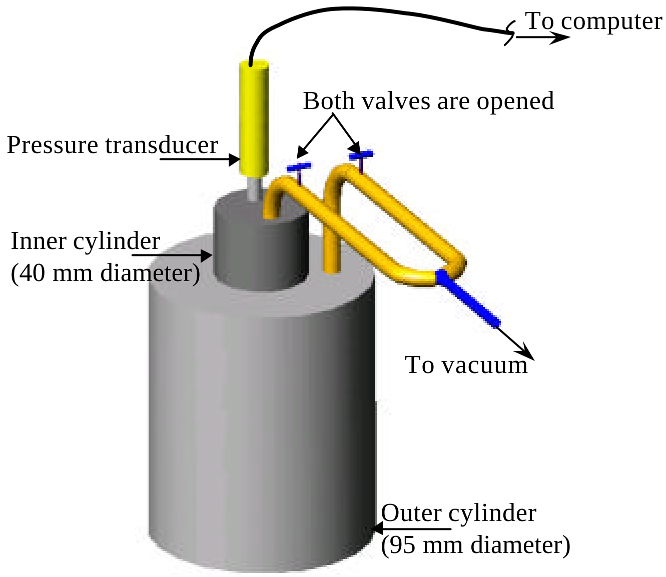


Figure 4.8(a) Zia-Guth air permeability test device (1 in. = 25 mm)

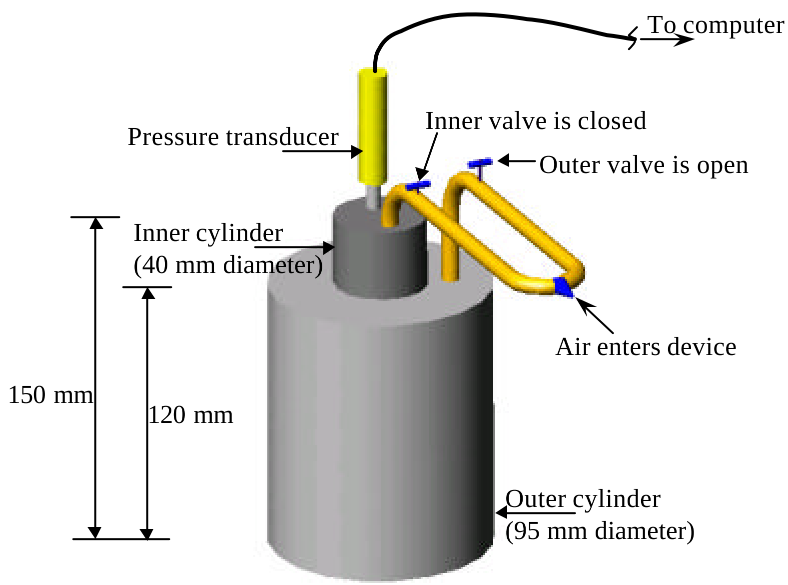


Figure 4.8(b) Zia-Guth air permeability test device (1 in. = 25 mm)

By opening the outer valve, see Figure 4.8(b), air is allowed to enter the outer chamber and flow through concrete into the inner chamber. Air pressure in the inner chamber gradually increases and the pressure readings are recorded for 5 minutes using a data logger. Figure 4.9 shows a typical air permeability test setup.

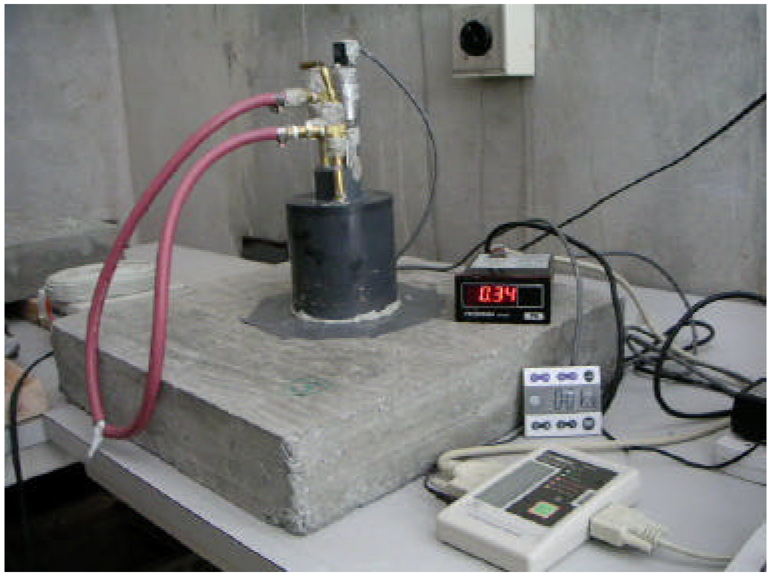


Figure 4.9   Typical air permeability test setup for slab specimens

The recorded pressure readings versus time are a measure of the air permeability of the concrete. The air permeability index (PI) of the concrete is directly proportional to the slope (S) of the pressure – time curve and is expressed as

$$\text{PI (in in}^2\text{)} = 0.66 \times 10^{-10}\ \text{S (in psi/sec.)} \qquad (4.1)$$

or

$$\text{PI (in mm}^2\text{)} = 6.17 \times 10^{-6}\ \text{S (in MPa/sec.)} \qquad (4.2)$$

The three 18 x 18 x 3 ½ in. (450 x 450 x 88 mm) slab specimens were cast in wooden forms made with 2 x 4 lumber as sides and plywood as bottom. They were cast at the same time as the three test girders, one for the normal concrete (Control C) and two for the SCC (SCC1 and SCC2). The slab made with the normal concrete was consolidated externally by vibrating the form, and no consolidation was applied to the SCC slabs. The specimens were shipped to the laboratory and left outside under ambient conditions until demolded at approximately 200 days.

Air Void Analysis – Air void analysis was performed, using test specimens obtained from both cylinders and slabs. The tests were conducted in general accordance with ASTM C457-98 "Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete." Two disk specimens for each concrete mixture were obtained by sawing 4 x 8 in. (100 x 200 mm) concrete cylinders at the top and the bottom (Figure 4.10). The disks were approximately 1 in. (25 mm) thick and 4 in. (100 mm) in diameter. The test was performed by counting 1350 points on a 6 in.^{2} (3750 mm^2) area using a 20X magnification for each disk specimen.

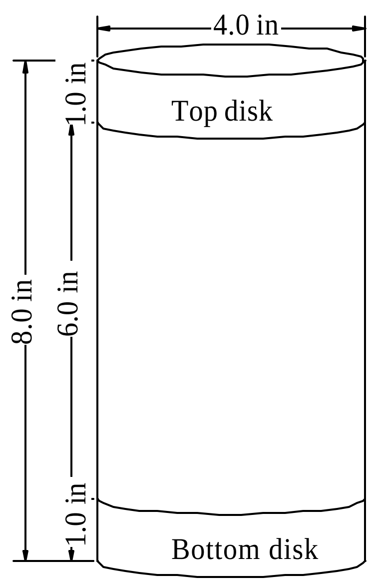


Figure 4.10 Top and bottom disks sawed from 4 x 8 in. cylinder.
(1in. = 25 mm).

All cylinders used to obtain the concrete disks were made when the test girders were cast at the prestressing plant. The normal concrete cylinders were made according to the standard procedures and the SCC cylinders were made without rodding or vibration. The cylinders were shipped to the laboratory, demolded immediately, and stored outside under the ambient conditions until sawing and testing at approximately 285 days.

Concrete cores were taken from the slab specimens, one for each specimen except for SCC2 from which two core samples were taken (Figure 4.11). The locations for coring in the slabs were selected after the air permeability tests were performed as described above. The cores were then sawed to obtain the top and bottom disks, approximately 1 in. (25 mm) thick and 4 in. (100 mm) diameter. Air void analysis was performed on each disk as before.

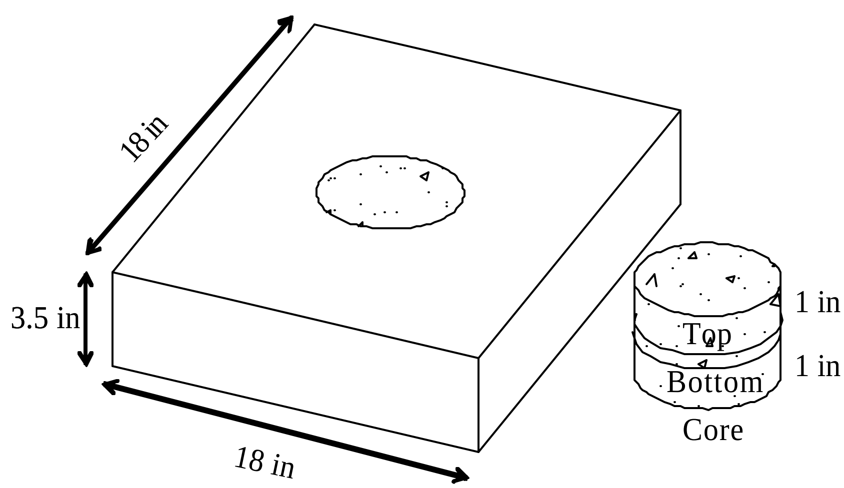


Figure 4.11 Cores drilled from a slab specimen (1 in. = 25 mm)

4.6 Load Testing of Girders

The three experimental girders – Control C, SCC1, and SCC2 – were load tested at the prestressing plant in Wilmington, NC on August 12, 2004 when the girders were 98 days old, as shown in Figure 4.12. Each girder was simply supported on steel bearing plates at each end. A single concentrated load was applied at midspan with a 60 tons (534 MN) hydraulic jack. The initial applied load was 12.4 kips (55.2 kN), followed by each load increment of 6.2 kips (27.6 kN) which was equivalent to 500 psi (3.45 MPa) hydraulic pressure on the jack. At each load level, the midspan deflection of the girder was measured by two dial gages placed below the bottom of the girder near each edge of the flange. The average of the two dial gage readings was taken as the deflection of the girder.

Figure 4.12 Load testing of girder SCC2

The loading was discontinued when it reached 55.8 kips (248 kN) or 4,500 psi (31 MPa) hydraulic pressure. At that load level, the maximum bottom fiber stress in the concrete was estimated to be 300 psi (2 MPa) in tension, which is slightly above the design service load level. Under the maximum loading of 55.8 kips (248 kN), no flexural cracks were observed in any of the girders. After unloading, there was full recovery of girder deflection, and the camber of each girder was measured for record. On November 15, 2004 when the girders were 193 days old, the cambers of the three girders were measured again for comparison and record (see Table 5.9).

5. TEST RESULTS AND DISCUSSION

5.1 Concrete Curing Temperature

Three thermocouples were embedded at midspan in each of the three test girders to monitor the concrete temperature during curing. One was placed in the middle of top flange, one at mid-height of the web, and one in the middle of bottom flange. In addition, a thermocouple was place under the tarpaulin cover and one outside the tarpaulin cover to monitor the ambient temperature. A multi-channel recorder was turned on at 1:50 p.m. just before test girder C was cast, to continuously record the thermocouple readings for 850 minutes. Figure 5.1 shows the curing temperature record of Control C.

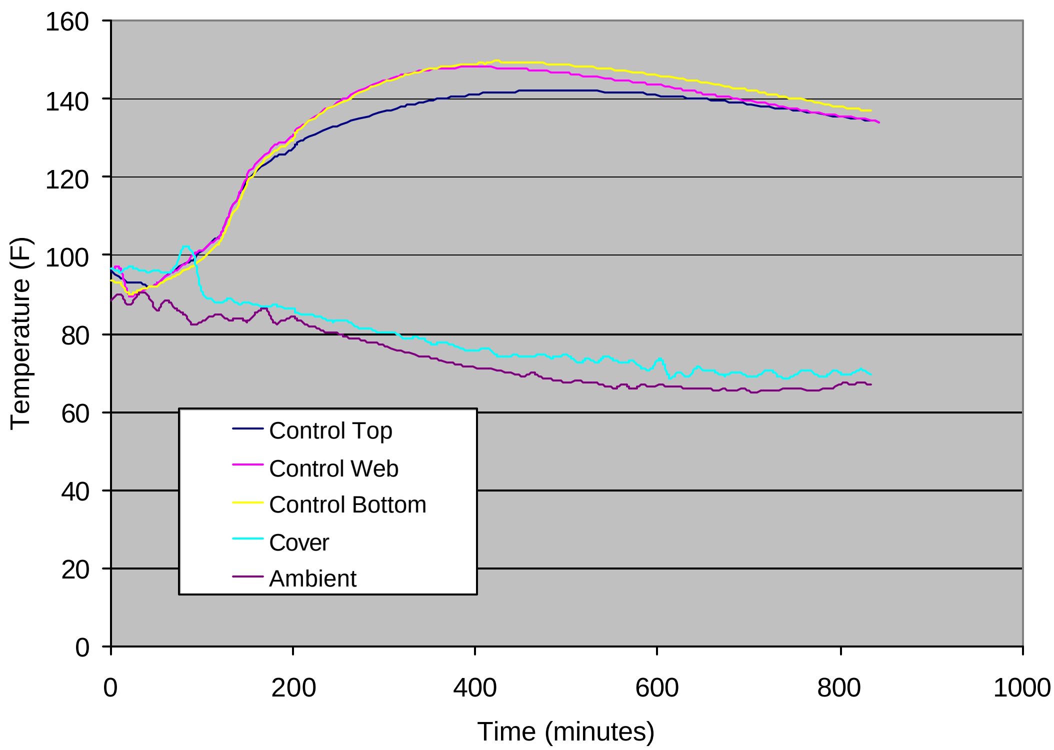


Figure 5.1 Curing temperature record of Control C [C = (F-32)/1.8]

It can be seen that the concrete temperature reached as high as 150 F (66 C). The temperature in the bottom flange was slightly higher than that in the web and in the top flange, but the difference was insignificant. The temperature under the tarpaulin cover and the ambient temperature were quite similar, & they dropped to as low as 70 F (21 C) at night.

As shown in Figures 5.2 and 5.3, the curing temperature records of test girders SCC1 and SCC2 are practically the same as that of Control C. In each case, the time between the initial rise of temperature and the peak temperature was about 300 minutes, or 5 hours.

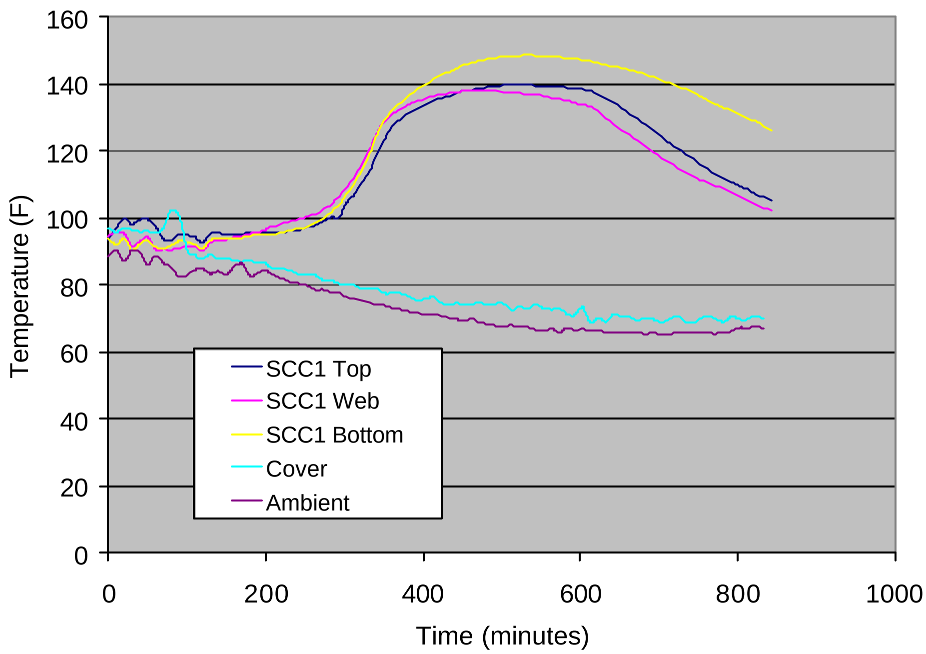


Figure 5.2 Curing temperature record of SCC1 [C = (F-32)/1.8]

It is noted that the test girder C reached its peak temperature at 400 minutes, SCC1 reached its peak temperature at 550 minutes, and SCC2 reached its peak temperature at 650 minutes after the recording was initiated. This apparent time difference represents nothing more than the difference in time between the consecutive castings of the three gird

test girder C, being cast first, reached the peak temperature ahead of SCC1, and SC

reached its peak temperature ahead of SCC2.

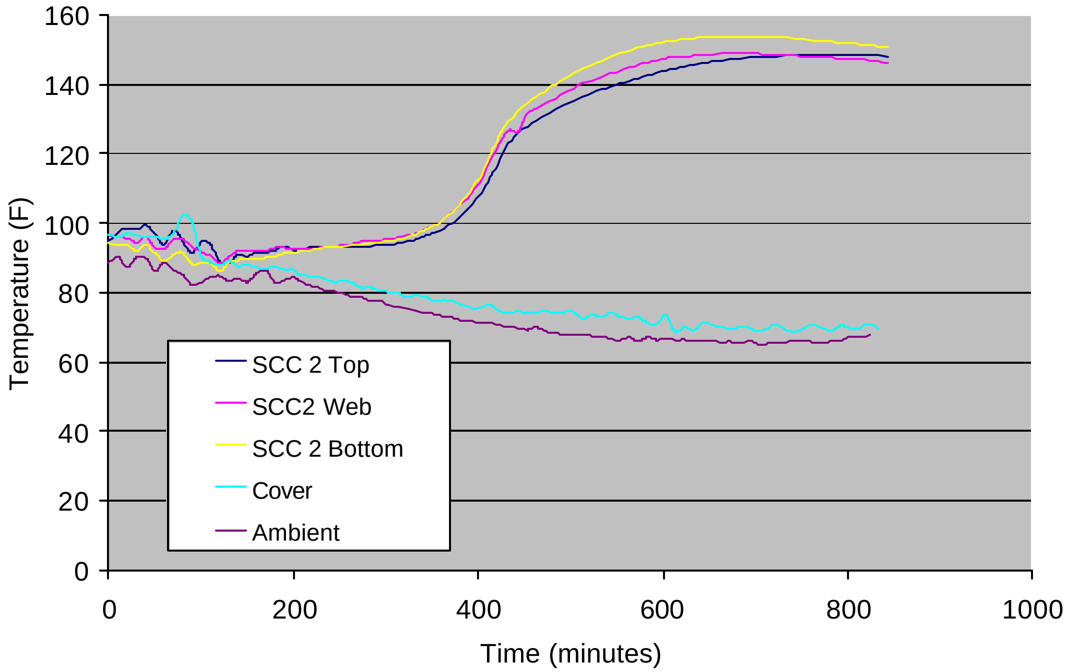


Figure 5.3 Curing temperature record of SCC2 [C = (F-32)/1.8]

5.2 Concrete Strength at Release of Prestress

After 16 hours of curing, two 4 x 8 in. (102 x 204 mm) control cylinders of the normal concrete cured with the girders were tested to determine the compressive strength of the concrete. The average result was only 3,700 psi (25.5 MPa), less than the required 4,000 psi (27.6 MPa) for releasing the prestress. So the prestress release was postponed for two more hours, at which time the compressive strength of the normal concrete reached 4,700 psi (33.1 MPa) based on the average of two test cylinders. Two 4 x 8 in. (102 x 204 mm) control cylinders of the SCC, one each representing SCC1 and SCC2, were also tested and their compressive strengths were 5,550 psi (38.3 MPa) and 5,450 psi (37.6 MPa), for an average of 5,500 psi (38 MPa). Thus the compressive strength of SCC at release of prestress was 800 psi (5.5 MPa) higher than the compressive strength of the normal concrete.

5.3 Initial Camber and Strand End-slip

As soon as the strands were released by flame cutting according to a prescribed sequence, the cambers and the strand end-slips at the south end of the three test girders were measured and the results are shown in Table 5.1. The initial camber of 0.25 in. (6.4 mm) was the same for the three test girders, which implies that the modulus of elasticity would be the same for the three test girders. By using the initial prestressing force of 29,640 lbs (131.8 kN) per strand as measured by the load cell, and allowing 4 % loss of prestress due to elastic shortening at the time of prestress release, and assuming the unit weight of concrete to be 150 lbs/ft^3 (2,403 kg/m^3), the modulus of elasticity of the three test girders was determined as 4.4 x 10^6 psi (30.3 GPa) at the time of prestress release as shown in Table 5.3.

Table 5.1 Initial Cambers and Strand End-slips

Test Girder	**Initial Camber in. (mm)**	**Strand End-slip in. (mm)**				
		Strand #1*	**Strand #2**	**Strand #3**	**Strand #4**	**Ave.**
C	0.25(6.4)	0.12(3.0)	0+	**	0.18(4.6)	0.15(3.9)
SCC1	0.25(6.4)	0.12(3.0)	0.18(4.6)	0.06(1.4)	0.06(1.4)	0.11(2.6)
SCC2	0.25(6.4)	0.12(3.0)	0.06(1.4)	0.18(4.6)	0.31(7.7)	0.17(4.2)

*Strand number is same as load cell number +Neglected in average
** Not measurable due to spilled concrete around strand

The measured strand end-slips seem to suggest that there was no significant difference in bond behavior between the top strand and the bottom strand. In addition, the average value of the strand end-slips of SCC1 and SCC2 is 0.14 in. (3.6 mm) as compared to 0.15 in. (3.9 mm) of the strand end-slip of Control C. Based on the overall behavior of the three test girders, there was no difference in performance between the control girder C and the two SCC girders.

5.4 Transfer Length

As described previously, to measure the transfer length of the strands, two strain transducer bars were installed at the south end of each of the three test girders. One bar was located at the level of the two top strands, and another bar was placed at the level of the second row of strands from the girder bottom. Each bar was 48 in. (1,219 mm) long with seven pairs of electrical resistance gages attached to it at 6 in. (152 mm) on centers. Since the transducer bar was embedded in the concrete, it would monitor the concrete strain profile at every 6 in. (152 mm) from the south end of the girder for a distance of 48 in. (1,219 mm).

Unfortunately, during concrete placement, a number of gages were damaged, and the entire group of the lead wires of the bottom bar in SCC1 was inadvertently destroyed by a crew member just prior to stripping the girder forms. However, the response of the remaining gages does indicate the trend of the concrete strain profile.

Figure 5.4 shows the strain profiles of the top bars in the three test girders. The trend indicates that the transfer length of the top prestressing strands would be in the range of 30 to 40 in. (762 to 1,016 mm). It is noted that the strain in the bar was very small since the concrete stress (and thus strain) at that level under eccentric prestressing was very low. Figure 5.5 shows the strain profiles of the bottom bars in Control C and SCC2. Again, the trend indicates that the transfer length of the bottom prestressing strands would also be in the same range as the top strands.

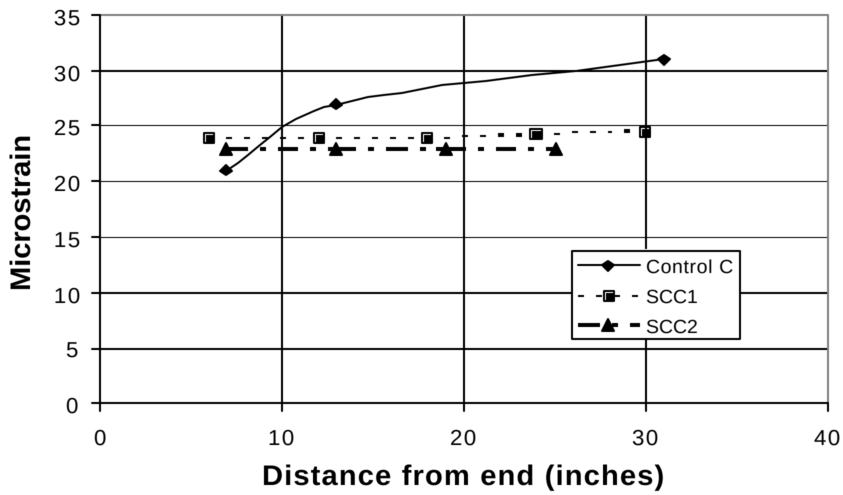


Figure 5.4 Transfer lengths of top strands (1 in. = 25.4 mm)

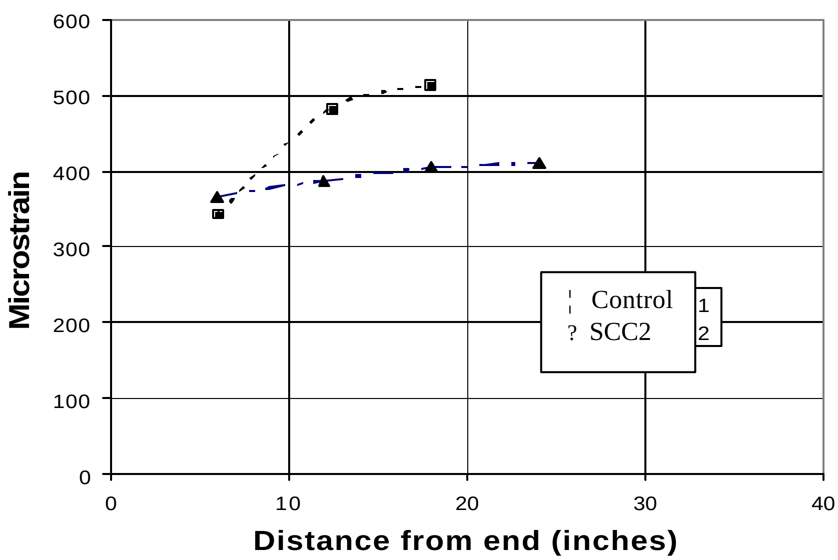


Figure 5.5 Transfer lengths of bottom strands (1 in. = 25.4 mm)

The strand transfer length can also be evaluated from the measured strand end-slips. By assuming linear variation of both strand and concrete strains over the transfer length in pretensioned member, Oh and Kim (2000) showed that the transfer length is

$$l_t = \frac{2E_p d}{f_{pi}} \tag{5.1}$$

where l_t = transfer length, E_p = modulus of elasticity of strand, d = strand end slip, f_{pi} = initial prestress of the strand just before detensioning.

Since E_p = 28.5 x 10^6 psi (197 GPa), f_{pi} = 29,640/0.153 = 193,725 psi (1,336 MPa), then

$$l_t = 294\, d \tag{5.2}$$

Applying the end-slip values given in Table 5.1, the transfer length would be 44.1 in. (1,120 mm), 32.3 in. (821 mm), and 50 in. (1,270 mm) for Control C, SCC1, and SCC2 respectively. The average of the transfer lengths of SCC1 and SCC2 is 41.2 in. (1,045 mm), which compares closely with the transfer length of Control C. These estimated transfer lengths are about 40% more than the requirement of the AASHTO specifications which recommends 60 strand diameters or 30 in. (762 mm).

5.5 Properties of Fresh Concrete

Plastic properties of both the normal concrete and the SCC were measured as described in EFNARC (2002), PCI TR-6-03 (2003), Vachon (2002), and Zia (2005). The results are summarized in Table 5.2. The unit weight of the normal concrete was 5 lbs (2.27 kg) more than the SCC as would be expected, since SCC contained much less coarse aggregate but more cement in order to achieve the desired flowability. The concrete temperatures, and air contents of the three concrete mixtures, as well as the slump of the normal concrete, were all within the specified limits.

The slump flows of both SCC1 and SCC2 were less than the optimum. A more desirable slump flow would be in the range of 26 to 28 in. (660 to 710 mm). However, the casting of the experimental girders did not encounter any difficulties and the outcome appeared to be quite satisfactory, in terms of surface finishes, camber, strand end-slip, and transfer length.

Table 5.2 – Properties of Fresh Concrete

Properties	C	SCC1	SCC2
Unit Weight, lbs/ft^3 (kg/m^3)	147 (2,355)	142 (2,275)	142 (2,275)
Concrete Temperature, F (C)	88.2 (31.2)	91.8 (33.2)	89.6 (32.0)
Air Content, %	3.4	4	5.7
Slump, in. (mm)	6 (152.4)	N/A	N/A
Slump Flow, in. (mm)	N/A	24 (609.6)	23.75 (603.3)
Visual Stability Index (VSI)	N/A	1 (Stable)	1 (Stable)
Flow Rate & Viscosity, T_{50} in Sec.	N/A	1.6	5.6
J-Ring Flow, in. (mm)	N/A	23.5 (596.9)	20.5 (520.7)
Passing Ability Index	N/A	0 (High)	2 (Low)
Blocking Ratio, H2/H1	N/A	0.5	0.52

Visual inspection of the circular spread of the concrete mixture during the slump flow tests determined that the SCC mixtures were quite stable and without mortar halo and aggregate segregation in the slump flow spread. Therefore the visual stability index (VSI) value of 1 was assigned to both SCC mixtures.

During the slump flow tests, the flow rate and viscosity of the SCC mixtures were determined by measuring the time required for the outer edge of the concrete spread to reach a diameter of 20 in. (500 mm). This measured time (T_{50}), in seconds, indicates the unconfined flow rate of the concrete mixture and thus its viscosity. It can be seen from Table 5.2 that SCC1 had a much higher flow rate and lower viscosity than SCC2.

The passing ability of the SCC mixtures was measured using both the J-Ring method and the L-box method. As shown in Table 5.2, SCC1 achieved a spread of 23.5 in. (597 mm) through the J-Ring, whereas SCC2 was able to achieve a spread of only 20.5 in. (521 mm). By comparing these spread values for SCC1 and SCC2 with their respective spread value without using the J-Ring, one can assign a passing ability index of 0 (high) to SCC1 and 2 (low) to SCC2. Based on the L-box tests, the blocking ratio (H2/H1) was 0.5 for SCC1 and 0.52 for SCC2. A more desirable blocking ratio should be at least 0.8.

5.6 Mechanical Properties of Hardened Concrete

Table 5.3 summarizes the results of the tests for compressive strength, flexural modulus, and modulus of elasticity. The compressive strength and the modulus of elasticity were determined by using 4 x 8 in. (100 x 200 mm) cylinders, unless otherwise noted. The flexural modulus was obtained by testing 6 x 6 x 24 (150 x 150 x 600 mm) beam specimens. All test specimens were cured in open air after their molds were removed three or four days after casting. Each result represents the average of two specimens.

Compressive strength — The development of compressive strength was excellent for both the normal concrete and the SCC. At 18 hours, the compressive strengths of both concretes were more than 4,000 psi (27.6 MPa) required for prestress release. At 7 days, the compressive strengths of both concretes reached well above the specified 28-day strength of 5,000 psi (34.5 MPa). At the age of 28 days, the compressive strength of the normal concrete exceeded 7,000 psi (48.3 MPa) and that of the SCC exceeded well over 10,000 psi (69 MPa).

Flexural modulus — As shown in Table 5.3, the flexural modulus was determined for the normal concrete and the SCC at 28 days. The values for both concretes are comparable, but they are lower than what should be expected of both concretes based on their compressive strengths. This is likely due to the lack of moist curing and the weak fine aggregate used in the concrete mixtures, which is manufactured sand made from porous marine marl limestone.

Table 5.3 Compressive Strength, Flexural Modulus, and Modulus of Elasticity (1 MPa = 145 psi)

Age	**Control C**	**SCC1**	**SCC2**
Compressive Strength f_c' in psi (MPa)			
18 hrs	4,700 (32.4)	5,550 (38.3)	5,450 (37.6)
7 days	6,600 (45.5)	8,980 (61.9)	7,435 (51.3)
28 days	7,280 (50.2)	10,970 (75.7)	10,540 (72.7)
Flexural Modulus in psi (MPa)			
28 days	568 (3.92)	551 (3.80)	547 (3.77)
Modulus of Elasticity in ksi (GPa)			
28 days	3,000 (20.69)	3,500 (24.14)	3,200 (22.07)
18 hrs*	4,400 (30.34)	4,400 (30.34)	4,400 (30.34)
90 days**	4,300 (29.66)	4,400 (30.34)	4,700 (32.41)
98 days***	4,600 (31.72)	4,700 (32.41)	4,400 (30.34)

*Based on initial camber measurements. **Based on elastic strain measured at loading for creep test. *** Based on load test of girders.

<u>Modulus of elasticity</u> — In spite of the excellent compressive strength that was achieved, the modulus of elasticity of both concretes determined from 4 x 8 in. (102 x 204 mm) cylinders at both 28 days and 90 days was much lower than expected (see Table 5.3). In comparison, the deficiency is more severe for the SCC than the normal concrete. The deficiencies can be attributed to three factors. First, the modulus of elasticity is dependent on the stiffness and porosity of the aggregates. Although the coarse aggregate used in both concretes was granite with low porosity and high stiffness, the fine aggregate used in both concretes was manufactured sand from crushed marine marl limestone with high porosity and low stiffness. Since the SCC contained proportionally more fine aggregate and less coarse aggregate than the normal concrete, the SCC would be expected to have lower modulus of elasticity than the normal concrete. Secondly, the modulus of elasticity is also dependent on the porosity of the cement paste matrix and the transition zone between the aggregate and the paste. Since the SCC contained much more cement than the normal concrete and, in addition,

all the test specimens were prepared under the hot summer sun in the casting plant (resulting loss of moisture) and were not moist cured, the microstructure of the paste matrix and the transition zone would be more porous. Thirdly, while the large mass of the girder produced significant heat of hydration during the initial curing period, the small size (mass) of the cylinders did not have the benefit of high heat of hydration during initial curing.

It is important to note that the modulus of elasticity determined from 4 x 8 in. (102 x 204 mm) cylinders does not reflect accurately the actual modulus of elasticity of the three test girders. As shown in Table 5.3, based on the measured camber of the three test girders at the time of prestress release, the modulus of elasticity was found to be 4.4 x 10^6 psi (30.3 GPa) for both the normal concrete and the SCC at the age of only 18 hours.

It should also be noted, as shown in Table 5.3, that the modulus of elasticities obtained at 98 days from actual load tests (described below) are comparable to the modulus of elasticity obtained from the initial camber measurements. This indicates that the aging of the concretes (without moist curing) did not enhance their modulus of elasticity even though their compressive strengths were improved.

<u>Creep</u> – One week after the test specimens were cast, a set of three creep specimens for each concrete was placed in the creep test frame. Data were collected frequently for about 60 days. Unfortunately, it was discovered that the Demec gage for measuring the strains was malfunctioning and the Demec gage points were made inaccurately. As the result, the data had to be discarded and the creep tests were started anew at 90 days after the Demec gage was adjusted and new gage points were attached to the creep specimens. As soon as the load was applied to the creep specimens, the instantaneous elastic strains were measured. The strains were 437, 525, and 555 microstrains for Control C, SCC1, and SCC2 respectively. The

corresponding stress applied to each set of creep specimens was 1,870 psi (12.9 MPa), 2,310 psi (15.9 MPa), and 2,630 psi (18.1 MPa) for Control C, SCC1, and SCC2 respectively. Accordingly, the modulus of elasticity can be computed as:

For Control C $\quad$ 1,870/437 x 10^{-6} = 4.3 x 10^{6} psi (29.7 GPa)

For SCC1 $\quad$ 2,310/525 x 10^{-6} = 4.4 x 10^{6} psi (30.3 GPa)

For SCC2 $\quad$ 2,630/555 x 10^{-6} = 4.7 x 10^{6} psi (32.4 GPa)

The above values are shown in Table 5.3 for comparison.

The creep strains measured between 90 days and 320 days are shown in Figure 5.6. The amount of creep was 290 microstrains for Control C, 320 microstrains for SCC1, and 350 microstrains for SCC2.

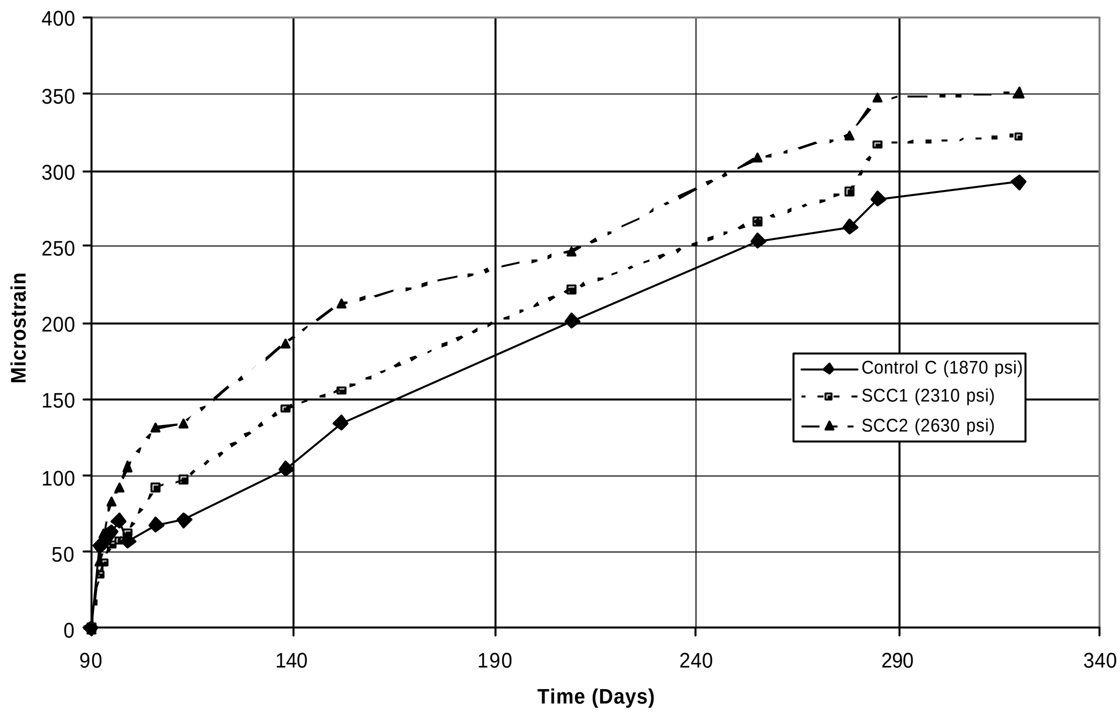


Figure 5.6 Creep of Control C, SCC1, and SCC2 loaded at 90 days

Since each test was loaded at a slightly different load level, the comparison will be made on the basis of specific creep. Dividing the creep strain by the applied stress, one obtains the specific creep shown in Table 5.4. It can be seen that the specific creep of the SCC is about 15% less than that of the normal concrete.

Table 5.4 Specific Creep of Control C, SCC1, and SCC2 for Loading at 90 days

Specimen	Control C	SCC1	SCC2
Specific Creep	0.16×10^{-6}	0.14×10^{-6}	0.13×10^{-6}

To consider the effect of loading at 90 days rather than at 7 days, one can make use of the time-of-loading factor given in AASHTO Eq. (5.4.2.3.2-1) for creep (AASHTO 2004). The time-of-loading factor is expressed as

$$F_{cr} = t_i^{-.0118} \frac{(t - t_i)^{0.6}}{10 + (t - t_i)^{0.6}} \tag{5.3}$$

where t_i is the age of concrete at loading and t is the total age of concrete, and in this case, t = 320 days. If the age of concrete at loading were 7 days, $F_{cr}(7) = 0.603$. For loading at 90 days, $F_{cr}(90) = 0.425$. The ratio $F_{cr}(7) / F_{cr}(90) = 0.603 / 0.425 = 1.42$. Therefore, the creep would be 42% more than the measured creep if the loading were applied at 7 days rather than at 90 days. The adjusted specific creep values are shown in Table 5.5. These values are comparable to the normal design values for prestressed concrete.

Table 5.5 Adjusted Specific Creep of Control C, SCC1, and SCC for Loading at 7 days

Specimen	Control C	SCC1	SCC2
Adjusted Specific Creep	0.23×10^{-6}	0.20×10^{-6}	0.18×10^{-6}

Shrinkage – Shrinkage was measured on the companion cylinders of the creep specimens. Figure 5.7 shows the shrinkage measured between 90 days and 320 days. The shrinkages for the normal concrete and the SCC were comparable, about 200 microstrains. It should be noted that these measured shrinkage values represent only a portion of the total shrinkage.

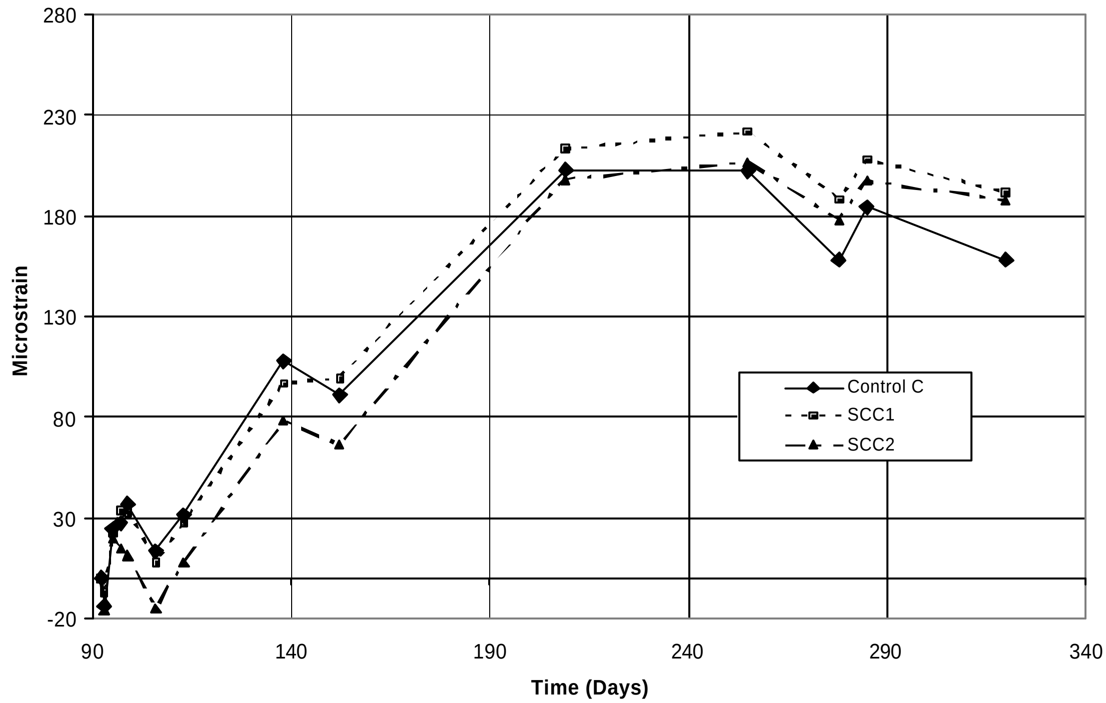


Figure 5.7 Shrinkage of Control C, SCC1, and SCC2 measured from companion cylinders of creep tests

To account for the effect of delayed measurement, one can consider the time factor given in AASHTO Eq. (5.4.2.3.3-1) for shrinkage (AASHTO 2004). The factor is expressed as

$$F_{sh} = \frac{t}{35 + t} \tag{5.4}$$

For t = 90 days, $F_{sh}(90) = 0.72$. It means that 72% of the total shrinkage would take place in the first 90 days. For t = 320 days, $F_{sh}(320) = 0.90$. It means that 90% of the total shrinkage would take place in 320 days. Therefore, the amount of shrinkage that would occur between 90 days and 320 days would be equal to 0.90 – 0.72 = 0.18 or 18% of the expected total shrinkage.

Since the measured shrinkage between 90 days and 320 days is roughly 200 microstrain, the expected total shrinkage would be 200 x 10^{-6}/0.18 = 1111 x 10^{-6}. This magnitude of shrinkage is substantially more than the shrinkage value normally used for prestressed concrete design.

However, considering the fact that the test specimens were not moist cured and were kept in the laboratory with a relatively constant humidity of 40%, the above value of 1111 x 10^{-6} would not seem to be unreasonable.

5.7 Air Permeability and Air Void Content

Figure 5.8 shows the pressure-time curve and the air permeability index measured at three different locations on the top and bottom surfaces of test specimens C. The same information for test specimens SCC1 and SCC2 are given in Figure 5.9 and Figure 5.10 respectively. As indicated in the figures, the test was performed at more than three locations for specimens SCC1 and SCC2. Figure 5.6 summarizes the results of the air permeability tests. It is interesting to note that for each of the test specimens, the air permeability index is much higher for the bottom surface than the top surface, especially for SCC2. In addition, the measurements made on the bottom surface had much more variability than on the top surface for all test specimens, particularly true for SCC2.

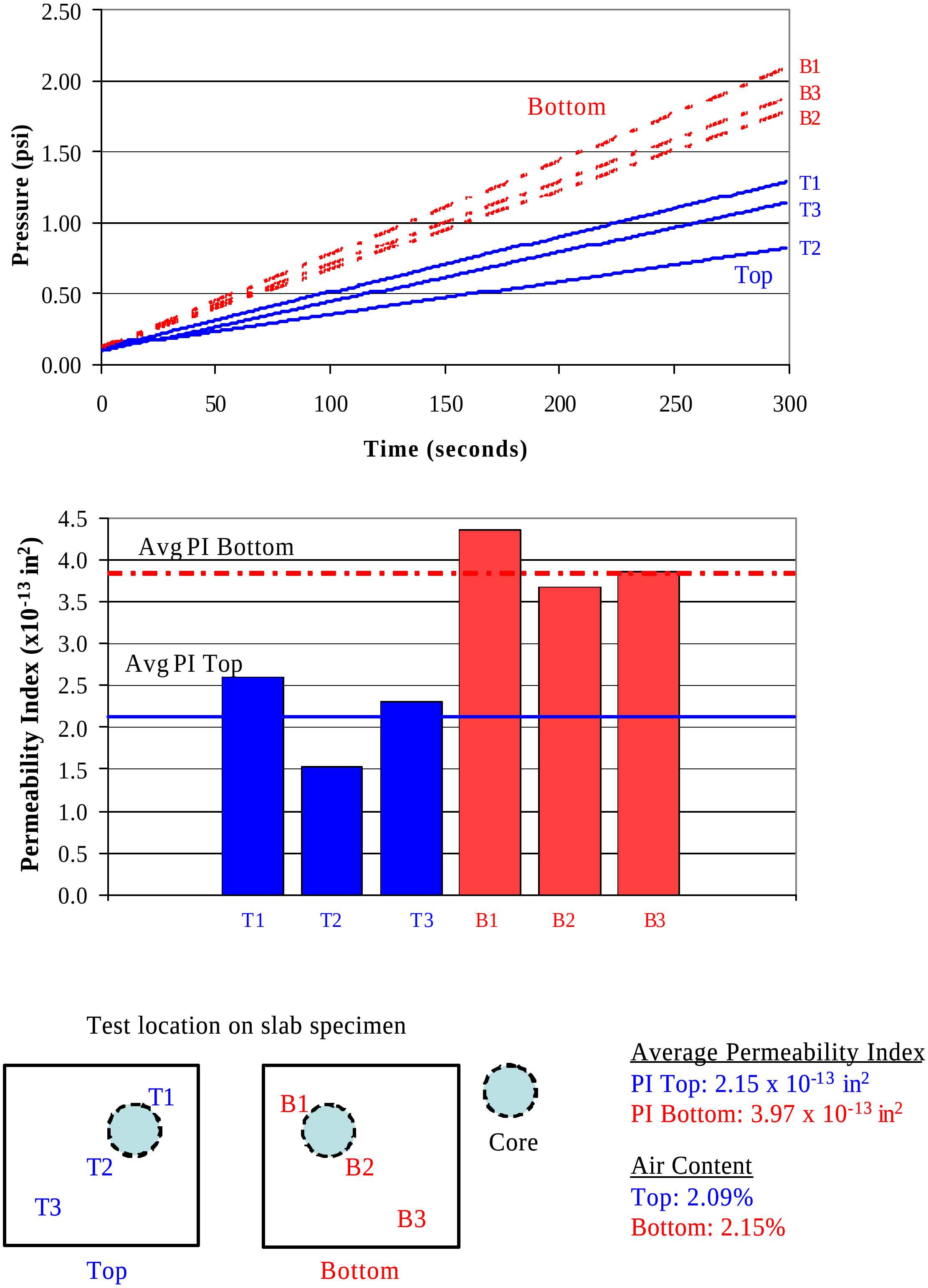


Figure 5.8 Pressure-time curves and permeability indexes for test specimen C

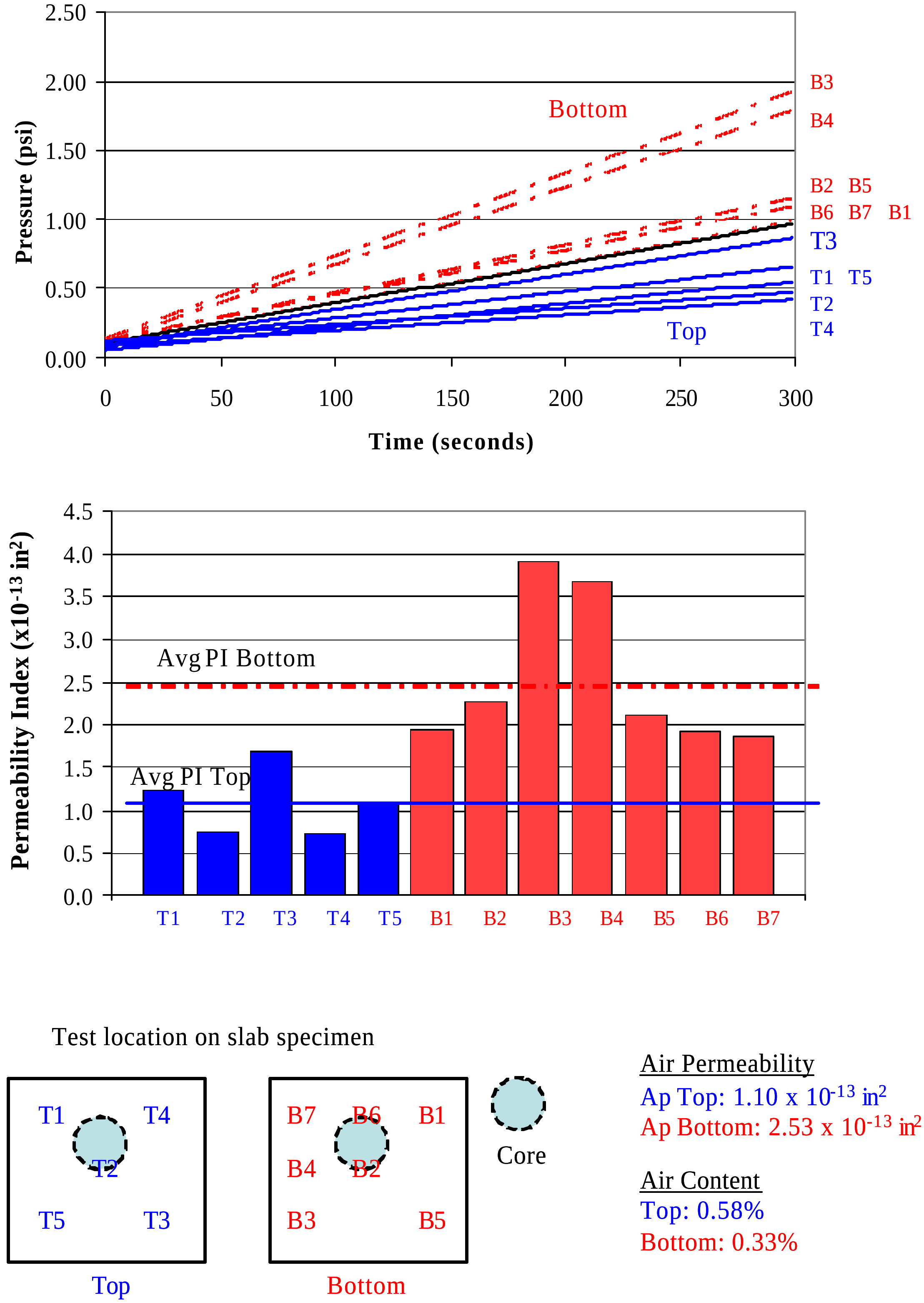
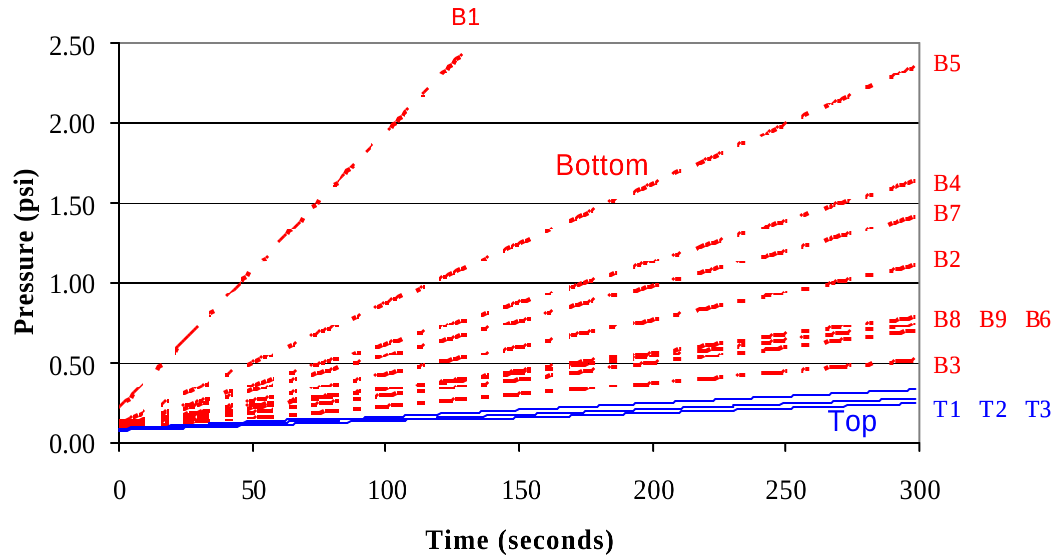
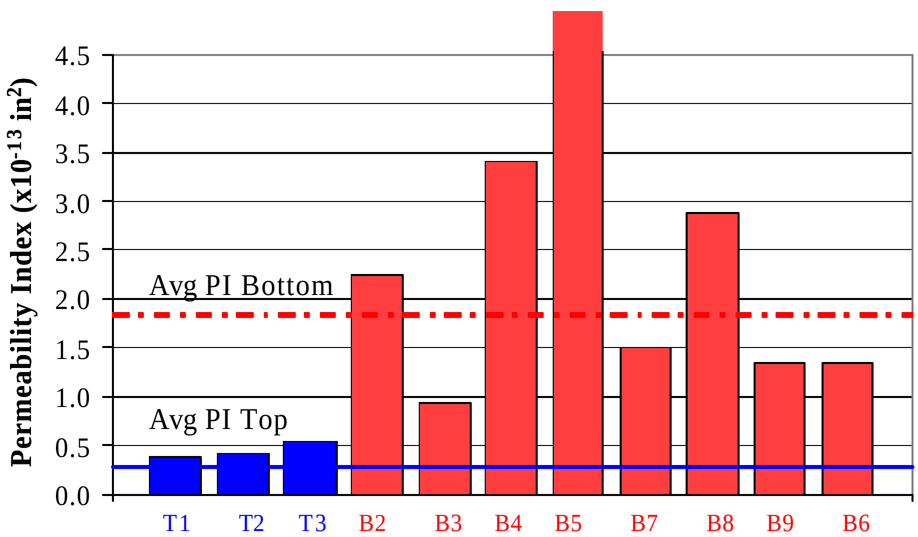
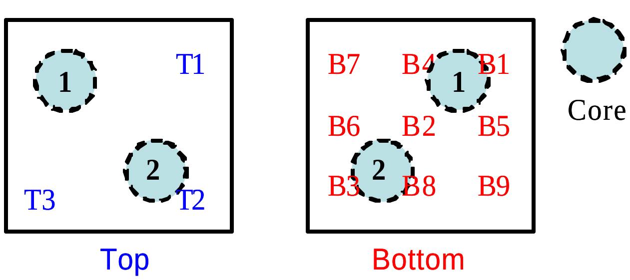


Figure 5.9 Pressure-time curves and permeability indexes for test specimen SCC1





Test location on slab specimen



Air Permeability
Ap Top: 0.44 x 10^{-13} in^2
Ap Bottom: 1.95 x 10^{-13} in^2
*Points B1 and B5 not considered for AP Average
** Point B1 not shown

Air Content

Core 1	Core 2
Top: 6.00%	Top: 5.75%
Bottom: 2.75%	Bottom: 2.50%

Figure 5.10 Pressure-time curves and permeability indexes for test specimen SCC2

Normally, it would be expected that the bottom formed surface should be less permeable than the top surface. However, it is believed that for these test specimens, the flywood bottom of the formwork was very dry under the hot sun during casting and became highly absorbent of moisture. The loss of moisture of the bottom surface of the test specimens would result in more permeability of the concrete surface layer.

Table 5.6 Results of Air Permeability Tests

Test Surface	Air Permeability Index (in^2)		
	Control C	**SCC1**	**SCC2**
Top Surface	2.15×10^{-13}	1.10×10^{-13}	0.44×10^{-13}
Bottom Surface	3.97×10^{-13}	2.53×10^{-13}	1.95×10^{-13}

Overall, the air permeability index for the SCC was much lower than that of the normal concrete. However, according to the study by Guth and Zia (2000), an air permeability index of less than 5×10^{-13} in.^{2} corresponds to less than 2000 coulombs in the rapid chloride permeability test and represents good concrete quality with low probability of deterioration due to freeze-thaw action or corrosion. Therefore, the SCC as well as the normal concrete used in this study can be considered to be of very good quality.

Table 5.7 shows the percentage of air voids for the three concrete mixtures. The air content of SCC1 and SCC2 was considerably lower than that of Control C measured from the bottom disks cut from the sample cylinders. Both SCC mixtures showed a higher air content in the top disks, in contrast to the Control C mixture for which the air content was nearly equal for the top and the bottom disks. The higher air content on the top of the SCC specimens was likely the result of lack of finishing. The SCC1 and SCC2 cylinders were made without any consolidation, and their top surfaces were not finished as was the case for the normal concrete cylinders. Since the SCC mixtures were self-consolidating, the entrapped air tended to rise to the top of the cylinder.

Table 5.7 Air Content in Concrete Disks taken from Cylinders

Disk	Control C	SCC1	SCC2
Top	3.33%	1.49%	3.59%
Bottom	3.85%	0.19%	0.86%

As described before, air content was also tested on disks cut from cores taken from the slab specimens used first for the air permeability tests. As noted in Figure 5.10, two cores were taken from the SCC2 slab. The air content test results from the disks cut from the cores are shown in Table 5.8.

Table 5.8 Air Content in Concrete Disks taken from Cores

Disk	Control C	SCC1	SCC2-1	SCC2-2
Top	2.09%	0.58%	6.00%	5.75%
Bottom	2.15%	0.33%	2.75%	2.50%

Of the three slab specimens, SCC1 had the lowest air content for the top and the bottom of the slab. The air content of the Control C slab was more uniform from the top to the bottom. On the other hand, the SCC2 slab had much more air content on the top than the bottom, and also more than both Control C and SCC1. Again, it is believed that the lack of surface finish and poor sampling are likely the cause for the large differences. Figure 5.11 shows sections of SCC2-1 and SCC2-2 in which air voids are clearly identifiable.

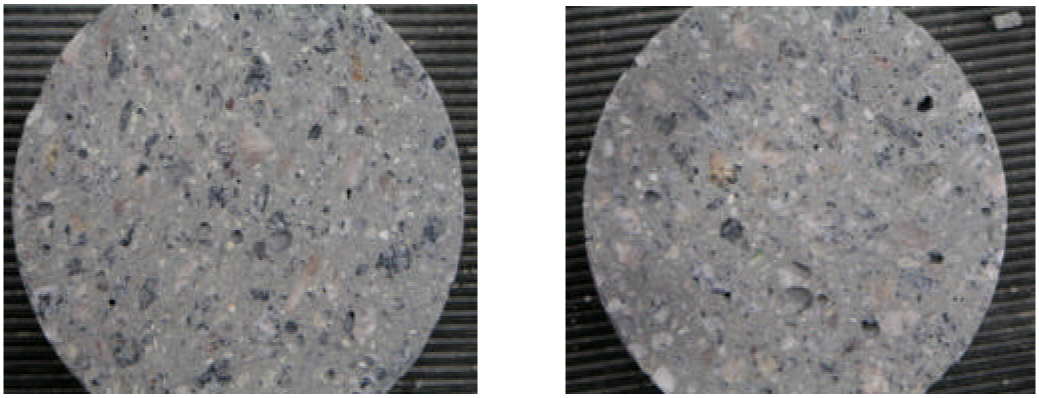


Figure 5.11 Sections of SCC2-1 (left) and SCC2-2 (right) showing air voids

5.8 Deformation and Stiffness of Test Girders

Figure 5.12 shows the plot of the load – deflection data from load testing of the three girders. It can be seen that all the girders behaved elastically, and SCC1 was slightly stiffer than Control C which in turn was slightly stiffer than SCC2. Based on the slope of the load – deflection curve, one can easily determine the modulus of elasticity for each girder as shown in Table 5.3. Under these load tests, the performance of the girders was excellent.

It is interesting to note the changes of camber of the three test girders over time. As shown in Table 5.9, the initial camber of the three girders at prestress transfer was identical. The camber of each girder grew substantially in the first 98 days when the season changed from spring to midsummer (May 6 to August 12). Then the camber reduced substantially in the next 95 days when the season changed from midsummer to fall (August 12 to November 15). While the seasonal changes of camber of a prestressed concrete member due to the temperature effect is well known, the camber variations for the two SCC girders were significantly more than for the control girder C. It suggests that under sustained loading the stiffness of the SCC girders would be reduced more than the stiffness of the control girder C, even though the stiffness of the three girders was identical under short-time loading such as under initial prestress and static load testing.

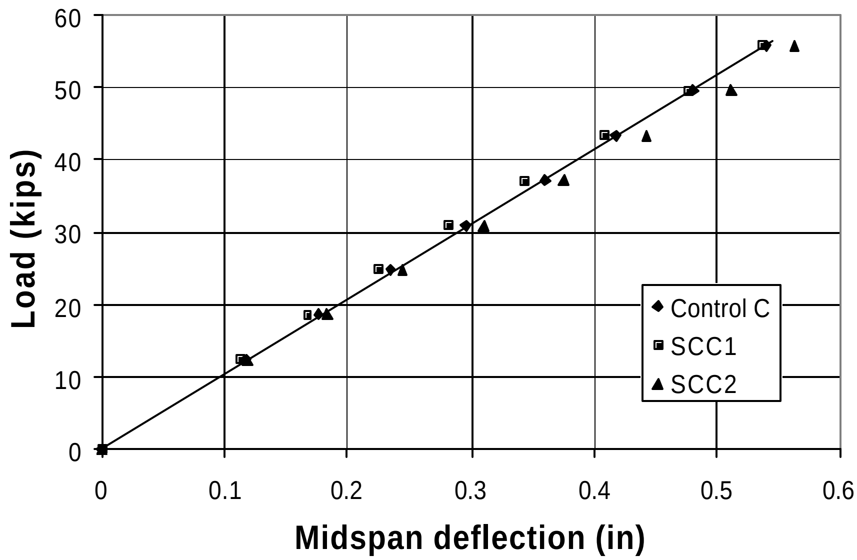


Figure 5.12 Load-deflection relationships of three test girders
(1 kip = 4.448 kN, 1 in. = 25.4 mm)

Table 5.9 Measured Camber of Test Girders

Test Girder	**Initial Camber**	**Camber @ 98 days**	**Camber @ 193 days**
Control C	1/4" (6.4 mm)	15/16"(23.8 mm)	5/8" (15.9 mm)
SCC1	1/4" (6.4 mm)	1-1/4" (31.8 mm)	1/4" (6.4 mm)
SCC2	1/4"(6.4 mm)	2" (50.8 mm)	5/8" (15.9 mm)

6. FINDINGS AND CONCLUSIONS

Two AASHTO Type III girders, each 54.8 ft (16.7 m) long, were cast with SCC to demonstrate the use of the material in full-scale production. The girders were cast together with three other identical girders cast with regular concrete in a single production line. The girders were produced for a 13-span bridge under construction over Upper Broad Creek in Craven/Pamlico Counties in eastern North Carolina (NCDOT Project 8.1170903).

One of the three regular concrete girders was chosen as control for comparison. The three experimental girders were load tested to determine their structural performance up to the design service load. In addition to the load test of the full-scale girders, the plastic and hardened properties of both the SCC and the regular concrete were monitored and measured.

Based on the results of the studies, the following are the findings and conclusions:

(1) Two SCC girders were successfully produced with two slightly different placement procedures. Both procedures were satisfactory. The surface finish of the girders was without blemishes and smooth with some small "bug holes" (< 1/8 in.) at the junctions of the web and the bottom flange. The finish was slightly better than that of the companion girders cast with regular concrete and consolidated with two internal vibrators. Each SCC was cast in 20 minutes in comparison with 30 to 45 minutes for casting the companion girders with regular vibrated concrete. With more experience, the savings in time and labor should increase in production with SCC.

(2) There was no difference in behavior between the SCC girders and the control girder based on the measurements of initial camber and strand end-slip at release of prestress. Under load test, the three test girders also behaved elastically and exhibited virtually identical load-deflection relationships up to the design service load, with no cracks observed. Upon

unloading, the girders exhibited full recovery of their deformations. The performance of the three girders was excellent and practically identical.

(3) The SCC mixture proportion should be improved. Its flowability and passability were less than desirable. Use of fly ash and inert limestone powder rather than increased amount of cement to increase the fine particles in the mixture could be beneficial.

(4) The SCC and the regular concrete were quite similar in their performance in many respects such as the concrete temperature development during curing, the development of compressive strength, modulus of elasticity, flexural modulus, and the bond characteristics with prestressing strand, both in terms of strand transfer length and strand end-slip. The bond behavior for the top strand was similar to that for the bottom strand in both concretes.

(5) The modulus of elasticity and the flexural modulus of both the SCC and the regular concrete were less than expected based on their achieved compressive strengths. This deficiency can be attributed to the lack of moist curing and the use of manufactured marine marl limestone as fine aggregate, which is more porous and less stiff.

(6) For all three test girders, the prestress transfer length was about 40% more than predicted by the AASHTO provision, most probably due to lower bond strength of both concretes because of the porous and soft fine aggregate used in the concrete mixtures.

(7) The stiffness of all three test girders was the same under short-time static loading. However, under seasonal temperature changes, the stiffness of the SCC girders appeared to decrease more than the stiffness of the regular concrete girder, resulting in greater changes in camber.

(8) Despite the loss of data for the first 90 days, the creep and shrinkage data (whether adjusted or not for the first 90 days) showed that these time-dependent properties of SCC were comparable to the corresponding properties of the regular concrete.

(9) The air permeability test and the air void analysis were performed as supplementary studies in this investigation. The Zia-Guth air permeability index for both the SCC and the regular concrete was much less than 5 x 10^{-13} $in.^2$, suggesting that both concretes can be classified as durable. With respect to the air void analysis, the results indicated that the air void distribution was more uniform in the regular concrete than in the SCC. However, the measured air content of the regular concrete was close to the lower limit of the specified amount, and the air content of the SCC was much less than the specified.

RECOMMENDATIONS

In view of the positive and encouraging results obtained from this experimental and demonstration project, it is recommended that:

(1) The two SCC girders should be accepted for installation along with the regular concrete girders for the intended bridge project.

(2) NCDOT should exploit the advantages of SCC technology by encouraging concrete contractors and prestressed concrete producers to consider SCC as an alternate material, particularly for large size projects involving repetitive use of standardized elements.

(3) NCDOT should specify SCC as the material of choice for structural members with narrow and thin sections and containing highly congested reinforcement details.

IMPLEMENTATION

Implementation plan will include presentations of the findings and conclusions of this investigation to share the information with the NCDOT engineering staff and the prestressed concrete industry. Such presentations will also include a discussion of the proposed special provisions for use of SCC in prestressed concrete applications (see Appendix C). Subject to any necessary revisions, the NCDOT is encouraged to use the proposed special provisions on trial basis.

Additionally, the implementation plan will include presentations of the findings of this study to national and internationally conferences and technical meetings. In this regard, two presentations have already been made by the principal investigator, one at the Seventh International Symposium on Utilization of High-Strength/High-Performance Concrete (see Zia et al. 2005), and the other the Fourth Middle East Symposium on Structural Composites for Infrastructure Applications (see Zia 2005).

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APPENDIX A

QUESTIONNAIRE FOR TRANSPORTATION AGENCIES

1. Have you ever used self-consolidating concrete (SCC) for any of your transportation projects? If your answer is "yes", please continue. If your answer is "no", please go to Questions 6 and 7.

2. When did you first use SCC and for how many projects have you used SCC?

3. What are the types of projects for which you have used SCC, such as bridge girders, culverts, drilled shafts, etc.?

4. Are you satisfied with your experience in terms of cost, quality control, quality of construction and product, etc.?

5. Do you have special provisions for design, materials, and construction when you specify SCC for your project? If so, please send a copy with your response.

6. If you have not used SCC, please check any of the applicable reasons listed below:

   a. Higher cost of the materials_____
   b. Lack of standard specifications_____
   c. Lack of standard test methods_____
   d. No producers of SCC in our area_____
   e. Lack of technical knowledge_____
   f. Need for increased quality control_____
   g. Don't have prior experience_____
   h. Others (please specify) _____

7. Please provide the name and address of the individual with whom we may make further contact.

   Name:
   Title:
   Mailing address:

   E-mail address:

THANK YOU

Please return you response by E-mail to Dr. Paul Zia at <p_zia@yahoo.com>

APPENDIX B

QUESTIONNAIRE FOR PCI PRODUCERS

1. Have you ever used self-consolidating concrete (SCC) for your precast and prestressed concrete products? If your answer is "yes", please continue. If your answer is "no", please go to Questions 6 and 7.

2. When did you first start using SCC for some or all of your products?

3. What are the types of products (architectural and/or structural) that you have used SCC, such as AASHTO girders, wall panels, double tees, beams, columns, piles, culverts, housing modules, pipes, etc.?

4. Based on your experience, what are the benefits and shortcomings of using SCC for your products?

5. Were you provided any special provisions or other specifications pertaining to design, materials, and construction for using SCC in your products? If so, please send a copy with your response.

6. If you have not used SCC, please check any of the applicable reasons listed below:

    a. Higher cost of the materials_____
    b. Lack of standard specifications_____
    c. Lack of standard test methods_____
    d. No suppliers of SCC admixtures in our area_____
    e. Lack of technical knowledge_____
    f. Need for increased quality control_____
    g. Don't have prior experience_____
    h. Others (please specify) _____

7. Please provide the name and address of the individual with whom we may make further contact.

    Name:
    Title:
    Mailing address:

    E-mail address:

THANK YOU

Please return your response by E-mail to Dr. Paul Zia at <p_zia@yahoo.com>

APPENDIX C

Proposed Special Provisions
on
Self-Consolidating Concrete (SCC)
for Prestressed Applications

Furnish and place Self-Consolidating Concrete (SCC) for Prestressed Members as noted on the plans. Perform this work in accordance with this Special Provision and the applicable parts of the Standard Specifications.

Self-consolidating concrete shall consolidate under its own weight without vibration, maintain its consistency and homogeneity, and completely fill the formwork, even in the presence of congested reinforcement. Do not vibrate SCC without permission of the Engineer.

<u>SCC Mixture Design</u>

A. Cement – Use a minimum of 639 lbs. per cubic yard and a maximum of 750 lbs. per cubic yard.

B. Fly ash – Although not required, fly ash is recommended as a way to enhance the flow of the mix. If fly ash is used, replace at least 20 % by weight of the required amount of cement with fly ash pound for pound.

C. Other pozzolans and powder materials – Pozzolans such as ground granulated blast furnace slag and silica fume may be used with the permission of the Engineer. Stone powder (limestone or granite) of less than 0.005 in. in size may be used to increase the powder amount of the SCC mixture as a means of enhancing the flow characteristics of SCC.

D. Coarse and fine aggregate – Maintain consistency of grading. Use a fine aggregate content of 50 % to 55 % of the combined coarse and fine aggregate weight, although a fine aggregate content of no less than 48 % may be acceptable.

E. Water – Water-cementitious materials ratio shall not exceed 0.42.

F. Admixtures – Use an air-entraining admixture to entrain 5 % +/- 1.5 % air in the mix. Although not required, a viscosity modifier is recommended as a means to enhance the homogeneity and flow of the mix. HRWR and other chemical admixtures shall be used as appropriate. Compatibility among the chemical admixtures and the cementitious materials shall be verified.

<u>Testing and Evaluation</u>

Submit the proposed mix design to the Engineer on M & T Form 312U. Attach supporting data from trial batches conducted by an approved testing laboratory. The Engineer will evaluate the data for compliance with the following requirements:

A. Slump flow – Slump flow, tested in accordance with the latest ASTM draft entitled "Standard Test Method for Slump Flow and Stability of Hydraulic-Cement Self-Consolidating Concrete," shall be within the range of 24 inches to 30 inches. The flow time T_{50} shall be 2 to 5 seconds. Report the Visual Stability Index (VSI), accompanied by a photograph, of each slump flow test. VSI shall not be greater than 1.

B. J-Ring test – Follow the "Interim Guidelines for the Use of Self-Consolidating Concrete in Precast/Prestressed Concrete Institute Member Plants (TR-6-03)" published by PCI. The difference in slump flow between tests with and without the ring shall not exceed one inch. The difference in height between the concrete inside and outside the ring shall not exceed 0.5 inch.

C. L-Box test – Follow the guidelines referenced in Item C for design of the L-box and conducting the test. The ratio of H2 to H1 shall be within the range of 0.8 to 1.0.

D. Air content – The air content of the plastic concrete, tested in accordance with AASHTO T-152 or T-196, shall be within the range of 5 +/- 1.5 %.

E. Compressive strength – Report the compressive strength of concrete cylinders made in accordance with AASHTO T-23 as modified herein or T-126 as modified herein and tested in accordance with T-22 at 3, 7, 14 and 28 days. The strength shall meet the requirements shown on the plans. Fill the cylinder molds in one layer with no rodding or vibration of the sample. Do not cast specimens until the J-Ring test has been completed.

F. Modulus of elasticity – Report the modulus of elasticity of concrete specimens made and tested in accordance with ASTM C 469 at 3, 14 and 28 days.

G. Shrinkage – Shrinkage, tested in accordance with ASTM C 157 as modified herein shall not exceed 0.04 % at 28 days. Use the same mix proportions to be used in production. Use steel molds 3 inches x 3 inches x 11.25 inches in size. Do not rod, vibrate or otherwise consolidate the concrete. Finish the exposed surface of each specimen with a steel trowel. Report the length change of each specimen to the nearest 0.001 % of the effective gage length at 3, 7, 14 and 28 days and 8 weeks.

<u>Demonstration</u>

Before the producer begins production, he shall demonstrate competence in using SCC by casting a mock item of like or similar design in the presence of the Engineer. With the permission of the Engineer, he may substitute in lieu of a mock item a production item being cast for another state or agency.

A representative of the admixture supplier experienced in the SCC technology shall be present during casting of the demonstration item. After production begins, the Engineer may waive this requirement.

Quality Control Test

For actual production, perform the following field tests on the plastic concrete using the standards and modifications listed above and the sampling rates listed herein:

A. Slump flow -- Test each load. Retest if the initial test fails. Reject the load if the original and the retest fail.

B. J-Ring -- Test each load. Retest if the initial test fails. Reject the load if the original and the retest fail.

C. Air Content -- Test each load by AASHTO T-152 or T-196. After production begins, the Engineer may waive the frequency of this requirement. Retest if the initial test fails. Reject the load if the original and the retest fail.

D. Compressive strength – Follow Section 1078 of the Standard Specifications.

E. Concrete temperature – Follow Section 1078 of the Standard Specifications.

SCC Placement

A representative of the admixture supplier experience in the SCC technology shall be present during casting of all production items. After production begins, the Engineer may waive this requirement.

Concrete shall remain plastic and within the specified range of slump flow during placement. Concrete delivery shall be timed such that the consecutive lifts will combine completely without creating segregation, visible pour lines or cold joints.

Concrete shall be placed from one point and be allowed to flow outward, or pumped from the bottom upward so as not to encapsulate air. Avoid opposing flow of concrete.

The distance of horizontal flow shall be limited to 30 ft and the vertical free fall distance shall not exceed 10 ft.