THE EFFECTIVENESS OF SELF-CONSOLIDATING CONCRETE (SCC) FOR DRILLED SHAFT CONSTRUCTION

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THE EFFECTIVENESS OF SELF-CONSOLIDATING CONCRETE (SCC) FOR DRILLED SHAFT CONSTRUCTION

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THE EFFECTIVENESS OF SELF-CONSOLIDATING CONCRETE (SCC) FOR

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THESIS ABSTRACT

THE EFFECTIVENESS OF SELF-CONSOLIDATING CONCRETE (SCC) FOR DRILLED SHAFT CONSTRUCTION

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Due to increasing design requirements and the advancement in technology, deep foundations have become larger and more congested over the years. Reinforcement congestion required to resist high lateral forces, has lead to an increased interest in alternative solutions to minimize problems associated with congested reinforcing cages. Self-consolidating concrete (SCC) is a highly flowable concrete that is not completely recognized by the U.S. construction industry, outside of the precast/prestressed industry. This thesis presents research supported by the Alabama Department of Transportation (ALDOT) to study the effectiveness of SCC for drilled shaft applications. The study

determines and presents an SCC mixture to be used for the construction of the middle two piers of the B.B. Comer Bridge in Scottsboro, Alabama.

The experimental program consists of a series of SCC mixtures that vary in water-to-cementitious (w/cm) ratio from 0.42, 0.40, and 0.38 and sand-to-aggregate (S/Agg) ratio varying from 0.45, 0.50, and 0.55. Nine mixtures are developed by pairing each of the w/cm with each of the S/Agg, and the fresh and hardened properties are tested and compared to a mixture representing the conventional drilled shaft concrete currently used in construction. One of the 9 SCC mixtures is chosen for an experimental field test where 3 drilled shafts will be constructed; two of the shafts will be constructed using the conventional concrete and the SCC mixture chosen. The third shaft will be constructed with a mixture similar to that of the SCC mixture, except that 10% of the cementitious material will be replaced with a non-cementing limestone powder in order to study its effectiveness for reducing excess bleed water.

The fresh properties tested in the laboratory consisted of the slump flow, including the T_{50} and VSI, slump flow retention, air content, unit weight, a Modified J-Ring, and the segregation column. The hardened properties tested were the compressive strength, modulus of elasticity, drying shrinkage, and the permeability. The tests revealed that SCC provided a more workable concrete without any signs of segregation. The material also provided workability over a longer period of time compared to the conventional mixture. The SCC provided a sound and durable concrete with low permeability and compressive strengths well beyond the required minimum. The SCC also showed less drying shrinkage compared to the conventional concrete. One of the SCC mixtures tested will be used in the construction of the B.B. Comer Bridge.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

Deep foundations, such as drilled shafts, are used as a means to support and transfer loads induced by the structure it supports. Over the years the need for larger, stronger drilled shafts has been required as structures grow in size and magnitude. These larger drilled shafts are designed with more reinforcement to resist higher bending moments created by lateral loads such as wind and seismic forces. The increase in reinforcement has caused tighter reinforcement configurations within the shafts, which in turn causes congestion. Research has shown that the denser reinforcing cages resist the flow of concrete in the shafts and cause deformities (Brown 2004). A more fluid concrete is needed in order to improve the integrity of the shaft and reduce blockage problems caused by congestion. Blockage problems are caused by less fluid concrete and the bridging of aggregates between reinforcement bars, which restricts the flow of concrete and causes large voids within the shaft. Another big concern in drilled shaft construction is the loss of workability of the concrete over time (Brown 2004). Deep foundations are mass concrete placements and can take many hours to complete. The prolonged placements, usually associated with large-diameter drilled shaft construction, lead to a loss of workability in the concrete that have been proven to cause voids and structural defects (Brown 2004). Lastly, drilled shafts can also create high pressures caused by the massive amount of concrete accumulated over the depth of the shaft. These high pressures can cause an excessive amount of water to "bleed" from the concrete and rise to the top of the shaft. The bleed water causes a loss of bond between reinforcing bars and the concrete, a larger interfacial transition zone between the concrete paste and aggregate, and bleed water channels that could ultimately reduce the structural integrity of the shafts (Mindess et al. 2003).

Problems incurred with drilled shaft concrete have led to an increase interest in alternative solutions to minimize defects. Alternative materials, such as self-consolidating concrete (SCC), have been introduced as possible solutions to problems associated with drilled shaft construction. SCC is widely used in the construction industry overseas, but typically only used for precast/prestressed construction in the United States. Improved workability, passing ability, segregation resistance, and reduced bleeding are fresh properties of SCC that may help to reduce such problems with drilled shaft concrete. The typical requirements of successful SCC mixtures are as follows (Khayat 1999):

- Excellent deformability: an increase of deformability can be achieved by the use of a high-range water-reducing (HRWR) admixture which disperses cement particles and reduces inter-particle friction. The inter-particle friction may also be reduced by increasing the paste volume (Khayat 1999).

- Good stability: stability of the mixture can be improved by lowering the water-to-powder ratio and by using a viscosity-modifying admixture (VMA) to increase the cohesiveness of the mixture.
- Low risk of blockage: blockage can be reduced by increasing the viscosity of the mixture such that segregation does not occur while flowing. It is also necessary to control the volume of coarse aggregate and to have a small maximum aggregate size in order to decrease collisions between aggregates.

Although SCC seems to be a sufficient replacement for conventional drilled shaft concrete, it is not currently used in practice. SCC is a relatively new product to the construction industry since its introduction to the U.S. concrete industry in 1999. The acceptance of a new construction product in the United States is typically a long and arduous process, which is why increased research and experience is needed in the actual use of SCC. As the construction community becomes more experienced and comfortable with SCC, the more likely mixing and testing procedures will be accepted and specified for use in drilled shaft construction.

1.2 RESEARCH OBJECTIVE

The primary objective of this research project is to determine the effectiveness of SCC for drilled shaft application. Comparisons will be made between two different types of SCC concrete and conventional drilled shaft concrete. The problems of conventional drilled shaft concrete are discussed and the advantages of SCC are presented along with any concerns that may result from the research. Multiple SCC mixtures were tested in a controlled laboratory setting to examine the fresh properties including filling ability, passing ability, segregation resistances, sustained workability, reduced bleeding, and extended setting times. The hardened properties were also tested at specific ages to compare compressive strength, modulus of elasticity, drying shrinkage, and permeability. The laboratory results will lead to an experimental field study at which point test shafts will be constructed and their properties compared. The flow of drilled shaft concrete will also be studied using different colored mortar cubes constructed in the lab and introduced into the concrete at different stages of the placement. The primary focus of this research is the application of SCC in the drilled shaft industry. The expectation is to introduce the potential benefits and to further encourage the use of SCC in drilled shaft construction.

1.3 SCOPE OF WORK

Following the introduction chapter, Chapter 2 introduces past literature related to extensive development and testing of SCC. SCC is introduced with a brief overview of its purpose and development in the construction industry. Current procedures used to test SCC in its fresh state are reviewed alongside a discussion of the fresh and hardened properties of SCC. Chapter 2 concludes by reviewing past experiences with drilled shaft construction. Potential problems involved with drilled shafts are discussed along with a review of past research conducted using SCC in drilled shafts.

Chapter 3 provides an in-depth look at the experimental program implemented with this research, as well as the requirements set forth as a level of quality control for the SCC produced. The materials used in the production of SCC were also discussed to further understand the SCC’s composition.

Chapter 4 introduces the procedure used to batch and mix the raw material in the laboratory. The chapter continues to describe the test methods that examine the fresh and hardened properties as well as the storage condition of the concrete between testing periods.

Chapter 5 presents the results recorded from the tests performed in Chapter 4. This presentation will include and in-depth discussion and analysis of the results obtained from SCC testing as well as a comparison between SCC and conventional drilled shaft concrete.

Chapter 6 details an experimental field study to be conducted in Scottsboro, Alabama for a bridge to be constructed over the Tennessee River. This chapter gives the construction details for the test shafts and the tests to be performed in the field. This field study will compare the fresh and hardened properties of SCC and conventional drilled shaft concrete in a field application as well as a study of concrete flow in a drilled shaft.

Finally, Chapter 7 provides conclusions and recommendations based on the results and analysis provided in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

The following chapter reviews past literature on self-consolidating concrete (SCC). This review will introduce SCC and consider the history and existing applications, current testing procedures, and the fresh and hardened concrete properties of SCC.

2.1 INTRODUCTION TO SELF-CONSOLIDATING CONCRETE

Concrete is derived from the Latin verb *concretus*, which means to grow together, and concrete dates back to ancient civilizations such as Egyptians, Greeks, and Romans (Mindess et al. 2003). The first proclaimed use of concrete was by the Greeks and Romans when they learned to add lime and water to calcined limestone (Neville 1996). There are many different types of concrete, depending on the cementing material, but the most commonly used concrete today is portland cement concrete.

2.1.1 HISTORY OF SELF-CONSOLIDATING CONCRETE

The development of self-consolidating concrete (SCC) began in Japan in the early 1980’s, where durability became an increasing concern with concrete structures (Okamura and Ouchi 1999). These concerns were a result of poor vibratory consolidation of the concrete by construction laborers. Throughout the 1980’s the issue became more prevalent as the number of skilled construction laborers became less and less. Hajime Okamura, professor at the University of Tokyo, began research and development of concrete that had the ability to consolidate without the assistance of external vibration. From Okamura's research the first prototype of SCC was developed in 1988 (Okamura 1999). SCC is defined as concrete which has the ability to flow under its own weight and consolidate without external vibration while still maintaining homogeneity (Day 2005). In the Technical Report 62, Day (2005) continues to define three fresh properties required of SCC as:

1. **Filling Ability**: the ability to flow into and completely fill all spaces within the formwork under its own weight.
2. **Passing Ability**: the ability to flow through and around confined spaces between steel reinforcing bars and other inclusions without segregation or blocking.
3. **Segregation resistance** (also called stability): the ability to remain homogeneous both during transport and placing, i.e. in dynamic conditions, and after placing, i.e. in static conditions.

2.1.2 CURRENT APPLICATIONS

After the development of SCC, studies spread quickly throughout the research community to further understand the properties and applications of SCC. SCC was first used in Japan on a construction site in June 1990 and later employed in a cable-stayed bridge in 1991 (Okamura 1999). The initial reasoning for using SCC as opposed to conventional concrete was to shorten construction periods, assure consolidation within formwork, and to eliminate noise due to external vibration. Other advantages of using SCC are the flexibility of reinforcing detailing and the reduction in excess (bleed) water

(Okamura 1999). These advantages are used more regularly overseas, as opposed to their infrequent application in the United States. This long and arduous process is part of a progression that any new technology has to undergo in order to become accepted in its respective field. SCC is a relatively new technology that requires the acceptance and coordination within the construction field; which can be broken down into owners, engineers, architects, contractor, and concrete manufacturers (Khayat and Daczko 2003). Just as mixing and test procedures become more standardized by organizations such as AASHTO, ASTM, and RILEM, so will the acceptance and use of SCC in the American construction industry rise and gain precedence in the future.

2.2 CURRENT TESTING PROCEDURES

As stated earlier, the three properties of fresh SCC are filling ability, passing ability and segregation resistance. These properties can be evaluated through a series of tests that are performed on the concrete before placement to assure the concrete's acceptance. There are many different test procedures used to evaluate SCC; procedures relevant to this project will be discussed in the upcoming sections along with hardened property testing procedures.

2.2.1 SLUMP FLOW TEST

The slump flow test is one of the more popular test used for the evaluation of concrete's filling ability due to the simplicity of the procedure and apparatus (Takada and Tangtermsirikul 2000). The slump flow test procedure has been standardized in ASTM C 1611 (2005). The slump flow test determines the deformation capacity and filling ability of the concrete. Other properties can also be determined from the slump flow test; the rate of deformation, viscosity, of the concrete is determined by measuring the T_{50}, the time needed for the concrete to flow 20 inches (50 cm) in diameter. The third property that can be determined from the slump flow test is the stability of the concrete. The stability is determined by visual inspection and is referred to as the Visual Stability Index (VSI).

The slump flow test is performed using the slump cone from the traditional slump test and placing it, upright or inverted, on a level impermeable surface. The upright and inverted methods are shown in Figure 2.1 and Figure 2.2 respectively. Past results have shown that similar slump flow values are given whether using the upright or inverted method; however, it is recommended that either method used should be performed consistently throughout concrete production (PCI 2003). After the method is determined, the cone is filled with concrete, and once it is filled, the mold is lifted. The cone is lifted until emptied and the average diameter of the resulting concrete patty is measured to give the slump flow (ASTM C 1611 2005).

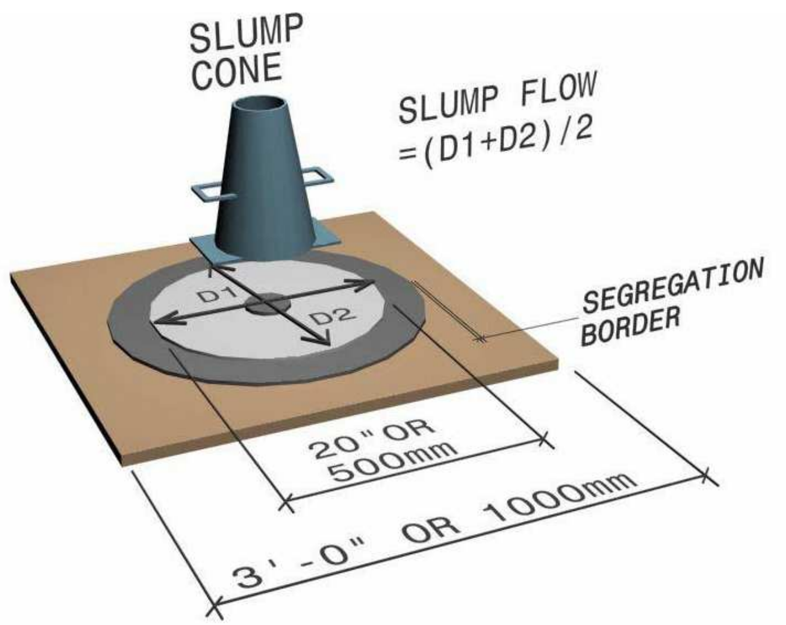


Figure 2.1: Upright slump cone method (PCI 2003)

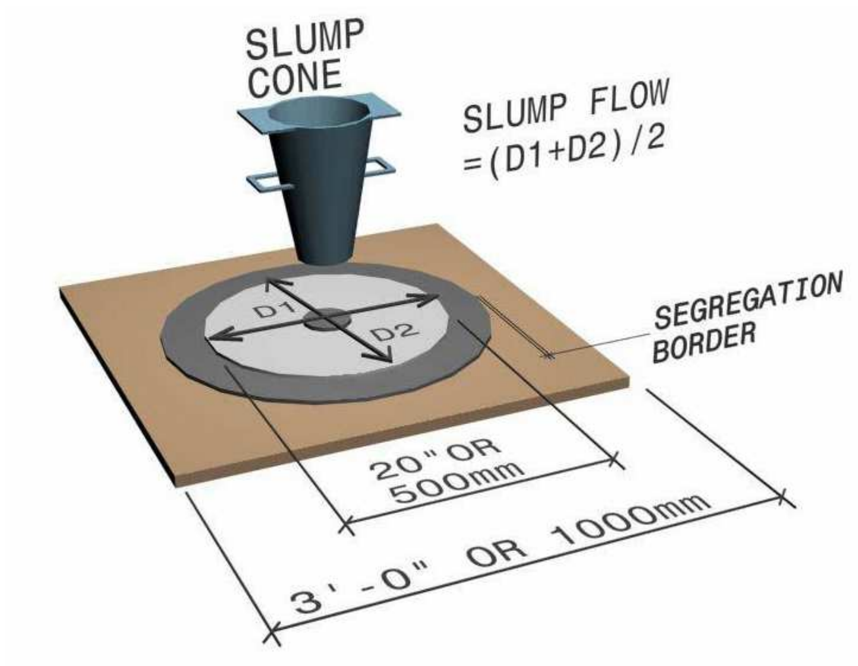
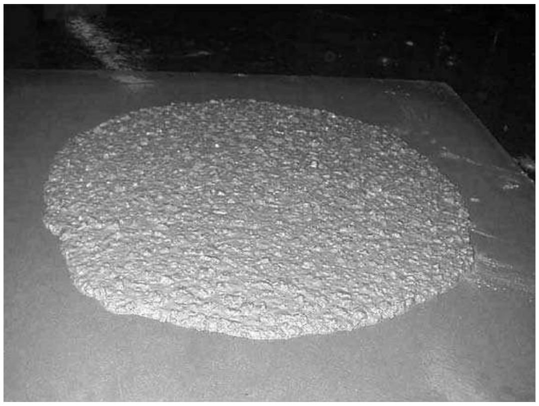


Figure 2.2: Inverted slump cone method (PCI 2003)

Takada and Tangtermsirikul (2000) state that the slump flow only determines concrete filling ability without any obstructions and does not reflect the concrete's passing ability.

The viscosity of the concrete, which is the resistance to flow, is determined by measuring the final flow time or the T_{50}. The final flow time is the time recorded from the start of the test until the completion of flow, and the T_{50} is the time recorded from the start of the test until the concrete reached a diameter of 20 in. (50 cm). The final flow time is affected by the slump flow value and is also subjective to the operator's judgment; therefore, the T_{50} is the value more readily used to evaluate the concrete's relative viscosity (Takada and Tangtermsirikul 2000). Takada and Tangtermsirikul (2000) go on to state that the T_{50} cannot determine the viscosity independently of the slump flow because as the slump flow changes the T_{50} will also change even if the viscosity of the mixture is held constant. Therefore, it should be noted that the T_{50} can only evaluate the relative viscosity of concrete for mixtures with comparable slump flows. The T_{50} also indicates possible inconsistencies of subsequent mixtures and identifies quality control problems between multiple concrete batches. The T_{50} is not usually used as a factor to reject a mixture, but instead as a quality control diagnostic test (PCI 2003).

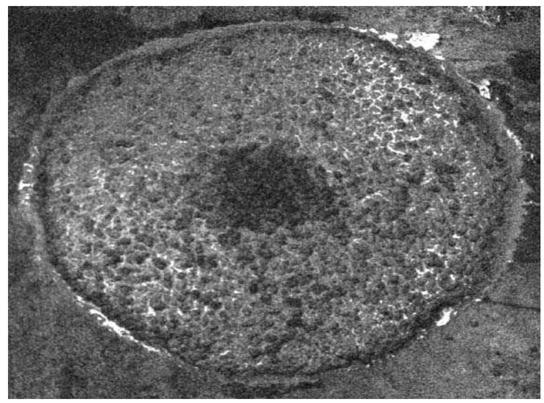
The Visual Stability Index (VSI) evaluates the concrete's resistance to segregation during transport and placement, which is also referred to as the dynamic stability of the mixture. The VSI is a numerical rating that is determined by visual observation of the homogeneity of the concrete mixture after performing the slump flow test. The VSI rating system shown in Figure 2.3 gives values with corresponding criteria to qualitatively evaluate the stability of the concrete. It should be noted, however, that the VSI is not suitable to quantify the concrete's static stability. The VSI rating is considered a dynamic stability rating when observed from the slump flow patty directly after mixing because the concrete can exhibit some non-uniform texture from the mixing and transportation. The VSI rating can also include some assessment of the static stability when SCC is observed from the wheelbarrow or the mixer after the concrete has undergone a period of rest (Khayat, Assaad, and Daczko 2004). Much like the T_{50}, the VSI rating is also used as a form of quality control, whether it is recorded from the dynamic or static state. However unlike the T_{50}, the VSI rating can be used as a criterion for rejecting mixtures due to material segregation (PCI 2003).



VSI = 0 – Concrete mass is homogeneous and no evidence of bleeding

VSI = 1 – Concrete shows slight bleeding observed as a sheen on the surface

VSI = 2 – Evidence of a mortar halo and water sheen



VSI = 3 – Concentration of coarse aggregate at center of concrete mass and presence of a mortar halo

Figure 2.3: Visual Stability Index rating (ASTM C 1611 2005)

2.2.2 J-RING TEST

The passing ability of SCC is an important fresh property because it is influential to the strength and durability of hardened SCC (Noguchi, Oh, and Tomosawa 1999). The J-Ring is a test used to indicate the passing ability of SCC and is shown in Figure 2.4. The J-Ring test is performed much like the slump flow test except that the J-Ring has reinforcement placed in a circular arrangement, 12 inches in diameter, providing obstructions around which the concrete must pass. Typical J-Ring dimensions are shown in Figure 2.4. According to PCI (2003) the spacing of reinforcement can be placed at different intervals as long as normal reinforcement requirements are met.

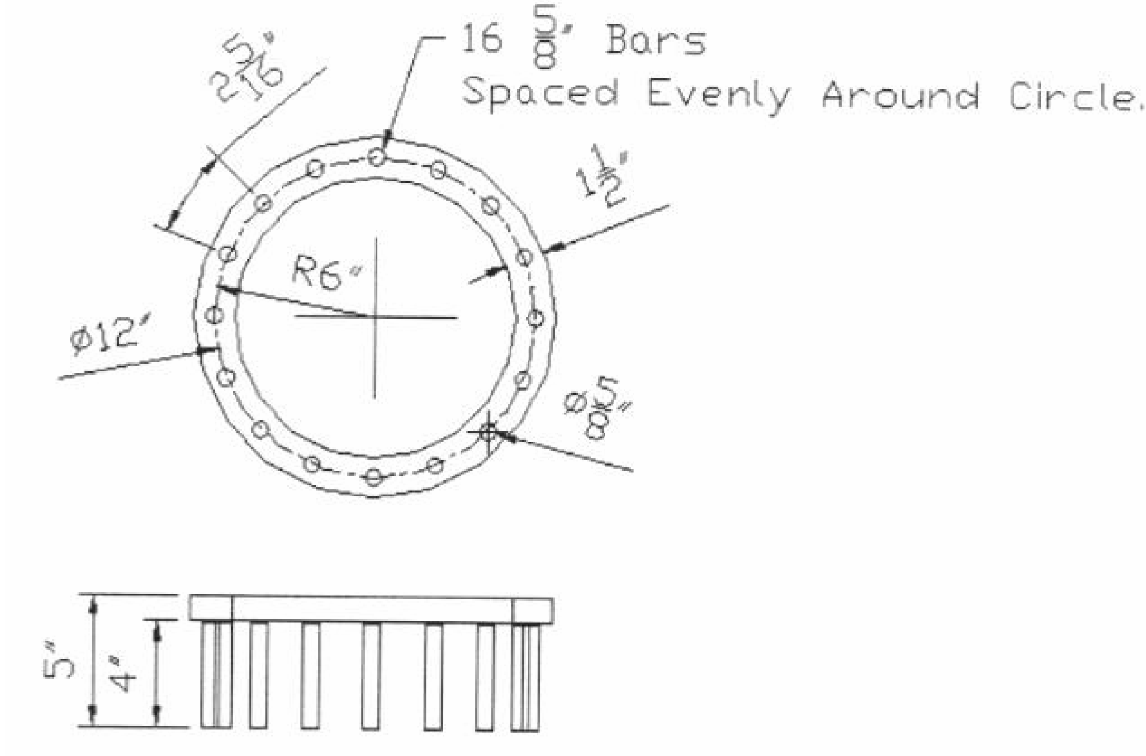


Figure 2.4: J-Ring testing apparatus (ASTM C 1621 2006)

The testing apparatus shown in Figure 2.4 is placed or built into a non-absorptive base plate. The process is then performed much like the slump flow test. A slump cone is placed in the center of the J-Ring, upright or inverted, and filled with concrete. The cone is lifted leaving a concrete patty. The J-Ring flow is the average of two diameters, measured perpendicular from one another, of the concrete patty. The difference of the slump flow and J-Ring flow indicates the concrete's passing ability (ASTM C 1621

2006). Assessment of passing ability, also referred to as the blocking potential, is shown in Table 2-1.

Table 2-1: Interpretation of J-Ring results (ASTM C 1621 2006)

Difference Between Slump Flow and J-Ring Flow	Blocking Assessment
0 to 1 in.	No visible blocking
> 1 to 2 in.	Minimal to noticeable blocking
> 2 in.	Noticeable to extreme blocking

2.2.3 SEGREGATION COLUMN

The third required property of SCC is its resistance to segregation, or what is also called the mixture's stability. The key to a successful SCC is the mixture's cohesiveness, for if not properly proportioned, the mixture may become susceptible to segregation. Cohesiveness is important for all SCC mixtures, but it is especially important for deep sections such as walls and columns (ASTM C 1610 2006). The segregation column is a plastic pipe made of Schedule 40 PVC that measures 8 inches in diameter and stands 26 inches tall. The column is cut into four sections with each section measuring 6.5 inches. The complete testing apparatus consists of the segregation column and collector plate shown in Figure 2.5.

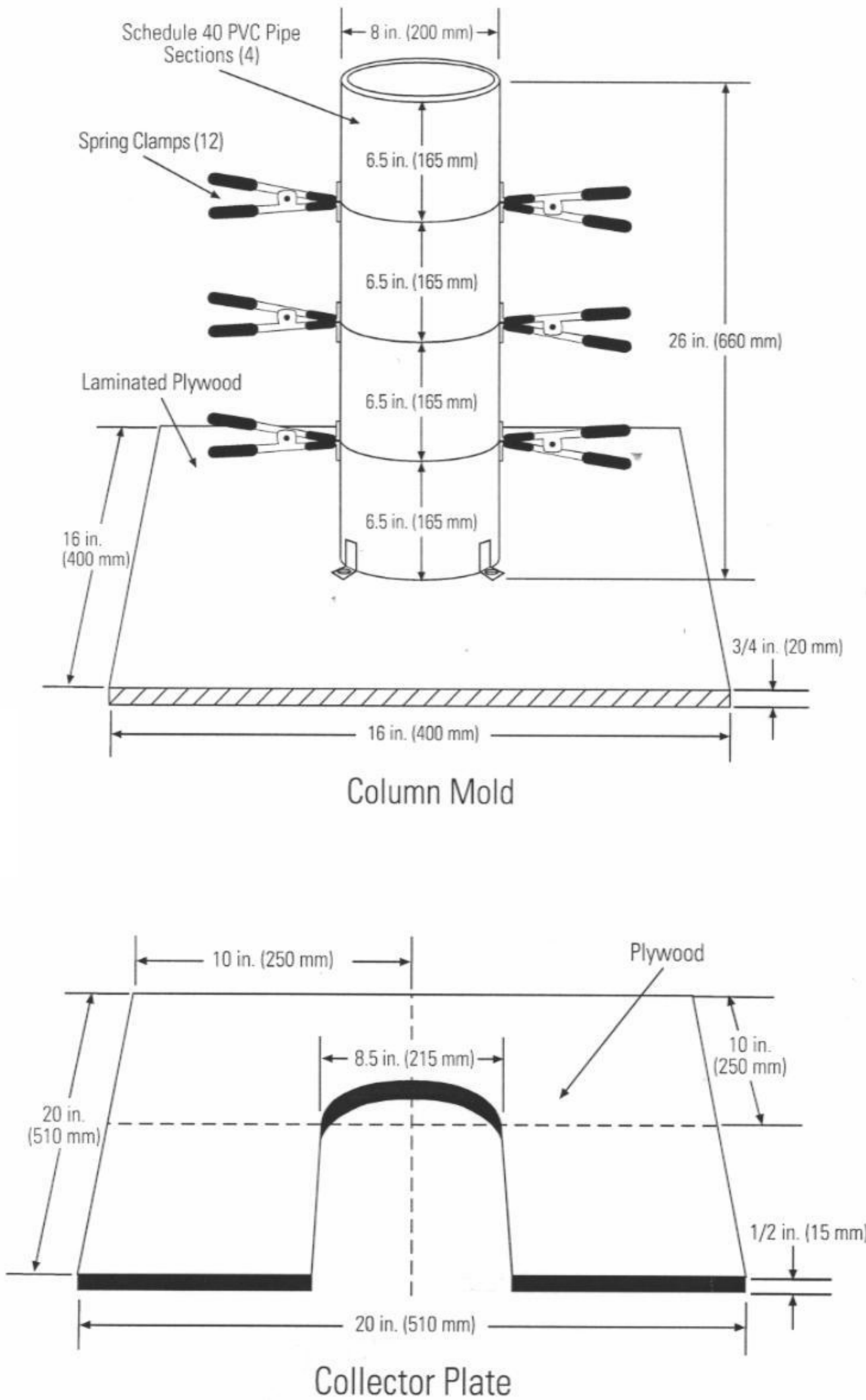


Figure 2.5: Segregation column test apparatus (ASTM C 1610)

The test is performed by filling the column with a sample of concrete in one lift and without the use of mechanical vibration. The excess concrete is then struck off the top of the column and the concrete is left undisturbed for 15 minutes. After the rest period, the concrete in the top and bottom sections of the column are recovered into separate buckets and washed over a number 4 sieve to remove all fine material. The coarse aggregate of each section is brought to saturated-surface-dry condition and then weighed. The percent static segregation (S) is calculated using Equation 2.1.

$$S = 2 * \left[\frac{(CA_B - CA_T)}{(CA_B + CA_T)} \right] * 100 \qquad \textbf{Equation 2.1}$$

Where, CA_B is the weight of coarse aggregate of the bottom section, lbs, and

CA_T is the weight of the coarse aggregate of the top section, lbs (ASTM C 1610 2006).

A tolerable percentage of static segregation has not yet been determined, but ACI Committee 237R (2007) states that a segregation less than 10% is acceptable for SCC.

2.3 FRESH CONCRETE PROPERTIES

The properties defined while in a deformable state, also referred to as fresh properties, of SCC are what separates it from conventional concrete. SCC has the ability to flow around obstructions without the use of external vibration while remaining viscous enough to withstand potential segregation and maintain stability. As described earlier, the three fresh properties required for an adequate SCC mixture are filling ability, passing ability, and resistance to segregation. These properties will be discussed in the forthcoming sections to provide a better understanding of SCC. But the term rheology must first be discussed to help understand the science behind the fresh properties of SCC.

2.3.1 RHEOLOGY

All fluid materials move and act differently which can be dependent on many different properties. Rheology is the science which deals with the deformation and flow of material under stress (Mindess et al. 2003). The stress on a material can be attributed to many different causes, but there are different concepts that explain flow characteristics. The Newtonian model is used to describe simple fluids, and is accurate for materials containing a very low volume of suspended solids. However, the Newtonian model becomes inaccurate as the volume of suspended solids becomes larger (Mindess et al. 2003). Concrete can be described as a suspension of particles that are very broad in size and contains time-dependent properties that result from chemical reaction (Khayat and Tangtermsirikul 2000). Based on the description by Khayat and Tangtermsirikul, concrete cannot be described by the Newtonian model, and is most often defined by the Bingham model, which is graphically depicted in Figure 2.6. In the figure, τ_o refers to the initial shear stress and μ refers to the plastic viscosity. The Bingham model is comparable to the Newtonian model, but the Bingham model defines a shear strength which must be exceeded before flow can begin to occur (Mindess et al. 2003). The initial shear stress that must be overcome is mainly influenced by inter-particle friction and free water content, each of which will be discussed in the following sections (Khayat and Tangtermsirikul 2000).

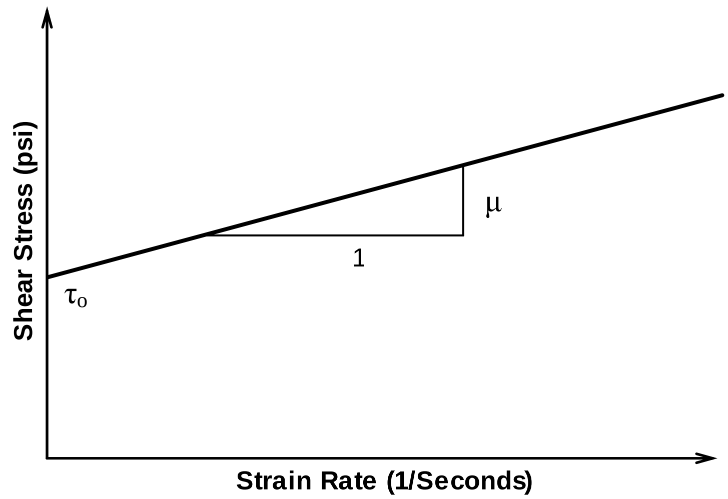


Figure 2.6: Bingham model (Khayat and Tangtermsirikul 2000)

The plastic viscosity and yield stress are used to characterize the behavior of fresh concrete (Khayat and Tangtermsirikul 2000). Rheometers and viscometers are devices that have been developed over the years that can accurately measure the plastic viscosity and yield stress of fresh concrete. These instruments have helped researchers to understand the effects that different variables have on the rheology of SCC. However, these instruments are not readily available for field testing due to cost and machine design. As mentioned earlier, tests have been done to try and compare fresh SCC testing to the concrete's rheology in order to accurately predict rheological characteristics of fresh concrete from field tests (Emborg 1999). Fresh property tests are used today to accept or reject SCC. In the future, smaller and more cost-effective rheometers will be designed, as it is conceivable that they could be used for field applications.

2.3.2 FILLING ABILITY

Conventional-slump concrete is placed into a form and then consolidated, typically by vibration, whereas SCC is capable of filling the same form without the assistance of any consolidation methods. This is typically referred to as the concrete's filling ability, which characterizes how far from the point of placement the material can flow, known as its deformation capacity, and the speed at which it flows, known as the velocity of deformation. There must be a good balance between the concrete's deformation capacity and velocity of deformation in order to achieve good filling ability (Khayat and Tangtermsirikul 2000). To ensure good deformability, it is important to reduce the inter-particle friction, which refers to the friction created by adjoining solid particles. Decreasing the aggregate content and increasing the paste volume can reduce inter-particle friction by increasing the distance between adjacent particles (Khayat et al. 2004). As opposed to increasing the water content, which reduces both the yield stress and viscosity of the concrete paste, Khayat and Tangtermsirikul (2000) suggest using a high-range water-reducing (HRWR) admixture, also known as a superplasticizer, to reduce friction because it decreases the yield stress of the paste with minimal reduction in its viscosity.

Admixtures, such as a HRWR admixture, are synthetic chemical admixtures that are used during the concrete mixing phase to alter the concrete's performance. A HRWR admixture attaches and gives the cement particles a negative charge which causes them to repel each other, called electrostatic repulsion. Figure 2.7 shows the HRWR admixture attaching to the cement particles and dispersing them by electrostatic repulsion. By doing so, the cement particles are held apart to allow water to attach to a larger surface area of the particles, or steric hindrance, which in turn improves the cement's hydration and decreases the inter-particle friction providing more workable concrete (Bury and Christensen 2003). As far as mixing is concerned, Neville (1996) suggests that the first dosage of the HRWR admixture should be soon after the water comes into contact with the cement; for if the water is allowed to begin hydration of the cement particles, the HRWR admixture will not be able to attach itself to the cement and repel surrounding particles.

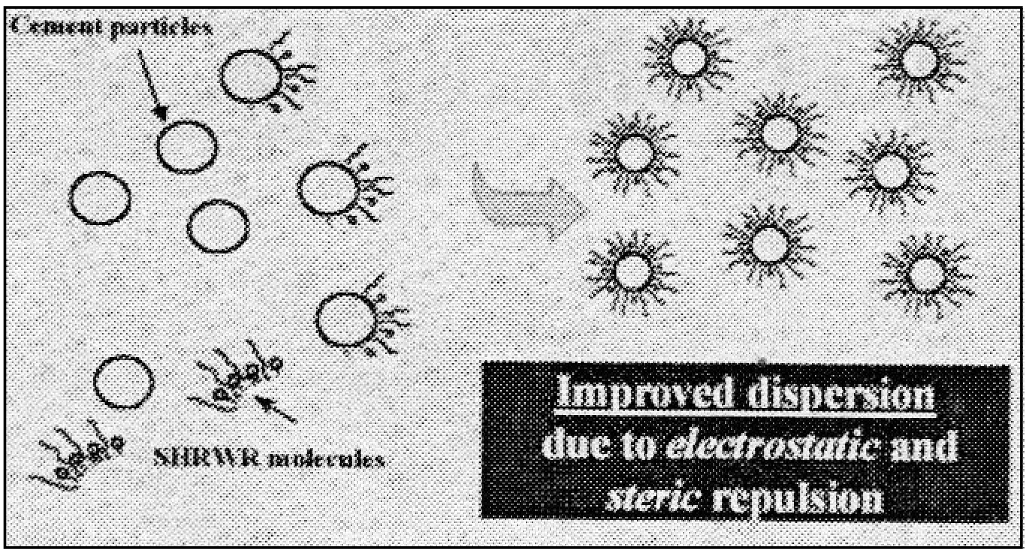


Figure 2.7: Dispersion of cement particles due to electrostatic repulsion (Bury and Christensen 2003)

The concrete's ability to flow decreases over time as the cement particles hydrate; how quickly the cement hydrates depends on many different factors. A major contributing factor affecting the loss of flow is the loss of moisture, whether it is due to dry aggregates or evaporation of water. The loss in flow is greater with dry aggregates because the water is absorbed by the aggregates and therefore decreases the amount of water provided for hydration of the cement particles (Neville 1996). Water is also lost due to evaporation. Mindess et al. (2003) states that flow decreases as ambient temperatures increase: higher temperatures increase both the rate of evaporation and the rate of hydration. Figure 2.8 shows a graph depicting the loss of slump versus temperature.

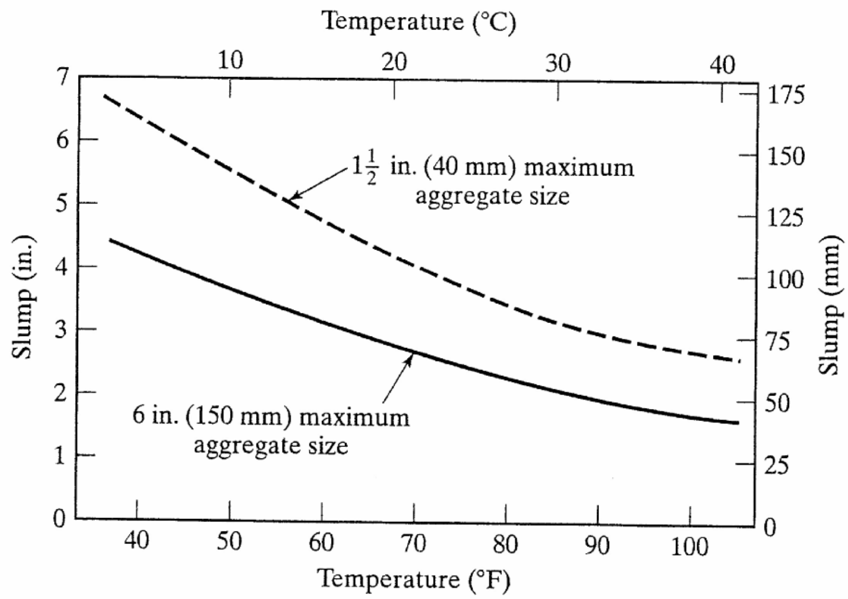


Figure 2.8: Slump versus temperature (Mindess et al. 2003)

To avoid this problem during summer conditions, many contractors try to place concrete either in the early mornings or late afternoons to avoid the high temperatures of the day. There are many ways to control the loss of workability, whether it is changing the materials used in the mixture or using hydration-controlling admixtures to control the concrete setting time. The most common form of setting control is the use of admixtures, because they allow an increase in flow without adding water or changing materials. Addition of water into the mixture, also known as retempering, is usually discouraged, because it increases the water-to-cement ratio, which can be highly detrimental to properties of the hardened concrete (Mindess et al. 2003).

2.3.3 PASSING ABILITY

The previous section discussed SCC's ability to flow and fill formwork, but most concrete structures have reinforcing to increase the strength and ductility of the structure. SCC not only has to be capable of filling the forms, it also must be able to flow around and through obstacles that are within the formwork. The passing ability of SCC is the second fresh property required for a successful SCC mixture. The passing ability is closely related to the filling ability and is a function of the viscosity of the mixture and the size of the aggregate used. There has to be compatibility between the size and amount of coarse aggregate in SCC, the spacing between the reinforcing bars, and formwork openings in order for the concrete to successfully pass. If compatibility is not achieved, arching may occur at openings, which is a result of the particles changing their flow paths and colliding with one another in an attempt to pass through the openings. Arching is depicted in Figure 2.9 and occurs when the maximum aggregate size is too large and the content of the coarse aggregate is too high (Khayat and Tangtermsirikul 2000). Khayat and Tangtermsirikul (2000) also concluded that in order to achieve good passing ability, the mixture must provide the following:

1. Enhanced cohesiveness to reduce aggregate segregation:
    - Use a low water-to-powder ratio, and
    - Use a viscosity-modifying agent.
2. Compatible clear spacing and coarse aggregate characteristics:
    - Use a low coarse aggregate volume, and
    - Use a low maximum aggregate size.

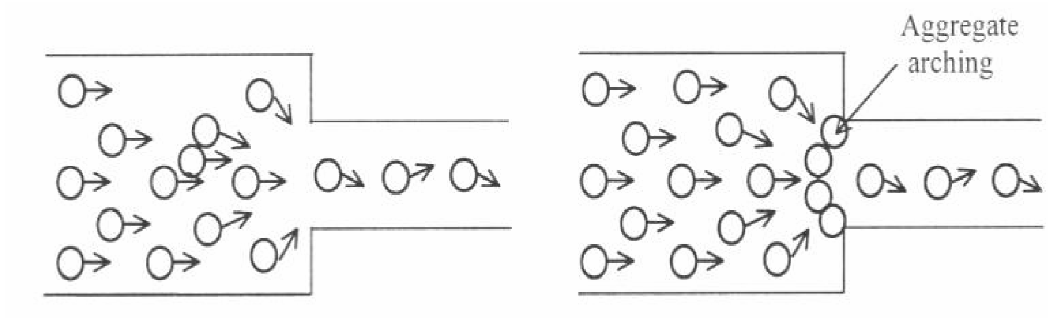


Figure 2.9: Blocking mechanism (Khayat and Tangtermsirikul 2000)

Khayat et al. (2004) also report that the key variables that affect the passing ability of SCC through confined spaces include the clearance between reinforcing bars, aggregate volume and rheological properties of the paste. This was shown by the research of Khayat et al. (2004) when studying the confined passing ability of SCC by using the J-Ring, L-box, and U-box. The test results showed that SCC mixtures with 843 lb/yd^3 (500 kg/m^3) of cement with relatively low viscosity had greater passing ability with closely placed obstructions. The mixtures with 649 lb/yd^3 (385 kg/m^3) of cement with a higher coarse aggregate content appeared to have collision risks among the coarse particles, which led to greater blockage between reinforcing bars when not consolidated. A similar test was also done to determine an effective coarse aggregate-to-concrete volume ratio and the results showed that mixtures with a coarse aggregate-to-concrete volume ratio of 0.27 and 0.31 had adequate passing ability compared to mixtures at 0.35 and 0.39 (Kim et al. 1998). Aggregate size is important when developing a SCC mixture to perform well in the presence of obstructions. The maximum aggregate size used for SCC depends on the type of construction, but the most common maximum aggregate size used in SCC ranges from 0.63 inches to 0.79 inches (Petersson 1999).

2.3.4 SEGREGATION RESISTANCE

One of the major concerns for SCC is its potential to segregate. SCC is more likely to segregate than conventional concrete due to high dosage of HRWR admixtures, which reduce the yield stress of the paste. The use of a HRWR admixture increases the workability of the concrete, as discussed earlier, but this extreme workability results in concerns about segregation. Segregation of fresh concrete is described as distribution of constituent materials such that the mixture is no longer homogenous. There are different types of segregation, which may include water bleeding, separation of paste and aggregate, blocking of coarse aggregate, and non-uniformity in air-pore distribution; these should never occur in either the stationary or flowing state of SCC placement (Khayat and Tangtermsirikul 2000).

The segregation of coarse aggregate from the paste can be difficult to recognize when placing concrete because one cannot see the distribution of material beneath the surface; therefore, precautions must be taken. Separation of aggregates from the paste can be reduced by increasing the viscosity of the mixture. By increasing the viscosity, the coarse aggregate is able to stay suspended within the mixture, which prevents the segregation of aggregates. The introduction of additional fine material is one way to increase the viscosity of the mixture. Additional fine material, sometimes referred to as “filler”, can either be cementitious or non-cementitious. Introducing additional fines helps improve the viscosity without using extra cement. Extra cement not only will increase the strength of the concrete, but it will also increase its cost and temperature (Khayat 1999). The use of a viscosity-modifying admixture (VMA) is another way to increase the concrete’s viscosity. While increasing the viscosity of the concrete, a VMA can also decrease the sensitivity of the concrete when additional water is introduced (Berke et al. 2003). This is especially relevant if the moisture content of the aggregates is not calculated accurately at the batch plant, which can often be the case because of the aggregate's frequent change in water content due to external storage. By increasing the viscosity, however, VMAs inherently decrease the flow of SCC and therefore should be used in conjunction with HRWR admixtures to achieve the adequate rheology required for SCC (Berke et al. 2003). Additional fine material and VMAs can be used separately or together in order to obtain the viscosity required to prevent SCC from segregating.

Another form of segregation happens when excess water rises to the top of freshly placed concrete; this movement of water is called bleeding. Water, having the lowest specific gravity, will float to the top if it is not adsorbed by the solid constituents of the mixture (Neville 1996). As the water rises it creates localized channels and can leave small water pockets at the mouth of each channel. These pockets and channels have a tendency to form under coarse aggregate particles or along reinforcing bars causing weak zones in the concrete and reducing concrete bond (Figure 2.10). These channels can even form along the surface of the formwork causing an aesthetically unpleasing finish (Mindess et al. 2003).

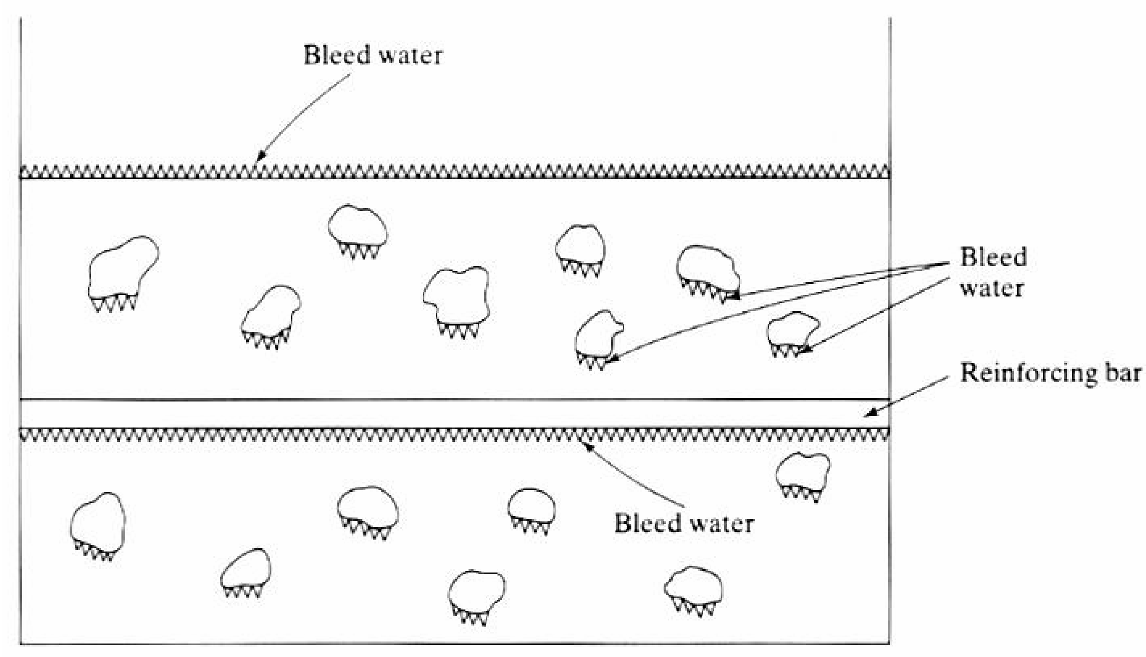


Figure 2.10: Illustration of bleeding in fresh concrete (Mindess et al. 2003)

Bleeding initially occurs at a constant rate and quickly decreases as the concrete stiffens to a point that water cannot pass through it (Neville 1996). There are a number of ways bleeding can be reduced (Mindess et al. 2003):

1. Increasing finely ground materials (cementitious or non-cementitious),
2. Increasing rate of hydration of the cement,
3. Using an air entrainment admixture, and
4. Reducing the water content.

2.4 HARDENED CONCRETE PROPERTIES

Design engineers usually specify concrete based on the final product or hardened properties. It is the hardened properties that determine the concrete's long-term performance in the structure. Previous research has shown that SCC acts quite differently than conventional concrete while in the fresh state, but studies have proven that the hardened properties of SCC are comparable to, if not better than, the hardened properties of conventional concrete (Carbo 2003). The hardened properties that pertain to this study are compressive strength, modulus of elasticity, drying shrinkage, and permeability. These will be discussed in this section.

2.4.1 COMPRESSIVE STRENGTH

Concrete is widely utilized in today's construction industry because of its ability to withstand high compressive loads. The compressive strength of concrete is typically used for the design of concrete structures and is a requirement used for quality control and quality assurance. There are many factors that influence the compressive strength of concrete such as the water-to-cement ratio, presence of fillers (cementitious or non-cementitious), curing conditions, type of cement, type of admixtures, and the size and type of aggregates (Tragardh 1999). However, Neville (1996) states that the two primary factors that determine the compressive strength of concrete made with specific materials at any given age are the water-to-cement ratio and the degree of compaction, when cured at a given temperature.

The largest single factor used in practice to determine the strength of concrete is the water-to-cement ratio (Neville 1996). Today the strength of concrete is considered to be inversely proportional to the water-to-cementitious ratio, shown in Figure 2.11, when the concrete is fully consolidated (i.e. 1% air voids), whereas the original "rule" used to determine concrete's strength was defined by Duff Abrams in 1919 as Equation 2.2 (Neville 1996):

$$f_c = \frac{K_1}{K_2^{w/c}}$$ **Equation 2.2**

Where, f_c is the compressive strength of the concrete,

K_1 and K_2 are empirical constants, and

w/c is the water-to-cement ratio.

Figure 2.11 shows that at around w/c = 0.38 there is a change in relation between cement-to-water ratio and strength. The shallower slope shown at water-to-cement ratios less than 0.38 (i.e. greater than c/w = 2.6) is due to less than 100% of the cement particles being hydrated. Therefore, the strength will increase as lower water-to-cement ratios approach a water-to-cement ratio of 0.38, indicating that more cement particles are being hydrated. It should also be noted from Figure 2.11 that as the water-to-cement ratio increases, the strength of the concrete decreases.

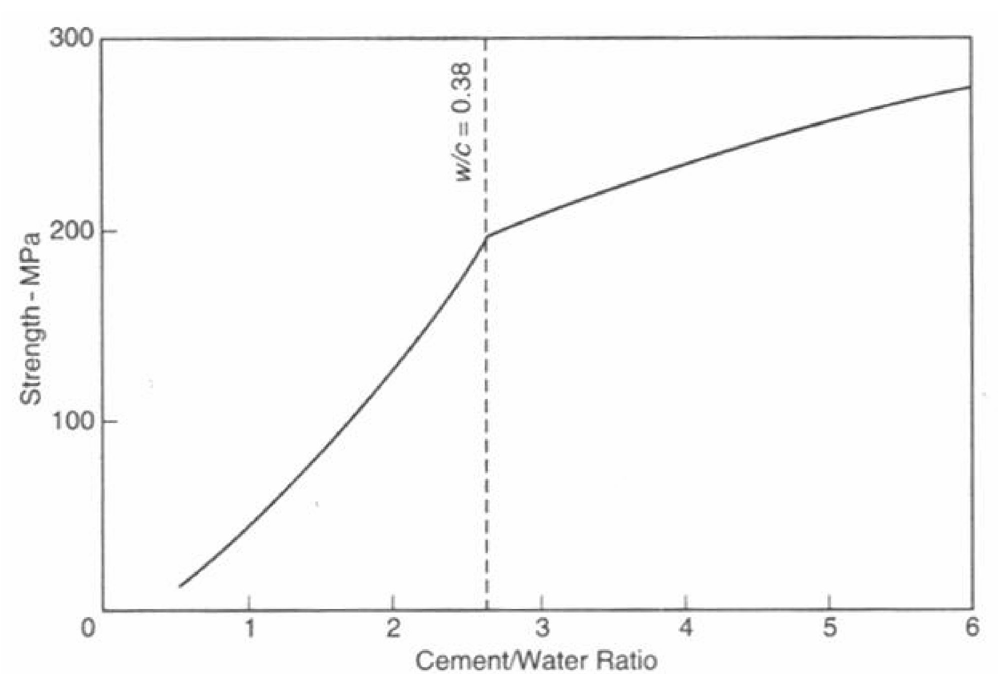


Figure 2.11: Strength versus cement-to-water ratio of paste samples (Neville 1996)

The use of the water-to-cement ratio to predict the strength of concrete is acceptable in normal design applications, but this is an oversimplification of the structure and strength of the concrete. The water-to-cement ratio does not take into account the thin area between the aggregate and the cement paste called the Interfacial Transition Zone (ITZ). The ITZ is typically 20-40 μm thick and has a lower density and strength compared to the cement paste and therefore greatly decreases the bond strength between the aggregate and the cement paste (Mindess et al. 2003). Cracking typically occurs within the ITZ because it is more prone to cracking than either the aggregate or the cement paste. Therefore, it is considered the “weak link” of concrete. The strength of the ITZ depends on the roughness of the aggregate face, amount of bleeding, preparation technique and the size of the pores in the ITZ (Mindess et al. 2003).

One of the most efficient ways to increase the strength of concrete is by decreasing the volume of pores, which affects the ITZ strength and the cement paste as a whole. Neville (1996) expressed the relationship of pore volume to concrete strength as a power function shown in Equation 2.3. Equation 2.3 shows that as the porosity increases the strength will decrease, which is also depicted in Figure 2.12.

$$f_c = f_{c,o}(1-p)^n \qquad \textbf{Equation 2.3}$$

Where, *p* is the porosity (volume of pores divided by the total volume of concrete),

f_c is the concrete’s compressive strength at porosity p,

$f_{c,0}$ is the concrete’s strength at zero porosity, and

n is a variable.

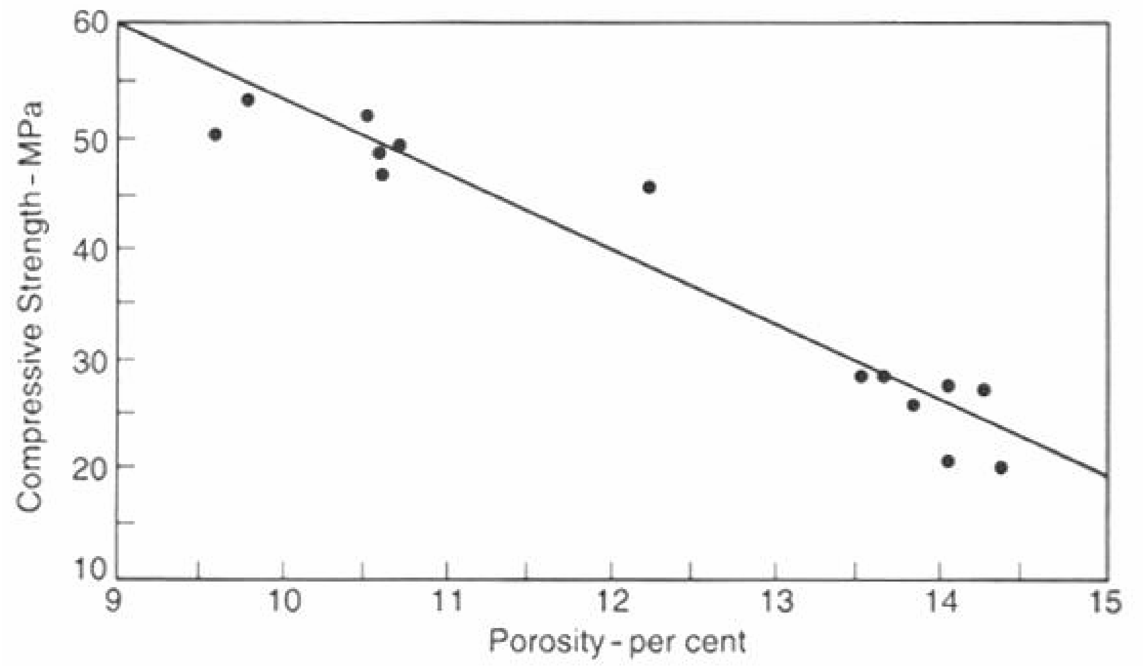


Figure 2.12: Compressive strength versus percent porosity (Neville 1996)

Mindess et al. (2003) mentions that filler material (cementitious or non-cementitious) is an effective way to decrease the size of pores and also increase the strength of the ITZ as well as the concrete. The use of fillers eliminates large pores and creates a denser ITZ by decreasing internal bleeding (Mindess et al. 2003). Focusing on the ITZ, Tragardh (1999) investigated the microstructure of conventional bridge concretes to self-consolidating concretes. All of the concretes had water-to-cement ratios within the range of 0.40-0.45, but the self-consolidating concrete was made with a limestone filler. The results showed a larger amount of coarse pores were present in the ITZ of the conventional concrete and in turn increased the porosity of the ITZ. The self-consolidating concrete showed a significantly lower porosity and the pores were more evenly distributed and smaller than the conventional concrete. These results indicated that microbleeding, causing increased pores in the ITZ, was greatly reduced in the self-consolidating concrete due to the use of the limestone filler (Tragardh 1999). By introducing the limestone filler, the microstructure of the ITZ was improved, which led to stronger concrete as indicated in Figure 2.13.

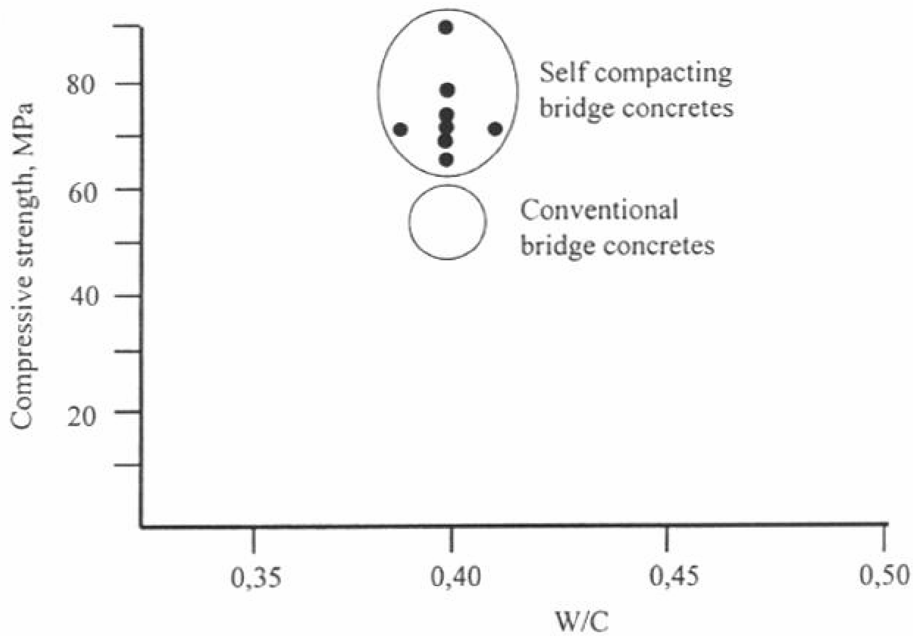


Figure 2.13: Compressive strength versus water-to-cement ratio of SCC and conventional-slump concrete (Tragardh 1999)

2.4.2 MODULUS OF ELASTICITY

The modulus of elasticity is a property closely related to the concrete's compressive strength. The modulus of elasticity is a measure of the stiffness of the concrete and can be estimated from the concrete's compressive strength. It is defined as the slope of a line on the compressive stress-strain curve of the concrete drawn from 50 microstrains to a stress corresponding to $0.40f'_c$ (ASTM C 469, 2002). ACI 318 (2005) approximates the concrete's modulus of elasticity based on the square root of the compressive strength and the density of the concrete as shown in Equation 2.4.

$$E_c = w_c^{1.5} 33\sqrt{f_c^{'}}$$ **Equation 2.4**

Where, E_c is the modulus of elasticity of the concrete in psi,

w_c is the unit weight of the concrete in lb/ft^3, and

f'_c is its compressive strength in psi.

It should be noted that this equation should only be used for unit weights, w_c, between the 90 and 155 lb/ft^3 (ACI 318 2005). The modulus of elasticity is much more sensitive to the density of the concrete than to the strength of the concrete, as shown in Figure 2.14.

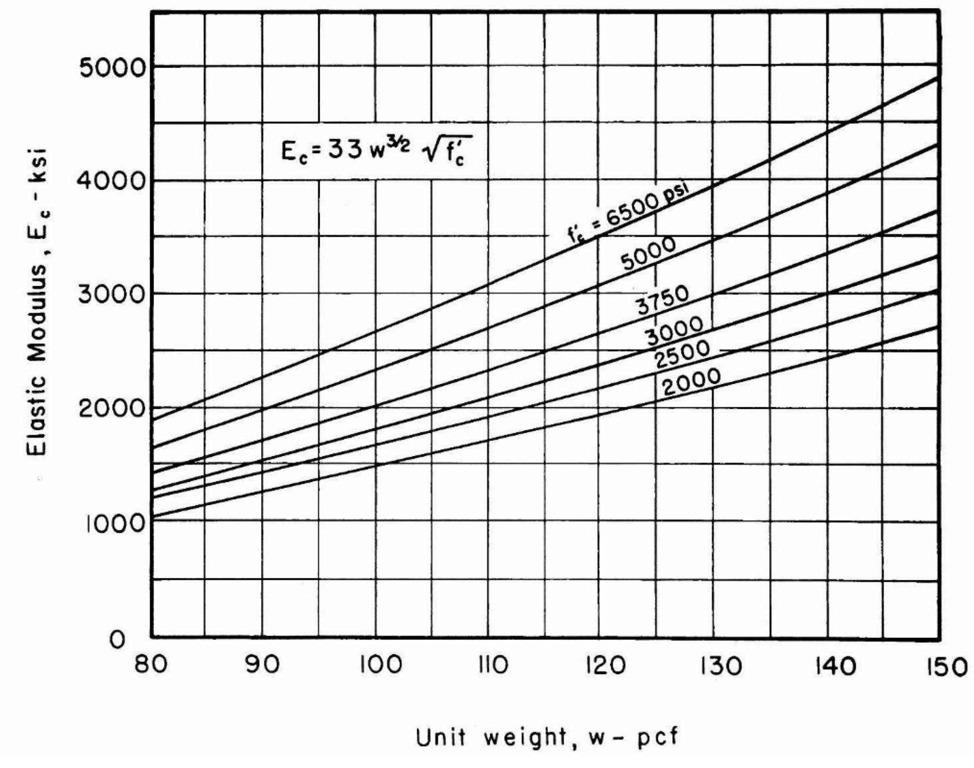


Figure 2.14: Elastic modulus as a function of strength and weight of concrete (Pauw 1960)

The modulus of elasticity is related to the strength of the concrete, and factors affecting strength will influence the modulus of elasticity, especially the porosity of the concrete: as the water-to-cement ratio increases, the modulus of elasticity will decrease.

Unlike compressive strength, the modulus of elasticity is more sensitive to the amount and properties of the aggregate than to the moisture content (Mindess et al. 2003). The amount of aggregate becomes an important factor when considering SCC because it typically has a lower total aggregate volume and a higher sand-to-aggregate ratio as compared to conventional-slump concrete.

A study conducted by Leemann and Hoffmann (2005) compared nine different SCC mixtures with four different conventional-slump concrete mixtures while using the paste volume and the sand-to-aggregate volume as variables. The aggregate consisted of sand and gravel that contained a high percentage of well-rounded particles with a maximum size of 0.63 in. and 1.25 in. for the SCC and conventional-slump concrete, respectively. The powder material used was Type I portland cement and fly ash, which created the paste when combined with the HRWR admixture and water. The S/Agg ranged from 0.40 to 0.60 for the SCC mixtures and was 0.32 for the conventional-slump concrete. Leeman and Hoffmann (2005) concluded that the modulus of elasticity of SCC was approximately 15% less than the conventional-slump concrete of similar compressive strength, which was attributed to the increased paste volume of SCC. The data also showed that as the S/Agg of the SCC mixtures increased from 0.40 to 0.60 the modulus of elasticity decreased. However, Leemann and Hoffman (2005) noticed that the relationship between the compressive strength and modulus of elasticity of SCC and conventional-slump concrete were similar when the maximum aggregate size and the paste volume were identical. Turcry et al. (2003) conducted similar tests by comparing two SCC mixtures with sand-to-aggregate ratios of 0.52 and 0.49 and two conventional concrete mixtures with sand-to-aggregate ratios held at 0.41. One of the conventional-slump mixtures and the SCC with S/Agg = 0.52 were made up of Type I cement, siliceous sand, and rolled coarse aggregate, and the second mixtures were made up with Type II cement, siliceous sand, and crush coarse aggregate. Turcry et al. (2003) also concluded that the modulus of elasticity of SCC was less than that of the conventional concrete due to the larger paste volume within the mixture. The data also showed that, despite having similar paste volumes, the modulus of elasticity increased from the first to the second SCC mixture, which contained crushed coarse aggregate.

In another study reported by Schindler et al. (2007), 21 SCC mixtures were developed with No. 78 dolomitic limestone and varying w/cm, S/Agg, and cementitious material. The mixtures incorporated different combinations of Type III cement, Class C fly ash, ground-granulated blast-furnace slag, and a densified silica fume. It was concluded that the modulus of elasticity was not influenced by changes in S/Agg for the SCC mixtures containing fly ash. However, the SCC mixtures containing ground-granulated blast-furnace slag experienced a minor decrease in the modulus of elasticity when the S/Agg was increased from 0.42 to 0.46 (Schindler et al. 2007). These finding are in agreement with work performed by Bailey (2005), who also concluded that the modulus of elasticity was not significantly affected by changes in sand-to-aggregate ratios for SCC mixtures containing fly ash. Bailey (2005) did not have any work that supported the effect of varying S/Agg on the modulus of elasticity for SCC mixtures containing ground-granulated blast-furnace slag.

2.4.3 CONCRETE SHRINKAGE

Shrinkage is a time-dependent property of concrete that cannot be avoided. Shrinkage is defined as the reduction in volume of concrete without the presence of external loads due to the loss of water (Rusch 1983). The change in volume is a result of autogenous and drying shrinkage. Autogenous shrinkage is defined as the macroscopic volume change resulting from the hydration of cement particles in which no moisture is transferred to the surrounding environment (Holt 2004). Drying shrinkage is the strain produced within hardened concrete due to the loss of water and can be influenced by surrounding conditions such as temperature, relative humidity and wind velocity (Neville 1996). Shrinkage can be detrimental to concrete structures causing cracking and warping if not considered during design.

Shrinkage occurs within the paste of the concrete and is restrained by the aggregate of the mixture (Mindess 2003 et al.). Aggregate is the most important factor because it helps restrain the paste from shrinking. The paste of concrete can deform as much as ten times that of the aggregate (Chopin et al. 2003). The size and grading of the aggregate does not necessarily determine the amount of shrinkage; but the more aggregate within the mixture, resulting in a leaner mixture, the larger the decrease of the amount of shrinkage (Neville 1996). The water-to-cement ratio is also an influencing factor for shrinkage. If the water-to-cement ratio is held constant and the cement content is increased, then shrinkage will increase due to the larger volume of paste. However, if the water content is held constant and the cement content is increased, then shrinkage will either be unaffected or will decrease due to the reduced water-to-cement ratio (Neville

1996). The relationship of aggregate content and water-to-cement ratio with respect to shrinkage is shown in Figure 2.15.

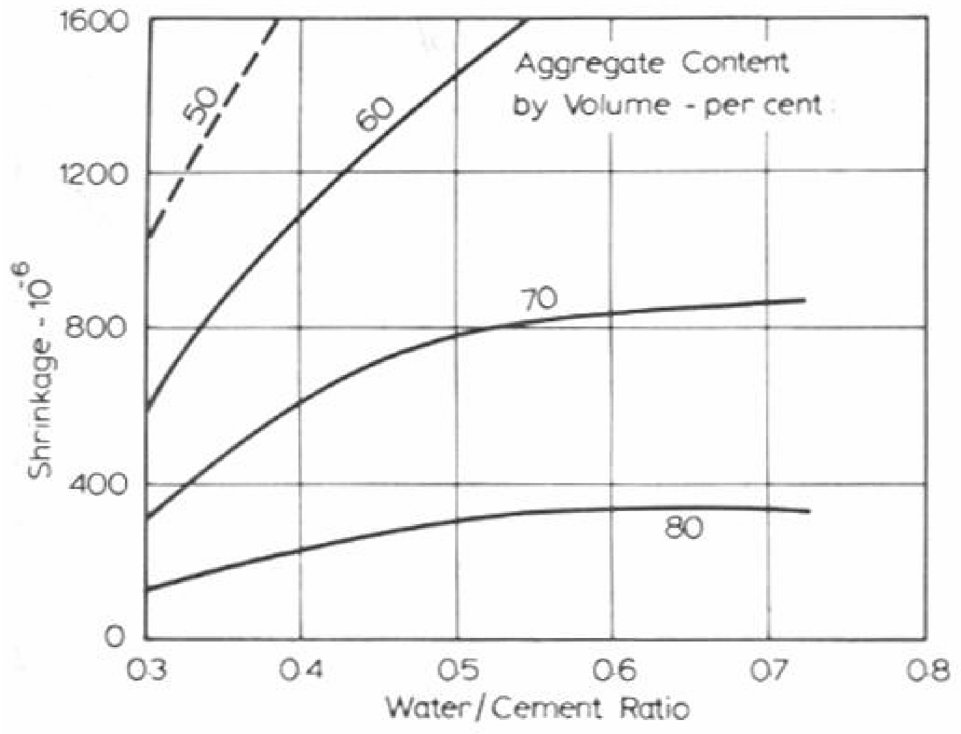


Figure 2.15: Influence of water-to-cement ratio and aggregate content on shrinkage (Neville 1996)

Chopin et al. (2003) compared the shrinkage values of a SCC and a conventional concrete mixture. The raw materials of the mixtures were composed of cement, river sand, and river gravel, but the SCC mixture included a limestone powder that increased the binder material of the SCC by approximately 40%. The SCC mixture had a water-to-cement ratio of 0.38 and a paste volume of 32.3%, whereas the conventional concrete had a water-to-cement ratio of 0.33 and a paste volume of 25.4%. The two mixtures were heat-cured for 18 hours and then placed in a controlled, dry environment for storage and testing. After approximately a year, Chopin et al. (2003) found that the SCC had about a

20% higher shrinkage than the conventional concrete. These results were attributed to the higher paste volume of the SCC, which was due to the addition of a limestone filler used to increase the viscosity of the paste to prevent segregation. It is also possible that the increase in water-to-cement ratio used could have been the reason why the SCC mixture exhibited increased drying shrinkage. However, a test was conducted by Raghavan et al. (2003) where the water content was held constant and the cementitious content was 1268 lb/yd^3 and 992 lb/yd^3 for the SCC and the conventional-slump concrete, respectively. The same materials were used for both of the mixtures, except that the SCC mixture used both cement and fly ash and the conventional-slump concrete only used cement. The results, shown in Figure 2.16, revealed that the shrinkage of the conventional concrete was 25% higher than for SCC. This test demonstrated that by increasing the powder content, which decreases the water-to-powder ratio, the shrinkage of the SCC was reduced. However, in the research by Schindler et al. (2007) previously mentioned in Section 2.4.2, the 112-day shrinkage values for the SCC and conventional-slump mixtures were compared and the SCC mixtures demonstrated similar or less drying shrinkage than the conventional-slump concrete. The study also concluded that changes in S/Agg had no significant effect on the 112-day drying shrinkage of the SCC mixtures (Schindler et al. 2007).

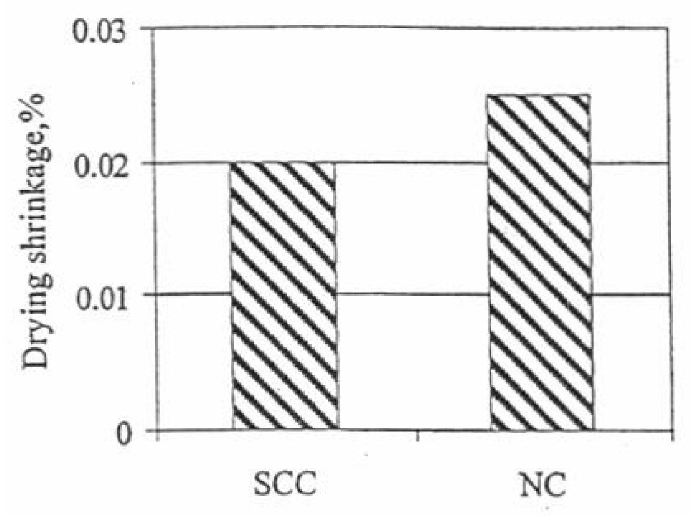


Figure 2.16: Drying shrinkage of SCC and conventional-slump concrete (Raghavan et al. 2003)

2.4.4 PERMEABILITY

Concrete is inherently considered a very durable material; however, if exposed to the certain aggressive exposure conditions for an extended period of time, it can be broken down and deteriorated. The deterioration of concrete can be caused by external or internal factors. Moisture that is absorbed by concrete can go through freezing and thawing cycles, as well as contain harmful chemicals that break the concrete down. Consequently, the permeability of the concrete is an important factor for the durability of the concrete (Mindess et al. 2003). Permeability is the flow of a liquid or gas through a porous medium and is controlled by the hardened cement's capillary porosity (Neville 1996). Permeability, however, is not solely dependent on the porosity of the concrete, which is the percentage of concrete occupied by voids, but it also depends on the size, distribution, shape, and continuity of the pores (Neville 1996).

The water-to-cementitious ratio is the largest influence on permeability because the porosity decreases as the water-to-cementitious ratio decreases. Figure 2.17 shows the relationship between permeability and the water-to-cement ratio. Mindess et al. (2003) states that permeability is significantly affected as water-to-cement ratios increase beyond a value of 0.42. Neville (1996) also states that as the water-to-cement ratio decreases from 0.75 to 0.45, the permeability of the concrete decreases by 2 orders of magnitude. Furthermore, Neville (1996) notes that when going from 0.75 to 0.26, permeability can decrease up to 4 orders of magnitude.

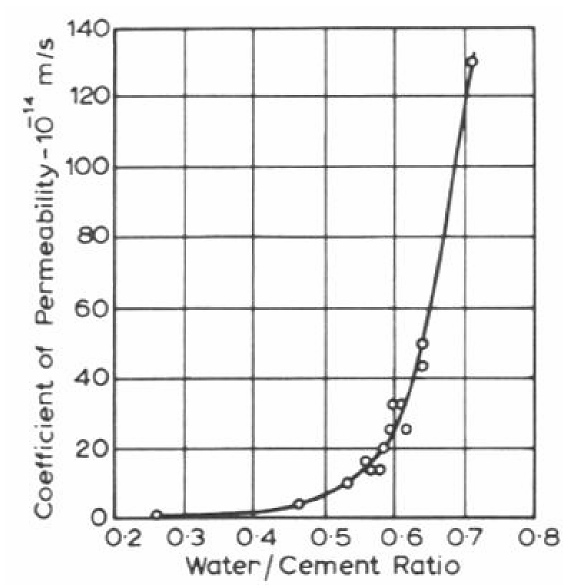


Figure 2.17: Coefficient of permeability versus water-to-cement ratio (Neville 1996)

Aggregate can also have an effect on the permeability of the concrete. The flow of fluid through concrete will naturally follow the path of least resistance, which is most often interrupted by aggregates. If the aggregate has a lower permeability than the cement paste, then the flow path of the fluid must travel around the aggregate, therefore increasing the effective path and reducing the permeability (Neville 1996). When considering the aggregates and their effect on permeability, the interfacial transition zone (ITZ) should also be considered. As mentioned earlier, the ITZ is more porous than the bulk cement paste and prone to microcracking, which one would expect to increase permeability. Tragardh et al. (2003) reported an increase in porosity near the surface of the aggregate due to fewer unreacted cement grains and an increased hollow-shell configuration in the ITZ compared to the bulk cement paste. However, Neville (1996) discovered that even though the ITZ had a higher porosity, the ITZ did not seem to contribute to flow, and the permeability of the concrete is still controlled by the bulk of the hardened cement paste.

The presence of higher fines in SCC typically reduces the water-to-cementitious ratio, which may lead to a denser microstructure and lower the permeability of the concrete. Tragardh (1999) compared SCC with a conventional concrete while holding the water-to-cement ratio at 0.40. The SCC was made with limestone powders, a HRWR admixture and placed without the use of vibration. The use of the limestone powder increased the viscosity of the concrete paste which reduced microbleeding, resulting in a less porous ITZ. Likewise, Raghavan et al. (2003) compared the durability of multiple SCC mixtures with other conventional-slump concrete mixtures. The rapid chloride permeability test ASTM 1202 (1997), was performed to determine the permeability of the concrete by applying a voltage to either side of the concrete specimen and measuring the total charge that passes over a 6-hour period. The results shown below in Figure 2.18 reveal that the SCC specimens passed 1,100-1,500 coulombs across the specimen compared to 4,000 coulombs passed by the conventional concrete. Raghavan et al.

(2003) concluded that the lower permeability of the SCC was due to the high powder content and low water-to-powder ratio which provided a denser, less permeable, microstructure than the conventional-slump concrete.

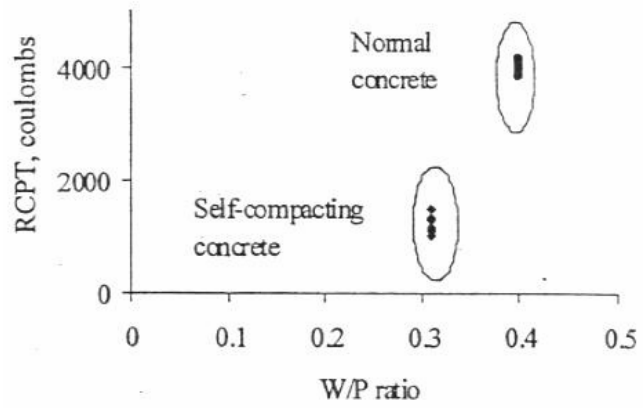


Figure 2.18: RCPT values of SCC and conventional concrete (Raghavan et al. 2003)

2.5 THE EFFECT OF FINELY GROUND LIMESTONE POWDER IN SCC

SCC is a highly workable, non-segregating concrete that can flow under its own weight to fill formwork without external consolidating methods. Changes, from the conventional-slump concrete, in the mixture proportioning must be made in order to produce such a highly workable, non-segregating concrete. Nehdi et al. (2003) states that the changes needed are as follows:

- Reduce coarse aggregate content and its maximum particle size,
- Incorporate high volumes of powder material to increase cement paste and improve concrete stability, and
- Introduce chemical admixtures to achieve required properties of SCC.

The reduction in coarse aggregate content and maximum aggregate size helps to reduce inter-particle friction. However, this reduction of aggregate content requires a higher volume of cement, which increases concrete cost and placement temperatures (Nehdi et al. 2003).

The temperature of the concrete must be considered when placing, especially large volumes of concrete. An increase in concrete temperatures accelerates the hydration process which will in turn reduce the concrete's workability (Brown and Schindler 2007). As a result, SCC typically uses fly ash, ground-granulated blast-furnace slag, and silica fume as supplementary cementing materials (SCMs) to reduce the amount of cement while maintaining the paste content required. Khayat (1999) suggests that using one or more of the SCMs can improve particle packing density and reduce inter-particle friction due to the different grain-size distribution of the materials. Another form of powder that is less commonly used in concrete production is that of a finely ground limestone powder.

Research was performed by Khayat et al. (2006) to compare the performance of SCC with different levels of limestone powder. The research included 4 SCC mixtures: the first of which was made with 100% Type I cement, and the remaining 3 mixtures were made with 10%, 15%, and 20% limestone powder replacement by mass of the cement. All mixtures contained the same water-to-binder ratio as well as the same amount of fine and coarse aggregate. The fine aggregate was a natural siliceous sand, and the coarse aggregate was a crushed limestone with a maximum size of 0.55 in. The results of the testing showed that the demand of HRWR admixture needed to obtain a targeted slump flow was decreased with increasing limestone replacement. Khayat et al.

(2006) reports that by lowering the HRWR demand with 10%, 15%, and 20% limestone powder, the unit cost of the SCC was reduced by 5%, 13%, and 25%, respectively. Khayat et al. (2006) also concluded that the presence of limestone powder led to an acceleration of cement hydration while slightly decreasing the maximum temperature of the concrete. Omya (2007) states that "Calcium ions (Ca++) of finely ground calcitic limestone filler help to accelerate the crystallization process of the Calcium-Silicate-Hydrate phases (C-S-H) within the first 10 hours", which would decrease concrete setting time. The one-day compressive strength of the SCC mixture with 10% replacement was approximately 10% higher than the SCC mixture without the powder. However, the mixtures with 15% and 20% replacement experienced minor losses in strength at the same age. As the concrete matured to an age of 28 days the strengths of the SCC mixtures containing the limestone powder were lower than the mixture without the powder, and the strengths decreased with increasing replacement percentages.

Similar mixtures and tests were performed by Omya Inc. and the results were evaluated and presented in July of 2007. Omya (2007) also concluded that the HRWR admixture demand decreased as the percentage of limestone powder increased, which resulted in a lower concrete unit cost. Further testing by Omya (2007) indicated similar stability between SCC mixtures without the limestone powder compared to the mixture with a 10% limestone powder replacement. However, the SCC mixtures containing 15% and 20% limestone replacement had as much as a 75% increase in static stability. The use of a limestone powder also showed a significant decrease in bleeding as indicated by Figure 2.19. In Figure 2.19, T10-REF refers to the SCC mixture without the limestone powder, T10-10% refers to 10% limestone powder replacement, and T10-15% refers to 15% limestone powder replacement.

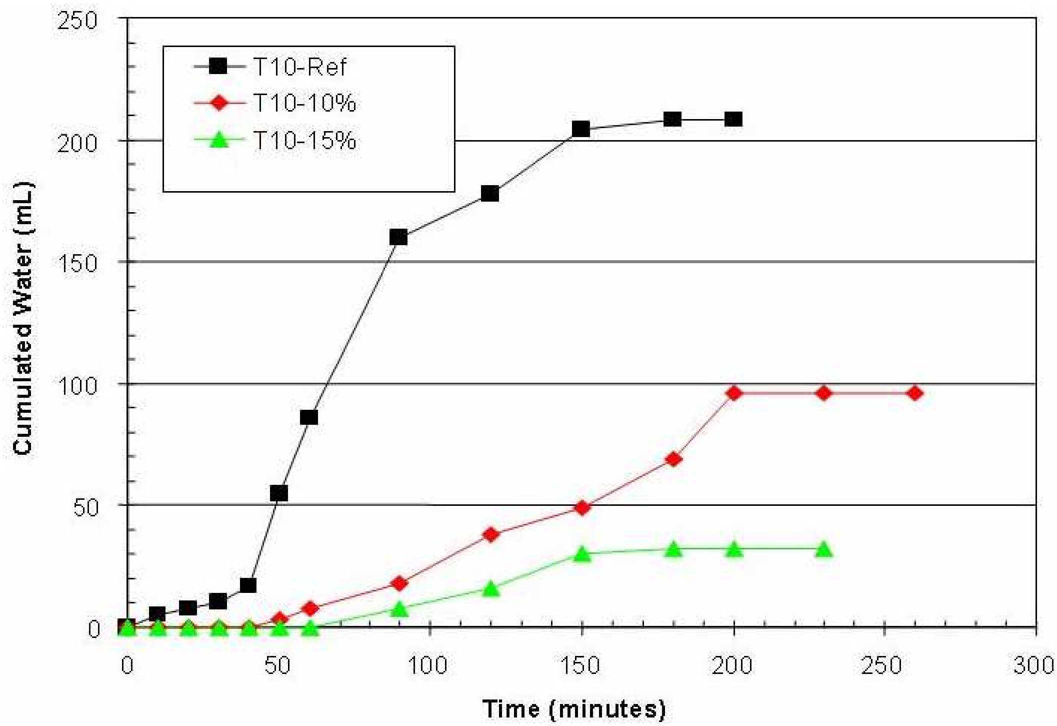


Figure 2.19: Bleeding of SCC mixtures containing limestone powder (Omya 2007)

In summary, tests were performed by Khayat et al. (2006) and Omya (2007) to show the effect of using a limestone powder in SCC. The results indicated that a limestone powder could be used effectively in SCC. The use of a limestone powder would help to decrease segregation and bleed water. The addition of a limestone powder may also decrease the cost of the mixture by reducing the amount of chemical admixtures needed for SCC mixtures. And curing temperatures could be reduced by replacing a portion of the cement content with a limestone powder; however, concrete compressive strengths may be negatively affected at later ages.

2.6 EXPERIENCE WITH DRILLED SHAFT CONCRETE

The purpose of this research is to compare and show the effectiveness of SCC in drilled shaft construction compared to the conventional-slump concrete used today. The previous sections have discussed the properties and testing procedures of a new innovative concrete called self-consolidating concrete (SCC). The following subsections will briefly discuss the ongoing problems with drilled shaft concrete currently used and recent studies using SCC for drilled shaft applications. However, the discussion will not include details of the design and construction of drilled shafts. It is recommended that the FHWA Drilled Shaft Manual, "Construction Procedures and Design Methods" (O'Neill and Reese 1999), be used as reference.

2.6.1 CONCERNS AND PROBLEMS WITH DRILLED SHAFT CONCRETE

With recent developments in non-destructive integrity testing used for drilled shafts, engineers and contractors are able to evaluate shafts after completion. This form of evaluation has revealed areas of concern about the quality of drilled shafts cast with current materials and designs. According to Brown (2004), the most common problems and concerns that compromise the quality of drilled shafts are due to a failure to consider one or more of the following:

- Proper workability and ability to maintain workability throughout the duration of the placement,
- Compatibility between concrete mixture and congested reinforcement cages, and
- Control of segregation and bleeding of concrete.

2.6.1.1 Maintaining Workability

Workability is used to describe the fresh property of concrete and typically encompasses many different meanings: consistency, flowability, mobility, pumpability, and compactibility (Mindess et al. 2003). Workability has been defined many different ways, but is generally considered as, "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished" (ACI 116R-90 1994). Workability is especially a big concern with drilled shafts because the concrete is placed without any consolidation methods; therefore the concrete must be able to fill the forms without any external energy. O'Neill and Reese (1999) state that the concrete used in drilled shaft must have "the ability to flow readily through the tremie, to flow laterally through the rebar cage, and to exhibit a high lateral stress against the sides of the borehole."

The most common test used to determine the workability of concrete is the slump test defined in ASTM C 143 (2005), *The Standard Test Method for Slump of Hydraulic-Cement Concrete*. For drilled shaft applications it is recommended that the slump value be 6 in. or greater for dry-hole construction and at least 8 in. for casing or wet-hole construction (O'Neill and Reese 1999). Brown and Schindler (2007) suggest that coarse aggregates with a No. 67 or 78 gradation and an increase in the sand content in proportion to the coarse aggregate will provide an increase in workability. Figure 2.20 and Figure 2.21 show two mixtures with proper workability, slump greater that 6 in., but Figure 2.20 has a high content of large aggregate, which is not ideal for tremie-placed concrete.

Figure 2.20: Concrete with adequate workability but large aggregate for tremie placement (O'Neill and Reese 1999)

Figure 2.21: Concrete with proper workability and mixture design for tremie placement (O'Neill and Reese 1999)

Workability is an essential fresh property of drilled shaft concrete needed to ensure a properly constructed shaft. If the concrete is not fluid enough then it will not have the ability to flow out of the tremie through the reinforcement cage to the edge of the shaft. If the concrete has the proper workability then there will not be more than a few inches difference in the concrete height between the inside and outside of the reinforcement cage. However, if the concrete is not fluid enough to flow through the reinforcement cage, then there will be a noticeable difference between the height of the concrete inside and outside the reinforcement cage as shown in Figure 2.22. Figure 2.23 and Figure 2.24 depict the results of concrete that did not have the required workability.

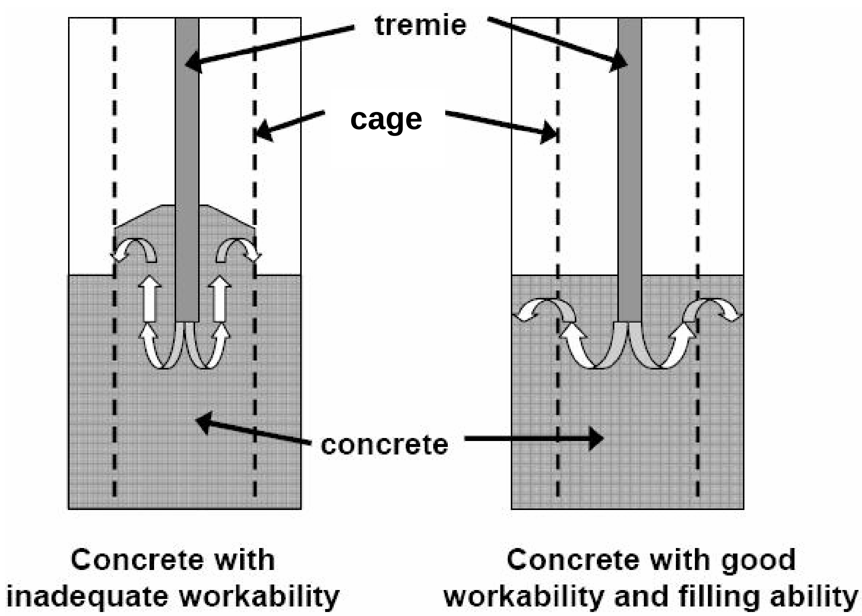


Figure 2.22: Concrete flow under tremie placement (Brown and Schindler 2007)

Figure 2.23: Shaft defects due to improper workability (Bailey 2005)

Figure 2.24: Shaft defects due to improper workability (Brown 2006)

It is important to have good workability when placing a drilled shaft. Not only does the concrete have to be workable when it arrives at the site, it must also maintain its workability throughout the duration of placement. The FHWA Drilled Shaft Manual states that a slump of at least 4 inches be maintained 4 hours after mixing (O'Neill and Reese 1999). However, Brown (2004) suggests that this is not adequate for most conditions. If the concrete is placed at a slump of 6 to 8 inches and by the end of the placement has a slump of 4 inches, there are two mixtures in the shaft with different fresh properties. The presences of two different mixtures can lead to unwanted material, or debris, entrapped in the concrete. As the concrete in the shaft begins to lose its workability and stiffen, it rises up the reinforcement cage and around the tremie. The fresh concrete flowing through the tremie is then forced out and can tend to "burp through" the stiffer concrete and entrap any debris that may be on the surface, depicted in Figure 2.25 (Brown 2004). The entrapped debris is called laitance, which is described as the contaminated concrete that sits atop the rising column of concrete (Brown and Schindler 2007). Figure 2.26 and Figure 2.27 are examples of drilled shafts with laitance exposed after construction.

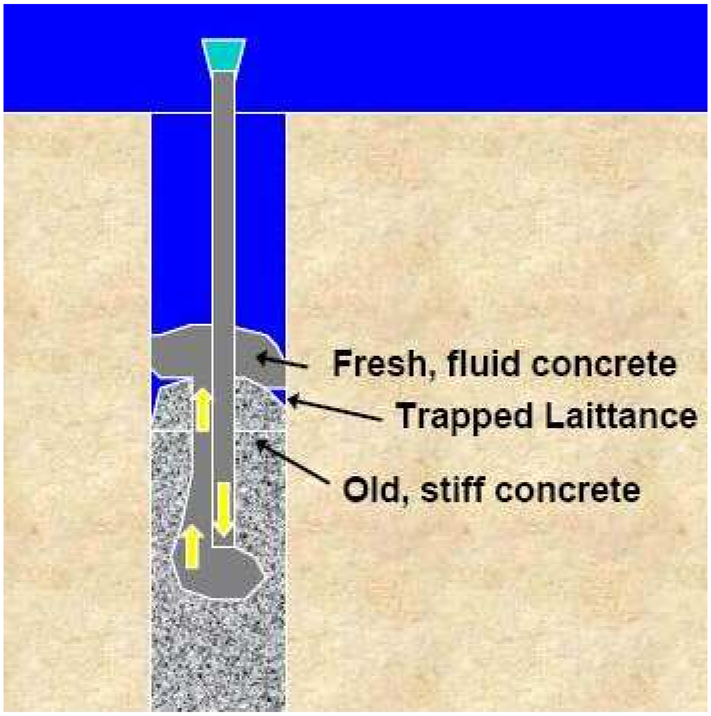
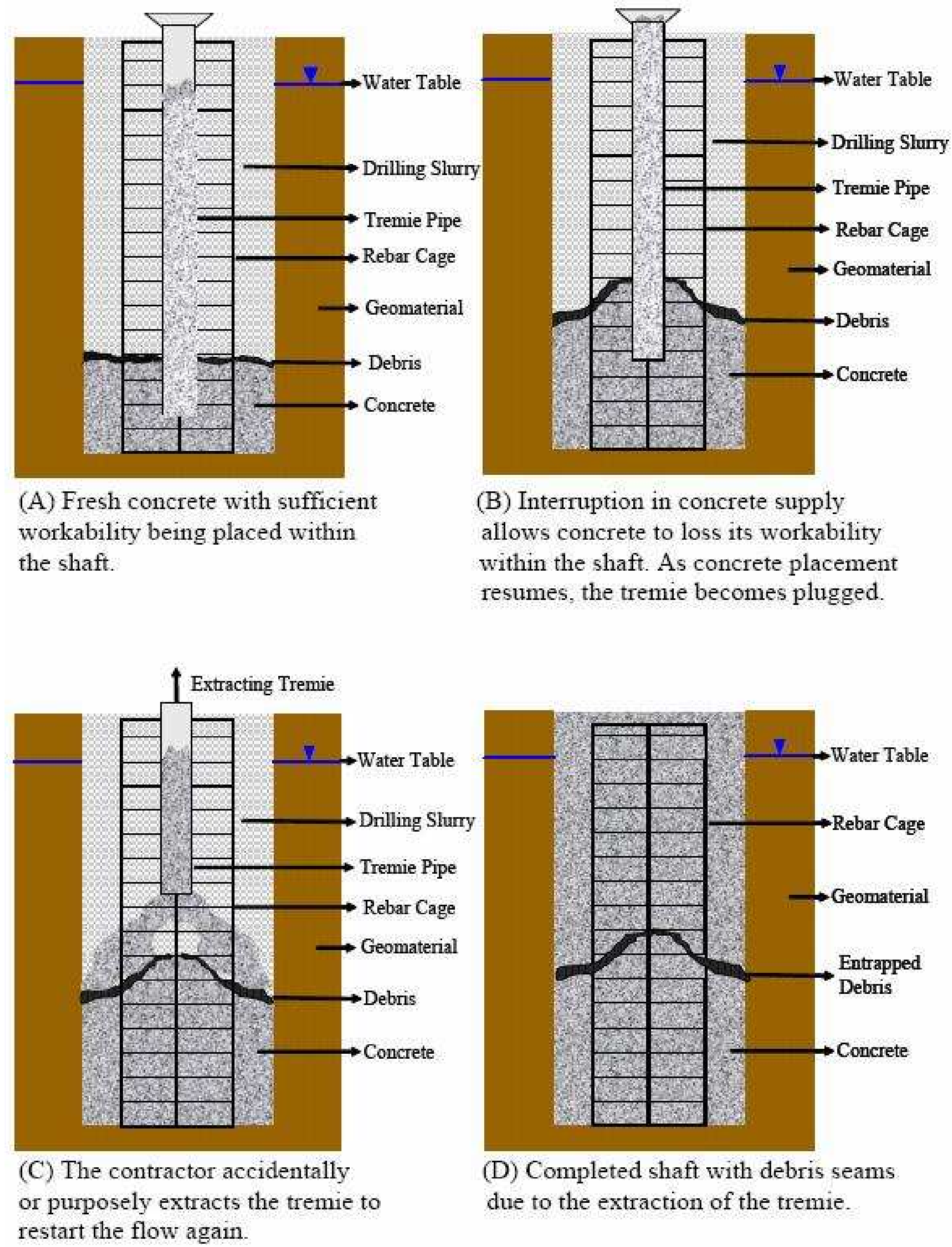


Figure 2.25: Entrapped debris due to loss in concrete workability (Brown and Schindler 2006)

Figure 2.26: Entrapped laitance found after casing removal (Brown and Schindler 2006)

Figure 2.27: Entrapped laitance found after casing removal (Brown and Schindler 2006)

The process of placing a drilled shaft can take many hours and may undergo many interruptions that could lead to problems. These can occur because of problems such as equipment breakdown and long interruptions between concrete deliveries. If such problems are not taken care of in a timely manner, the concrete will begin to lose its workability if not properly retarded. A Texas Department of Transportation (2008) publication states that if the concrete begins to stiffen around the tremie then it must be “broken” free to restore flow sometimes leading to the tremie being lifted out of the concrete. The publication also states that it is critically important that the tremie maintain a minimum 5 feet of embedment; failure to do so may cause the entrapment of soil cuttings, sediment, and washed out concrete in the shaft (Texas Department of Transportation 2008). The FHWA Drilled Shaft Manual (1999) also recommends that the embedment of the tremie remain 5 ft below the top of the fresh concrete (O’Neill and Reese 1999). This concern of tremie embedment is depicted below in Figure 2.28.



(A) Fresh concrete with sufficient workability being placed within the shaft.

(B) Interruption in concrete supply allows concrete to loss its workability within the shaft. As concrete placement resumes, the tremie becomes plugged.

(C) The contractor accidentally or purposely extracts the tremie to restart the flow again.

(D) Completed shaft with debris seams due to the extraction of the tremie.

Figure 2.28: Illustration of entrapped debris seams due to extraction of the tremie (Bailey 2005)

2.6.1.2 Congested Reinforcement Cages

Over the years, with the development of construction practices and equipment, contractors have had the ability to construct larger diameter shafts. Engineers have taken advantage by increasing the design of drilled shafts to withstand larger lateral design forces. This also allows the engineer the ability to use a smaller footprint for design, which is advantageous when working on congested sites, because they are able to design one large drilled shaft rather that many smaller ones to withstand the same loadings (Brown 2004). The minimum reinforcing bars used in drilled shafts are usually No. 8, which is 1 inch in diameter; however, larger sizes are often used. The bars must be spaced in order allow sufficient passage of concrete through the reinforcement cage without the use of external consolidation. The clear spacing between bars should be a minimum of 5 times the size of the largest aggregate or 3 inches, whichever is larger (O'Neill and Reese 1999). Brown (2004) states that this guideline is routinely violated in practice, especially in areas were seismic loading is critical.

As stated earlier, if concrete has the proper workability, it will not have more than a few inches of difference in concrete height between the inside and outside of the reinforcement cage. However, even if the concrete has ample filling ability, the configuration of the reinforcing cage along with the size and shape of the aggregate can restrict the concrete from passing (Brown and Schindler 2007). If the lateral flow of concrete is significantly obstructed the concrete will continue to rise inside the reinforcement cage and tend to become much higher compared to the concrete outside the cage, as shown in Figure 2.29. As the hydraulic pressure builds inside the reinforcement cage the concrete is pushed sideways through the lateral reinforcement, which can entrap debris. The entrapment of debris due to a dense reinforcement cage is illustrated in Figure 2.30, and Figure 2.31 shows the effect of a congested reinforcement cage, which leads to poor concrete coverage.

Figure 2.29: Restriction of lateral flow by reinforcing cage (Brown and Schindler 2007)

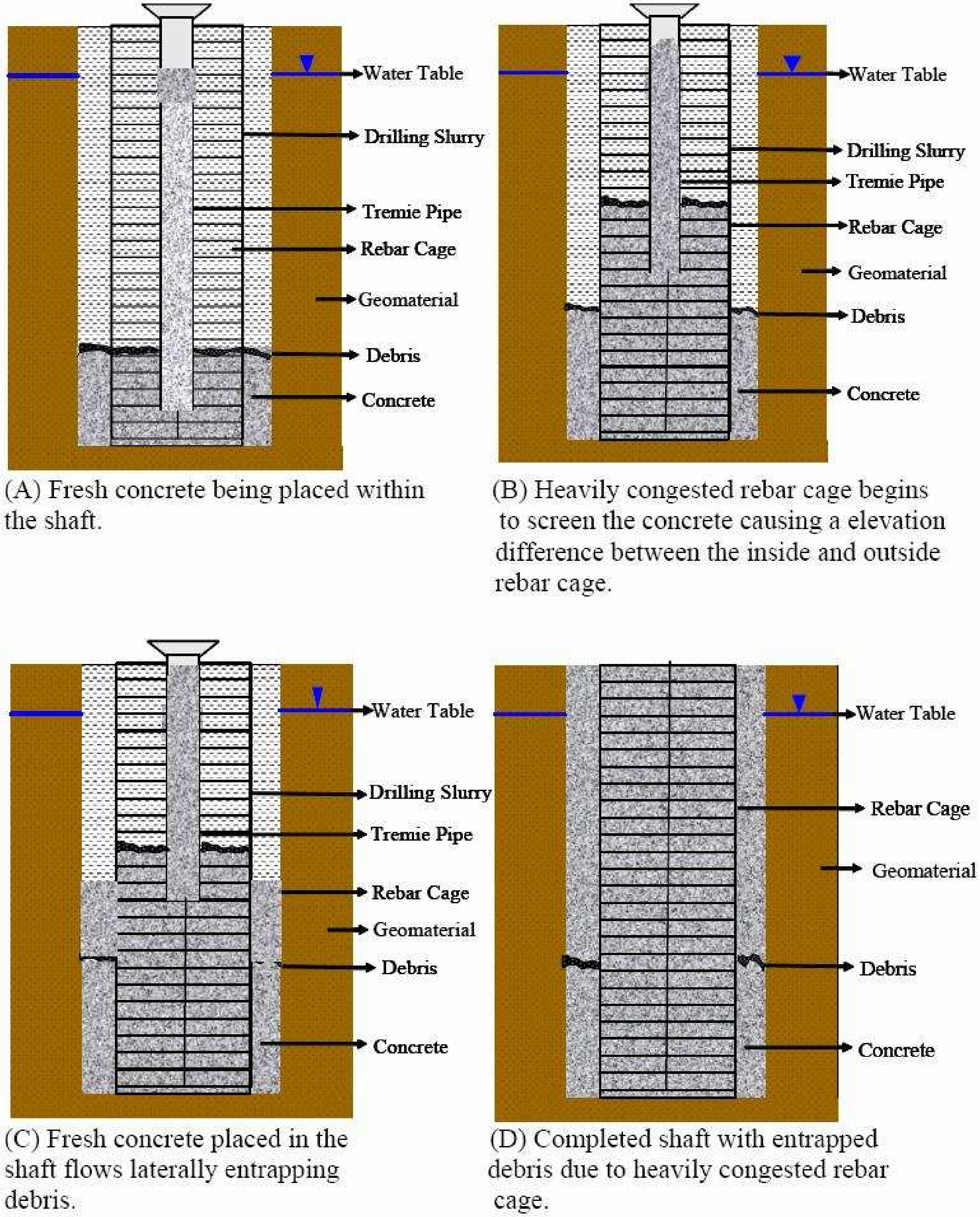


Figure 2.30: Entrapment of debris due to congested reinforcing cage (Bailey 2005)

Figure 2.31: Shaft defect due to congested reinforcement cage (Bailey 2005)

2.6.1.3 Segregation and Bleeding

The previous sections have shown the importance of the concrete's workability in drilled shaft construction, but increased workability and improper mixture proportioning causes concern for segregation of the concrete. As stated in Section 2.3.4, segregation is the separation of constituent materials such that they are no longer homogenous. Factors that cause increased segregation are as follows (Mindess et al. 2003):

- Larger maximum particle size over 1 inch and proportion of the large particles,
- A high specific gravity of the coarse aggregate compared to that of the fine aggregate,
- A decreased amount of fines,
- Changes in the particle shape away from smooth, well-rounded particles to odd-shaped, and rough particles, and

- Mixtures that are either too wet or too dry.

Bleeding is a specific form of segregation that is very common in drilled shaft construction. Bleeding of concrete occurs when the solid constituents are unable to absorb all of the mixing water and the free water rises to the surface (Neville 1996). The most common bleeding problems occur when drilled shafts are constructed using a casing, which prevents the excess water from escaping into the surrounding soil (Brown 2004). Bleeding is even more of a concern in drilled shaft applications because of the increased hydrostatic pressures caused from the mass amounts of concrete. Bleed water travels along the path providing the least amount of resistance creating bleed water channels along the reinforcement, tremie pipe, or the permanent casing (Brown and Schindler 2007). Bleed water channels may seem small and insignificant, but they can reduce the bond between the concrete and the reinforcement reducing the cover of the concrete and reinforcement, which can lead to potential durability problems. Excessive bleeding can also cause weaker concrete in the top portion of the shaft causing expensive and time-consuming repairs (Brown and Schindler 2007). As previously mentioned in Section 2.3.4, bleed water can also form on the underside of the aggregate, leading to the formation of the ITZ which weakens the concrete. Figure 2.32 and Figure 2.33 show bleed water channels on the interior and exterior of the drilled shaft, respectively.

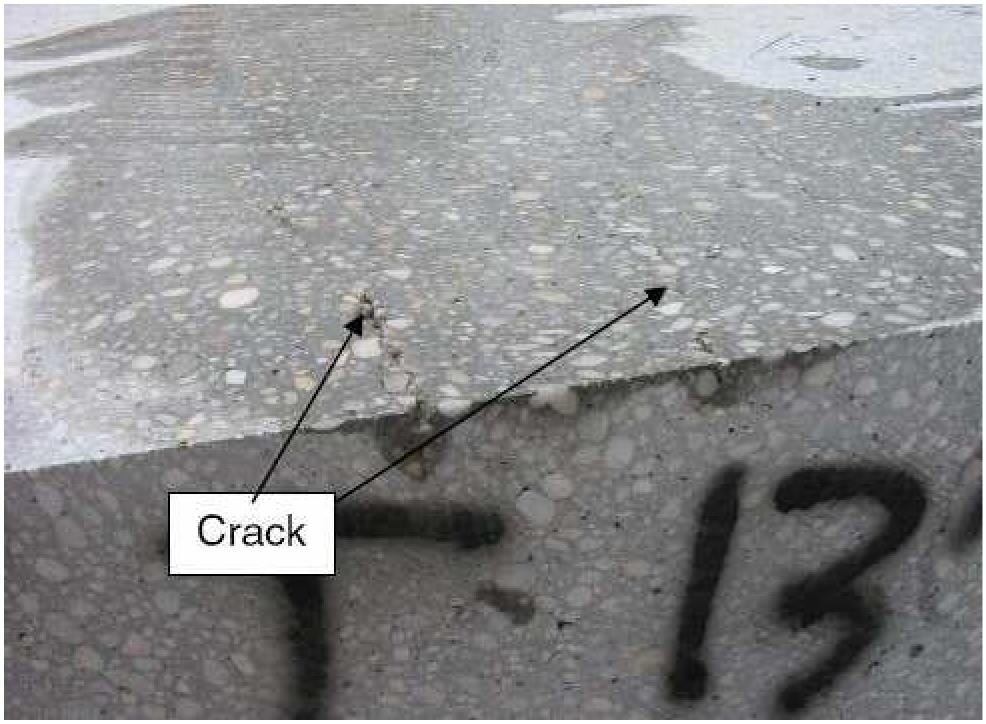


Figure 2.32: Bleed water channel on the interior of drilled shaft (Brown and Schindler 2007)

Figure 2.33: Bleed water channels of exposed surface of drilled shaft (Brown and Schindler 2007)

2.6.2 APPLICATIONS OF SCC IN DRILLED SHAFT CONSTRUCTION

With the growing performance concerns of the conventional-slump drilled shaft concrete currently being used, alternative solutions are being investigated to produce quality in-place drilled shafts. This has led to research programs applying the use of SCC for drilled shaft construction. The following section will introduce past research and discuss the results comparing the use of SCC and conventional-slump concrete in the construction of drilled shafts.

Case Study 1 *(after Hodgson et al. 2005)*

In this particular research project five drilled shafts were constructed, examined and compared using five different mixtures. Three of which used conventional-slump concrete and the other two used SCC. The mixture proportions of the five mixtures are given in Table 2-2. Two of the shafts were constructed using conventional-slump concrete with No. 57 crushed limestone, one shaft of conventional-slump concrete with No. 7 uncrushed river gravel, and two shafts of SCC also using No. 7 uncrushed river gravel. All five shafts were approximately 3 feet in diameter and 25-feet deep. The fresh properties of the concrete were tested using the slump, slump flow, T_{50}, L-Box, and V-Funnel test methods. It was noted that the slump flow, T_{50}, L-Box, and V-Funnel were performed on the conventional-slump concrete for comparison purposes even though they are not typically used when testing conventional-slump concrete. The target slump differed for the conventional-slump concrete but was typically 9.5 ± 0.5 in., and the target slump flow for the SCC mixtures was 24-28 in. The hardened properties tested were the compressive strength, modulus of elasticity, and Poisson's ratio; each of which was tested at a concrete age of 28 days. The results of the test shafts are shown in Table 2-3.

Table 2-2: Mixture proportions for test shafts (Hodgson et al. 2005)

Parameter	Shaft Identification				
	TS-1	TS-2	TS-3	TS-4	TS-5
Type of concrete	Conventional	Conventional	Conventional	Self-Consolidating	Self-Consolidating
Cement (lb/yd^3)	588	607	588	418	418
Fly Ash (lb/yd^3)	148	152	147	228	226
GGBF Slag (lb/yd^3)	0	0	0	98	96
Water (lb/yd^3)	261	256	260	322	322
Coarse Aggregate SSD (lb/yd^3)	2012	2073	2020	1222	1229
Fine Aggregate SSD (lb/yd^3)	1131	1070	1130	1596	1591
w/cm	0.35	0.34	0.35	0.43	0.43
Air entraining agent (mL/yd^3)	70	70	70	0	0
High range water reducing admixture (mL/cwt)	0	0	0	522	522

Note: TS=test shaft; and GGBF=ground granulated blast furnace.

Table 2-3: Properties of concrete mixtures used in test shafts (Hodgson et al. 2005)

Parameter	Shaft Identification				
	TS-1	TS-2	TS-3	TS-4	TS-5
Type of concrete	Conventional	Conventional	Conventional	Self-Consolidating	Self-Consolidating
Aggregate size (number)	57	7	57	7	7
Slump (in)	8.5	9.0	7.0	10.0	10.5
Air content (%)	1.5	3	2	4	7
Slump Flow (in)	18.0	12.0	10.5	24	25
T50 (s)	-	-	-	< 1	< 1
L-box (in/in)	0	0	0	0.78	1
Mortar V-funnel (s)	6.4	2.4	-	3.8	1.5
Compressive Strength (psi)	6048	5830	6208	4757	4975
Elastic modulus (ksi)	5800	3568	5500	3757	3800
Poisson's ratio	0.20	0.16	0.12	0.17	0.18

Note: TS=test shaft

The three shafts made with conventional-slump concrete were constructed to have a clear reinforcement spacing of approximately 4 inches, whereas the shafts with SCC were designed slightly denser. The concrete was placed using a tremie, and the concrete height was recorded inside and outside the reinforcement cage using plumb bobs. A head difference between the inside and outside of the reinforcement cage was recorded as high as 18 inches for the conventional-slump concrete and only 4 inches for the SCC. It was also observed that the conventional-slump concrete did not fill in a uniform manner; the concrete flowed within the reinforcement cage until a certain head of concrete developed and the concrete spilled over the hoops and "rolled" to the outer edge. This "rolling" action is very capable of collecting and encapsulating debris, whereas the SCC mixtures showed a uniform upward flow along the entire length of the shaft, which is not as likely to entrap debris. The shafts were also constructed with sand bags placed in specific locations to represent debris to examine encapsulating ability of the concrete.

Four months after construction the shafts were exhumed, cleaned, and visually inspected for comparison. It was noted that the two conventional-slump mixtures made with No. 57 crushed limestone displayed multiple locations of honeycombing and unable to fully encapsulate the artificial debris. The SCC and the conventional-slump mixture with No. 7 uncrushed gravel showed no sign of honeycombing and were able to fully encapsulate the artificial debris. The mixtures made with No. 7 river gravel also appeared to have a more consistent distribution of coarse aggregate along the shaft cross section and showed fewer instances of aggregate blocking at the reinforcement cage; whereas the mixtures with No. 57 crushed limestone exhibited more segregation by displaying more areas of aggregate and mortar concentrations. Vertical segregation was also observed in the mixtures containing No. 57 crushed limestone and the other three mixtures did not show any signs of vertical segregation.

The SCC mixtures displayed higher air voids compared to the conventional-slump concrete, which was attributed to extra mixing caused by additional dosage of the HRWR upon arrival to the site. The SCC mixtures met the strength requirements after 91 days of curing; whereas the conventional-slump mixtures met the strength requirements after only 28 days of curing. This slower strength development was attributed to the higher water-to-cementitious materials ratio and the higher amounts of supplementary cementing materials used in the SCC mixtures. At the completion of the research, the authors stated that SCC was a promising solution to drilled shaft concerns but more research was recommended to evaluate its performance in large-scale applications.

Case Study 2 *(after Brown et al. 2007)*

This project took place in South Carolina and construction was performed at the Lumber River Bridge on US-76. This project was funded by the Federal Highway Administration (FHWA) to evaluate SCC in drilled shaft applications by constructing experimental castings. Two experimental shafts were constructed 6 ft in diameter and 30 ft deep to compare the conventional-slump drilled shaft concrete used in South Carolina, referred to as the SC Coastal mixture, and SCC. The mixture proportions for the two drilled shaft mixtures are given in Table 2-4. Both shafts were constructed using temporary casing and a drilling slurry. The shafts were placed, exhumed, and cut to visually inspect the cross section as well as the surface quality.

Table 2-4: Mixture proportions for drilled shafts (Brown et al. 2007)

Item	Mixture Type	
	SCC	SC Coastal
Target consistency requirement	18-24 in. Slump Flow	9-10.5 in. Slump
Type I cement content, lb/yd^3	500	540
Class F fly ash content, lb/yd^3	250	162
Water content, lb/yd^3	306	283
No. 67 coarse aggregate, SSD, lb/yd^3	1,071	1,020
No. 789 coarse aggregate, SSD, lb/yd^3	395	775
Fine aggregate content, SSD, lb/yd^3	1,366	1,149
Water-to-cementitious material ratio	0.41	0.40
Sand-to-total aggregate ratio (by volume)	0.48	0.39
Extended-set control admixture, oz/cwt	9	4
Viscosity-modifying admixture, oz/cwt	2	0
Midrange water reducing admixture, oz/cwt	4	0
HRWR admixture, oz/cwt	10	9

Note: SSD = saturated-surface dry

Upon placing the concrete, the slump of the SC Coastal mixture was measured around 10 to 10.5 in., and the slump flow for the SCC was around 24 to 27 in. The SC Coastal mixture lost 2 in. of slump for the first batch placed and 0.5 in. of slump for the second batch after 2 hours from the time of placement. The SCC lost 8 and 3 in. of slump flow after 2.5 hours from the time of placement for the two batches, respectively. Once the shafts were completed and the casing was removed, noticeable amounts of bleed water had accumulated at the top of the shafts, the majority of which was concentrated at the location from which the tremie was removed. It should be noted that when tested in accordance with ASTM C 232, *Standard Test Methods for Bleeding of Concrete*, the SCC mixture accumulated significantly less bleed water than the SC Coastal mixture.

The shafts were extracted, pressure washed, and cut after 6 to 8 days to visually inspect the cross-sections. The exterior surface of each shaft showed no sign of irregularities despite the excess amount of bleed water that accumulated after placement. However, once cut the interior of each shaft showed noticeable bleed channels that ranged from 3 to 38 in. long. Even with the design of a congested rebar cage for each shaft, both mixtures were capable of passing through the rebar cages and filled void spaces with sound concrete. Despite the fluidity of the mixtures, there was not any indication that segregation had occurred. However, trapped laitance or silt was discovered within a shaft, shown in Figure 2.34, but the inclusions were small enough so that the structural integrity of the shaft was not affected.

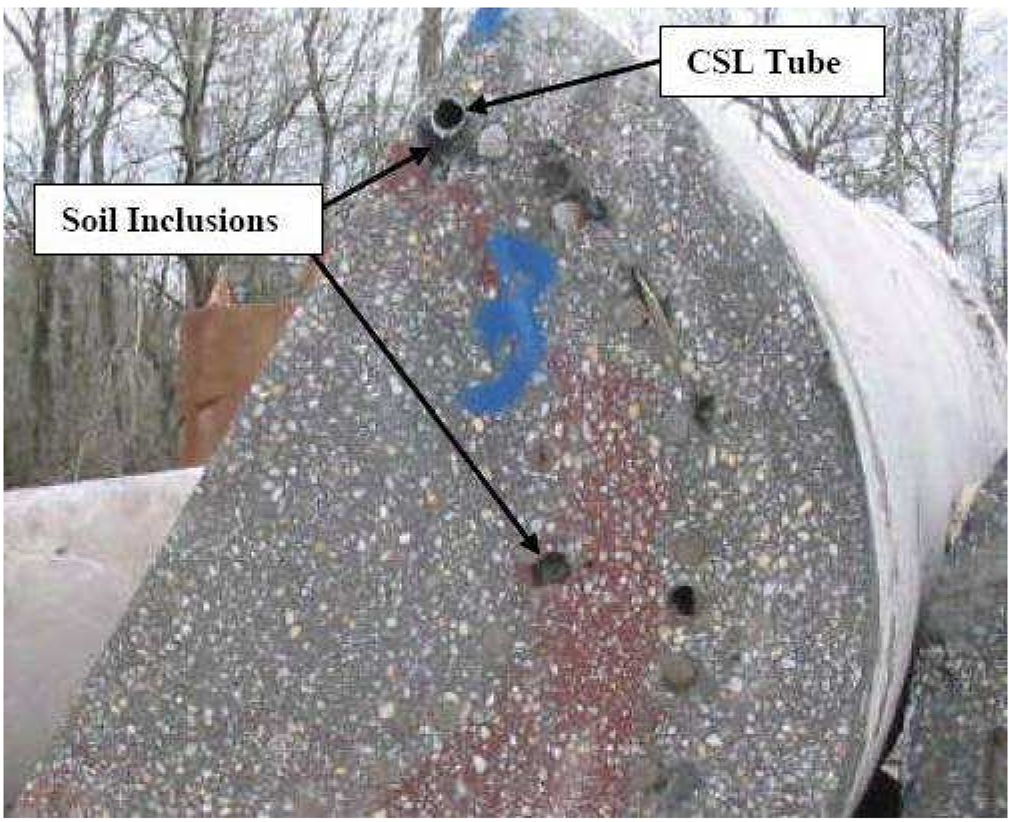


Figure 2.34: Soil inclusions discovered in shaft (Brown et al. 2007)

Temperature probes were positioned in the shafts to record temperature data throughout the placement and curing of the shafts. At placement, the temperature of the shafts was approximately 50 ˚F. The temperatures reached as high as 106 ˚F and 97 ˚F in the center of the SC Coastal and SCC shaft, respectively. The recorded temperatures prove that the higher cementitious content of the SCC mixture does not necessarily increase temperature within the shaft. Even though the SCC mixture had a larger cementitious content, the SC Coastal mixture had a higher portland cement content, which was attributed to the higher 28-day compressive strength of the SC Coastal mixture. Both mixtures surpassed strengths of 6,000 psi at 28 days, meaning that even though the SCC mixture had a lower strength, both mixtures were well within the requirements. Cores were also taken at various depths of the shafts to compare the hardened properties of the in-place concrete at different depths. Results of the in-place compressive strengths were all within the design requirements, but it was noted that cores taken at a depth of 7.5 ft from the top of the shafts had lower strengths. This reduction of strength was thought to have been caused by the presence of bleed water channels. Permeability tests were also taken at various locations within the shaft, and the tests showed that both mixtures had moderate to low permeability. Interestingly enough, the lowest permeability was recorded in the cover region of the reinforcement cage, compared to the interior region of the shaft.

Concluding Remarks About Case Studies

Both projects showed the use of SCC as a feasible replacement for conventional-slump drilled shaft concrete. The improved workability proved beneficial where detailing requirements resulted in congested reinforcement cages. The SCC used in the shafts was able to pass through the congested reinforcement cages and uniformly fill the cover region without signs of segregation. Both studies showed that SCC met the compressive strength requirements but took longer to achieve the required strengths due to the use of supplementary cementing materials (SCMs). However, the use of SCMs lowered the in-place temperatures within the shafts, which can prove to be beneficial when constructing large diameter shafts that may be susceptible to thermal cracking. SCC has been proven to have improved fresh properties while maintaining adequate hardened properties, compared to those of conventional-slump concrete. Through continued research SCC may be accepted as a suitable replacement for the drilled shaft concrete currently used in practice.

CHAPTER 3

LABORATORY TESTING PROGRAM AND MATERIALS

3.1 INTRODUCTION

SCC is relatively new to the construction industry and is used more regularly overseas than in the United States. In order for a new technology, such as SCC, to be approved for use in the United States its properties must be evaluated. This project will be used to help introduce SCC to drilled shaft construction in Alabama.

The objective of this research project was to determine the effectiveness of SCC for drilled shaft application. A number of SCC mixtures were produced in the laboratory and the fresh and hardened properties will be evaluated and compared to conventional-slump drilled shaft concrete. From the test results an SCC mixture was chosen to be used alongside a conventional-slump concrete shaft in a full-scale test for further comparison under typical field conditions. The results will be presented to the Alabama Department of Transportation (ALDOT) for approval of SCC for the construction of the middle piers of the B.B. Comer Bridge in Scottsboro, AL.

3.2 SCC REQUIREMENTS

The requirements for the SCC mixtures were determined and agreed upon prior to mixing. The objective of this section is to discuss the requirements for the fresh and hardened concrete used for acceptance of the mixture.

3.2.1 FRESH PROPERTIES

The fresh properties used for acceptance or rejection of each mixture are the slump flow, VSI, percent air, slump flow retention, and setting time. The targeted values are as follows:

- **Filling Ability**: The concrete slump flow was recorded at two different stages of the mixing process, before and after a 50-minute transportation period. The details of the mixing procedure are discussed in Section 4.2. A target of 26 in. was used for reference prior to transportation (i.e. when leaving the batch plant), accounting for a loss in slump flow during the transportation period. After transportation, the specified slump flow was 21 ± 3 in. to provide proper filling ability.
- **Passing Ability**: The passing ability of the concrete was tested by determining the difference between the slump flow and J-Ring values. ASTM C 1621 (2005) states that a difference greater than 2 in. is "noticeable to extreme blocking". However, the dimensions of the J-Ring were modified to simulate reinforcement in deep foundations; the modifications are detailed in Section 4.4.4. Therefore, a passing requirement was not determined due to the uncertainty of the concrete's passing ability determined from the Modified J-Ring compared to actual field conditions.

- **Stability**: The concrete patty resulting from the slump flow test was required to have a VSI rating no greater than 2.0, because segregation becomes a concern for higher values.
- **Workability Retention**: To ensure proper flow throughout construction, the SCC was required to have a conventional slump, performed in accordance with ASTM C 143, of no less than 6 in. after 6 hours. It was estimated that these shafts will be completed in six hours. Therefore, it is also required that the concrete reach final set no earlier than 18 hrs. from the time of placement.
- **Total Air Content**: The total air content was also required to be within a range of 4 ± 2% after the transportation period.

If the defined parameters were not met, the concrete was discarded and remixed. Other fresh properties were recorded such as the T_{50}, J-Ring value, segregation index, and unit weight, but these were not used as a means of accepting or rejecting the concrete.

3.2.2 HARDENED PROPERTIES

The average compressive strength (f'_{cr}) of three concrete cylinders was specified to be no less than 5,200 psi at a maturity of 28 days. This value was chosen to ensure a specified compressive strength (f'_c) of 4,000 psi, based on the requirements of ACI 318 (2005) shown in Table 3-1. Other hardened properties such as modulus of elasticity, drying shrinkage and permeability were not specified, but were still monitored and recorded for quality control of the concrete specimens and to compare to the values from the conventional-slump concrete.

Table 3-1: Required average compressive strength when data are not available to establish a sample standard deviation (ACI 318 2005)

Specified compressive strength, psi	**Required average compressive strength, psi**
$f'_c < 3000$	$f'_{cr} = f'_c + 1000$
$3000 \le f'_c \le 5000$	$f'_{cr} = f'_c + 1200$
$f'_c > 5000$	$f'_{cr} = 1.10\ f'_c + 700$

3.3 EXPERIMENTAL PROGRAM

The experimental program was split into two phases. The first phase was the development of two SCC mixtures in the laboratory. The SCC mixtures were to be placed in a test shaft alongside a similar shaft made of the conventional-slump drilled shaft concrete used by ALDOT. The fresh and hardened properties were tested for each mixture and compared. At a later date the test shafts will be exhumed and inspected for defects. The second phase of the project will include the use of one of the SCC mixtures for the foundation construction of the B.B. Comer Bridge in Scottsboro, AL. The research provided herein was for the first phase of the project, which was the laboratory development and testing of the SCC mixtures.

The mixtures were developed to evaluate the effect of different combinations of water-to-cementitious material ratios (w/cm) and sand-to-aggregate ratios (S/Agg) on fresh and hardened properties. Three w/cm and S/Agg were chosen, and each w/cm was paired with each of the S/Agg resulting in a total of nine SCC mixtures to be tested. Table 3-2 lists the different w/cm and S/Agg and gives the name used to identify each mixture. It should be noted that 30% of the total cementitious content was replaced with Class F fly ash for each of the 9 mixtures. The materials used for the mixtures include Type I Cement, Class F Fly Ash, limestone powder, and coarse and fine aggregate. Each of the materials are discussed in Section 3.5. The limestone powder was used to create a modified version of Mix 2, referred to as Mix 2 (LP), in an attempt to reduce bleed water. Mix 2 was chosen because it had the better fresh properties and will be used in the field study discussed in Chapter 6; therefore, Mix 2 (LP) was created to evaluate the performance of limestone powder in large SCC applications.

Table 3-2: SCC w/cm and S/Agg vales used for experimental program

Item		**w/cm**		
		0.38	0.40	0.42
S/Agg	0.45	Mix 3a	Mix 2a	Mix 1a
	0.50	Mix 3	Mix 2*	Mix 1
	0.55	Mix 3b	Mix 2b	Mix 1b

* Mix 2 was also made with limestone powder; that mixture is denoted as Mix 2 (LP)

Another purpose of this research will be to monitor the flow of concrete in a drilled shaft when placed using a tremie. To study and understand the flow of concrete better, different-colored 1/2-in. mortar cubes will be placed into the tremie at different stages of the concrete placement. Mortar cubes were chosen because they have a specific gravity similar to that of concrete, meaning that they will not float or sink when placed in the concrete. Five different colors – red, blue, yellow, green, and orange – of mortar cubes were made using a powder coloring agent. Approximately eight thousand 1/2-in. mortar cubes were made for each color to be distributed between the test shafts constructed in the field. A record will be kept of when each color is put into the tremie and how much concrete has been placed at that time. When the test shafts are exhumed they will be sawed in half, along the longitudinal axis, to expose the mortar cubes. The shafts will be visually inspected, and the different mortar cubes will be located and their position within the shaft noted. The data will be compared with the time at which the cubes were placed.

3.4 CONCRETE MIXTURE PROPORTIONS

The nine SCC mixtures shown in Table 3-2 were made with Type I cement and 30% Class F fly ash. The w/cm ranged from 0.38 to 0.42 and the S/Agg ranged from 0.45 to 0.55. The conventional-slump drilled shaft concrete, referred to as the "Control" mixture, used 25% Class F fly ash and had a w/cm of 0.40 and a S/Agg of 0.36. Mix 2 was chosen to be used in the field study discussed in Chapter 6. In an effort to reduce the amount of bleed water, a related tenth SCC mixture, Mix 2 (LP) was developed. It was designed to have the same proportions as Mix 2, except the limestone powder made up 10% of the powder material (cement, fly ash, and limestone powder) and 30% of the cementitious material (cement and fly ash) was fly ash. For the purpose of this research, the limestone powder was considered an inert material and was not predicted to contribute to the compressive strength of the concrete. Therefore, the presence of limestone powder in Mix 2 (LP) reduced the amount of cementitious material and increased the w/cm to 0.44. Detailed mixture proportions are given in Table 3-3 for all ten SCC mixtures as well as the Control.

Table 3-3: Concrete mixture proportions

Item	Water, lb/yd^3	Cement, lb/yd^3	Fly ash, lb/yd^3	Limestone powder, lb/yd^3	Coarse aggregate, lb/yd^3	Fine aggregate, lb/yd^3	HRWRA, oz/cwt	HSA, oz/cwt
Control	280	525	175	0	1892	1080	6*	4
Mix 1	280	470	201	0	1496	1489	10	2.5
Mix 1a	280	467	200	0	1646	1346	8	2.5
Mix 1b	280	467	200	0	1343	1642	12	2.5
Mix 2	274	475	209	0	1493	1493	12	2.5
Mix 2(LP)	274	432	185	69	1492	1492	8.5	2.5
Mix 2a	274	475	209	0	1645	1346	9	2.5
Mix 2b	274	475	209	0	1343	1642	12	2.5
Mix 3	267	483	219	0	1493	1493	12	2.5
Mix 3a	267	483	219	0	1644	1345	10	2.5
Mix 3b	267	483	219	0	1344	1643	11	2.5

Notes: HRWRA = high-range water-reducing admixture; HSA = hydration-stabilizing admixture
* Used a water-reducing admixture

3.5 RAW CONCRETE MATERIALS

The raw materials used to develop the SCC mixtures were made up of powder material, chemical admixtures, and coarse and fine aggregate. The materials used for this research were obtained from a concrete plant located in Scottsboro, AL which is where the B.B. Comer Bridge is located. The following sections describe each raw material used, its source and specific details.

3.5.1 POWDER MATERIAL

The powder material used throughout the course of this research included Type I portland cement, Class F fly ash, and finely ground limestone powder. The cementitious material was composed of a cement and fly ash mixture. The finely ground limestone powder was used as a filler and consisted of mostly inert calcium carbonate material. All mixtures were prepared with Type I cement and Class F fly ash, but the limestone powder was only used in one of the SCC mixtures.

3.5.1.1 Type I Portland Cement

The Type I portland cement use for this project was manufactured by National Cement Co. in Ragland, Alabama. Type I portland cement is a general purpose cement and commonly utilized in general construction as well as drilled shaft construction. It was used in the Control mixture as well as the SCC mixtures. The chemical composition of the cement was tested by a commercial laboratory and is provided in Table 3-4.

Table 3-4: Chemical composition of National Type I portland cement

Item	% by Weight
Silicon Dioxide (SiO_2)	20.47
Aluminum Oxide (Al_2O_3)	4.59
Iron Oxide (Fe_2O_3)	3.31
Calcium Oxide (CaO)	63.40
Magnesium Oxide (MgO)	2.61
Sodium Oxide (Na_2O)	0.05
Potassium Oxide (K_2O)	0.77
Total Alkalies as Na_2O	0.56
Titanium Dioxide (TiO_2)	0.24
Manganic Oxide (Mn_2O_3)	0.04
Phosphorus Pentoxide (P_2O_5)	0.06
Strontium Oxide (SrO)	0.05
Barium Oxide (BaO)	0.03
Sulfur Trioxide (SO_3)	2.81
Tricalcium Silicate (C_3S)	58.99
Tricalcium Aluminate (C_3A)	6.56
Dicalcium Silicate (C_2S)	14.18
Tetracalcium Aluminoferrite (C_4AF)	10.06

3.5.1.2 Class F Fly Ash

The Class F fly ash was provided by SEFA, Inc. and manufactured in Cumberland, Tennessee. Fly ash is a by-product of coal burning and is collected from the stacks of coal plants. It is a fine material that provides cementing properties when mixed with cement and water. Fly ash is less expensive than portland cement and is specified for both the conventional-slump and SCC mixtures. Table 3-5 details the chemical composition of the Class F Fly Ash provided for this project.

Table 3-5: Chemical composition of SEFA Class F fly ash

Item	% by Weight
Silicon Dioxide (SiO_2)	47.45
Aluminum Oxide (Al_2O_3)	19.05
Iron Oxide (Fe_2O_3)	17.60
Calcium Oxide (CaO)	8.30
Magnesium Oxide (MgO)	1.36
Sodium Oxide (Na_2O)	0.75
Potassium Oxide (K_2O)	2.17
Titanium Dioxide (TiO_2)	1.01
Manganese Dioxide (MnO_2)	0.05
Phosphorus Pentoxide (P_2O_5)	0.13
Strontium Oxide (SrO)	0.05
Barium Oxide (BaO)	0.07
Sulfur Trioxide (SO_3)	1.44

3.5.1.3 Finely Ground Limestone Powder

Omya Canada Inc. out of Quebec, Montreal provided the finely ground limestone powder used during the course of this research. The powder had a mean particle size of approximately 3 μm and was introduced in an attempt to control bleed water. Results collected by Khayat et al. (2006) showed that concrete containing limestone powder experienced an increase in early strength, but lower strengths were reported at an age of 28 days. Since early strength is not required for drilled shafts, it was assumed that the limestone powder would not contribute to the compressive strength of the concrete. The powder was used to adsorb excess water not consumed in the hydrating process. The limestone powder is finer than the cement, therefore providing more surface area for attachment of excess water and ultimately reducing bleed water. The limestone powder was used in the SCC mixture labeled Mix 2 (LP), and the chemical composition of the material is given in Table 3-6.

Table 3-6: Chemical composition of Omya 3-μm limestone powder

Item	% by Weight
Silicon Dioxide (SiO_2)	3.46
Aluminum Oxide (Al_2O_3)	1.29
Iron Oxide (Fe_2O_3)	0.30
Calcium Carbonate ($CaCO_3$)	93.08
Magnesium Carbonate ($MgCO_3$)	1.64
Sodium Oxide (Na_2O)	0.03
Potassium Oxide (K_2O)	0.29
Titanium Dioxide (TiO_2)	0.01
Manganese Dioxide (MnO_2)	0.01
Phosphorus Pentoxide (P_2O_5)	0.01
Strontium Oxide (SrO)	0.02
Barium Oxide (BaO)	0.01
Sulfur Trioxide (SO_3)	0.01

3.5.2 CHEMICAL ADMIXTURES

Chemical admixtures alter the performance of concrete to provide favorable results such as increased workability, reduction in water content, changes in setting times, and increase durability, just to name a few. Three different admixtures were used in this project to increase the workability and setting time of the concrete. Grace Construction Products provided the admixtures discussed in the following sections.

3.5.2.1 Water-Reducing Admixture

WRDA® 64 is the water-reducing admixture used for the conventional-slump drilled shaft concrete specified by the Alabama Department of Transportation (ALDOT). It is a polymer-based aqueous solution that reduces the amount of water needed to obtain a certain level of workability (Grace 2008). The dosage of this admixture was obtained from approved mixture proportions developed by Kirkpatrick Concrete Co. and tested in the laboratory for verification. WRDA® 64 is specified to meet the requirements of

ASTM C 494 (2005) Type A and Type D, *Standard Specification for Chemical Admixtures for Concrete*.

3.5.2.2 High-Range Water-Reducing Admixture

The high-range water-reducing admixture, sometimes referred to as a superplasticizer, was ADVA® 380. This admixture is a high-efficiency polycarboxylate solution chosen to aid in the production of SCC. ADVA® 380 was selected because of its ability to provide increased workability while maintaining concrete stability. ADVA® FLEX and ADVA® Cast 555 are HRWR admixtures that were used at the beginning of the experimental program. However, the use of these admixtures resulted in high total air content from extended mixing times of the transportation period. After many trial batches, ADVA® 380 gave the best results and was chosen to be used in the SCC mixtures. The dosage was determined through laboratory testing and later tested at a concrete production plant to find the full-scale dosage rates. ADVA 380 is designed to comply with ASTM C 494 (2005) and was used in the production of all SCC mixtures.

3.5.2.3 Hydration-Stabilizing Admixture

The hydration-stabilizing admixture used for the concrete produced throughout this study was called Recover®. Recover® provided delayed setting times to compensate for the lengthy placements associated with drilled shaft construction. The dosage rate was initially tested in the laboratory and then later tested at a concrete batch plant to determine dosage for full-scale production. The dosage was selected to achieve final set no earlier than 18 hours after the placement of concrete. Recover® was used for all SCC and conventional-slump concrete mixtures, and it complies with ASTM C 494 (2005).

3.5.3 COARSE AGGREGATE

The coarse aggregate was supplied by Vulcan Materials Co. in Scottsboro, Alabama. The coarse aggregate chosen was a crushed limestone that consisted of No. 67 and No. 78 gradation for the conventional-slump concrete and the SCC, respectively. The maximum aggregate size of the No. 67 was 3/4 inch and the No. 78 had a maximum aggregate size of 1/2 inch. The smaller aggregate size was chosen for the SCC mixtures in order to increase the flowing and passing ability of the concrete. The No. 78 aggregate was transported from Scottsboro, Alabama, and a stockpile was created at Twin City Concrete in Opelika, Alabama. As needed, the coarse aggregate was shoveled into 55-gallon barrels and stored in the Harbert Engineering Center laboratory on the Auburn University campus for testing. However, the No. 67 aggregate was shipped directly to Auburn University in three 55-gallon barrels; due to the small amount of material needed, a stockpile was not necessary. Once the No. 78 material was delivered, its gradation, specific gravity, and absorption capacity were determined. These tests were not performed for the No. 67 aggregate because a stockpile was never created; therefore an adequate representative sample could not be achieved for testing. However, the information was provided by Vulcan Materials Co. The specific gravity (SSD) and absorption capacity were 2.73 and 0.64%, respectively, for the two aggregates. The gradation for the No. 78 aggregate is provided in Figure 3.1 along with the gradation requirements from Table-1 of the American Association of State Highway and Transportation Officials (AASHTO) M 43-88 (1997).

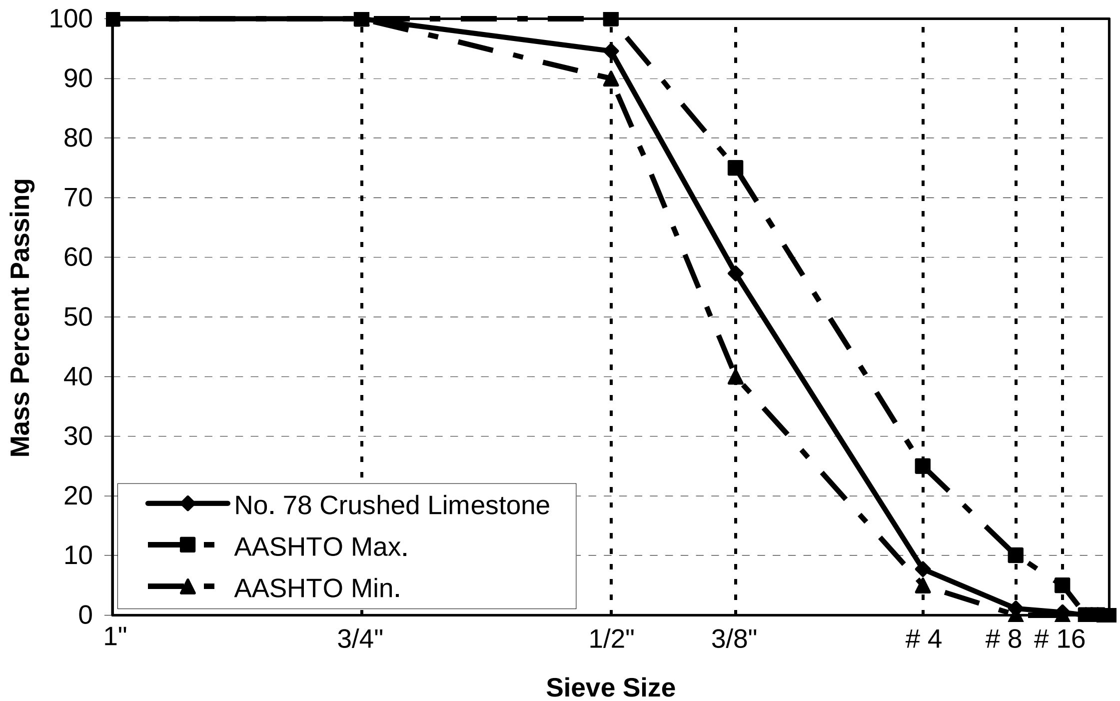


Figure 3.1: No. 78 coarse aggregate gradation

3.5.4 FINE AGGREGATE

The fine aggregate was provided by Madison Materials from Summit, Alabama. The material was required for the conventional-slump drilled shaft concrete, and the material was also used for the SCC mixtures for consistency. Like the No. 78 aggregates, the material was delivered and stockpiled at Twin City Concrete in Opelika, Alabama. When needed for testing, the material was shoveled into 55-gallon barrels and stored in the laboratory. The material was tested for its specific gravity, absorption capacity, and gradation. The specific gravity (SSD) and absorption capacity were 2.71 and 1.58%, respectively, which was consistent with the values provided by the supplier. The gradation of the fine aggregate was tested and provided in Figure 3.2 along with the maximum and minimum requirements of AASHTO M 6-93 (1997).

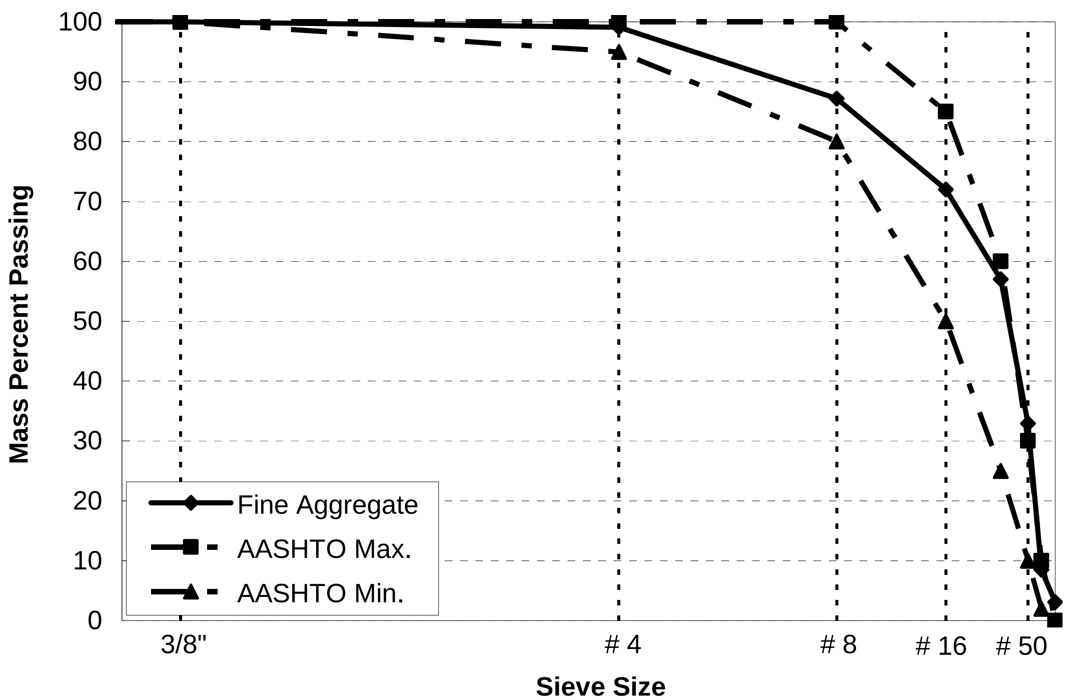


Figure 3.2: Fine aggregate gradation

CHAPTER 4

LABORATORY MIXING AND TEST PROCEDURES

4.1 INTRODUCTION

Auburn University has a concrete mixing facility within the Harbert Engineering Center. The mixing facility, shown in Figure 4.1, was completed in the summer of 2003 and allows for a more controlled environment for concrete mixing and testing. This area has a 12-ft^3 concrete mixer, drainage tank, area for moisture correction and a material weight station. Along with the mixing facility, Harbert Engineering Center also has a concrete testing laboratory. The concrete testing laboratory houses a moist curing room for specimen curing, two Forney compression machines, a permeability machine and a length comparator for drying shrinkage readings. The concrete research facility at Auburn University provides the necessary state-of-the-art equipment needed to accurately mix and test concrete specimens.

Figure 4.1: Auburn University Concrete Mixing Facility (Bailey 2005)

4.2 BATCHING AND MIXING PROCEDURE

All raw materials were shipped and stored in 55-gallon drums in the concrete research laboratory. Batching of materials began by weighing all powder material, cement, fly ash and/or limestone filler in 5-gallon buckets properly sealed with a lid to keep out and seal in moisture. Once the powder material was batched out, the coarse and fine aggregate were ready to be batched. The aggregates were batched into 5-gallon buckets to an estimated amount. Moisture corrections were performed on the aggregates to determine their moisture state. Once the moisture corrections were done, the exact amount of aggregates and water could be determined. The aggregates and water were then weighed out in 5-gallon buckets and sealed to keep any moisture from escaping. After all the raw materials were properly weighed out, they were placed next to the mixer on top of the mixing deck. The chemical admixtures were then measured using 10- and 60-mL syringes.

Before any mixing began, a “butter batch” was prepared by taking a small amount, about 5 pounds, of cement and fine aggregate. The cement and fine aggregate were thrown into the 12-ft^3 concrete mixer, shown in Figure 4.2, with some water to properly coat the wall of the mixer so the cement paste of the mixing concrete would not stick and be lost to the mixer wall. Once the mixer was “buttered”, the concrete was ready to be made. Due to the size of the mixer and the amount of concrete needed for testing, two batches were created for each concrete mixture. The mixing procedure for the second batch of concrete is slightly different from the first, and both procedures are shown in Table 4-1 and Table 4-2. The first batch required two additional air readings and a slump flow reading in the “Mixing at Batch Plant” section of Table 4-1 to determine the fresh properties before transportation, whereas these values were not required for the second batch. As mentioned in Section 3.5.2.2, other HRWR admixtures increased the total air content throughout the mixing process; therefore, the additional total air content tests were performed to monitor the development of air throughout the mixing process. Likewise, the additional slump flow was determined at the end of the “Mixing at Batch Plant” section to ensure the correct dosage of HRWR admixture was used to obtain desired filling ability after the transportation period. A slump flow of 21 ± 3 in. was required once the concrete arrived at the jobsite; therefore, a slump flow of approximately 26 in. was targeted at the batch plant, accounting for a loss in slump flow during transportation. The slump flow, Modified J-Ring, total air content, unit weight and temperature were tested at the end of the mixing procedures for both batches. Other tests performed from the first batch of concrete included: the slump flow retention, segregation column, setting time, a 6 in. Ø x 12 in. cylinder to be placed in a semi-adiabatic calorimeter, as well as three 6 in. Ø x 12 in. cylinders to be tested for compressive strength and modulus of elasticity for quality control purposes. The hardened properties were to be tested using the concrete from the second batch, which included: the compressive strength, modulus of elasticity, drying shrinkage, and permeability.

Table 4-1: Procedure used to create batch No. 1

Step	Phase
1. Butter the mixer. 2. Add coarse and fine aggregate into the mixer. 3. Add 80% of the mixing water. 4. Mix for 1 minute. 5. Stop the mixer.	Blending of Aggregates
6. Add all cementitious materials (**Start Time**). 7. Add the rest of the mixing water. 8. Mix for 2 minutes. While mixing add • Retarder ("Recover") 9. Stop the mixer and take a **water slump** reading (≤ 3in.) and **total air content reading.** 10. Mix for 5 minutes, while mixing add • Any HRWR admixture ("ADVA 380") 11. Stop Mixer. 12. Test the **slump flow** (≈ 26 in.) and take **total air content reading.**	Mixing at Batch Plant *(Lowest Mixing Speed, 18 rpm)*
13. Run the mixer for an additional 10 minutes while covered. 14. Stop the mixer and leave mixer off for additional 30 minutes. 15. Run the mixer for an additional 10 minutes while covered. 16. Stop mixer and take **total air content reading** (4% ± 2%) along with all other **fresh and hardened concrete properties**. (Slump flow = 21" ± 3in)	Transportation to Site *(Lowest Mixing Speed, 18 rpm)* Mix with bucket 5˚ off vertical

Table 4-2: Procedure used to create batch No. 2

Step	Phase
1. Butter the mixer. 2. Add coarse and fine aggregate into the mixer. 3. Add 80% of the mixing water. 4. Mix for 1 minute. 5. Stop the mixer.	Blending of Aggregates
6. Add all cementitious materials (**Start Time**). 7. Add the rest of the mixing water. 8. Mix for 2 minutes. While mixing add • Retarder ("Recover") 9. Stop Mixer and take **water slump** reading (≤ 3"). 10. Mix for 5 minutes, while mixing add • Any HRWR admixture ("ADVA 380")	Mixing at Batch Plant *(Lowest Mixing Speed, 18 rpm)*
11. Run the mixer for an additional 10 minutes while covered. 12. Stop the mixer and leave mixer off for additional 30 minutes. 13. Run the mixer for an additional 10 minutes while covered. 14. Stop mixer and take **total air content reading** (4% ± 2%) along with all other **fresh and hardened concrete properties**. (Slump flow = 21" ± 3in)	Transportation to Site *(Lowest Mixing Speed, 18 rpm)* Mix with bucket 5˚ off vertical

The two mixing procedures shown in Table 4-1and Table 4-2 are divided into three phases, “Blending of Aggregates”, “Mixing at Batch Plant”, and “Transportation to Site”. This was done to simulate the mixing process that would occur during the construction of the B.B. Comer Bridge. It was assumed that the concrete would remain in the concrete truck for approximately 50 minutes after batching; this took into account the commute from the batch plant to the jobsite as well as any delays that might occur once at the jobsite. It should also be noted that the mixing speed was specified to imitate speeds that would occur while the concrete was in the concrete truck. When the material is first place into the concrete truck it is mixed at higher revolutions-per-minute (rpm), but the speeds significantly slow down once the concrete truck begins the commute to the jobsite. It was assumed that the initial mixing and transportation speeds of the concrete truck were 18 and 7 rpm, respectively. However, the lowest speed of the laboratory mixer was 18 rpm. In order to properly simulate the low mixing speeds during transportation, the laboratory mixer was raised to approximately 5˚ off vertical. By doing so the agitation experienced by the concrete in the laboratory was reduced to match that of the concrete truck during transportation. This mixing procedure was also credited with reducing the entrapped air of the concrete due to additional agitation from higher mixing speed, and therefore reducing the total air content of the mixture upon arrival to the construction site.

Figure 4.2: 12-ft^3 concrete mixer (Bailey 2005)

4.3 MORTAR MIXING AND CUBE PREPARATION

Mortar cubes, discussed in Section 3.3, were made using silica fume, Type I White Cement, Madison Sand and water. The silica fume made up 5% of the total cementitious material and was used to modify and strengthen the mortar's pore structure. The mixture proportions for the colored mortar cubes are given in Table 4-3. The material was batched much like the concrete, using 5-gallon buckets to weigh out the material. The fine aggregate was estimated and then weighed after moisture corrections were performed. The material was placed into the mixer and allowed to mix for two minutes, at which point the concrete color and HRWR admixture was added. The concrete color was a powder admixture provided by L.M. Scofield Company. Initial proportions were calculated for the coloring admixtures, but additional coloring was typically added as needed to obtain the desired appearance as noted in Table 4-3. The material continued mixing for five minutes until the mortar was sufficiently mixed. Once completed, the mortar was placed into a wheel barrow and transported to the location where the cubes were made.

Table 4-3: Mixture proportions for colored mortar cubes

Item	Water, lb/ft^3	Cement, lb/ft^3	Silica fume, lb/ft^3	Fine aggregate, lb/ft^3	*Coloring admixture, lb/ft^3	HRWRA, oz/cwt
Red	14	44	2	107	3	24
Blue	14	44	2	107	2	21
Yellow	14	44	2	107	6	24
Orange	14	44	2	107	8**	24
Green	14	44	2	107	3	24

Notes: HRWA = high range water reducing admixture
*Additional color was added as needed for desired appearance
**Comprised of 2 lb of Red and 6 lb of Yellow

A 2 ft. by 4 ft. Polystyrene light diffuser panel with 1/2 in. spacing, shown in Figure 4.3, often utilized as a florescent light cover, was used as the form to make the cubes. The lighting fixture was attached to a piece of 1/4-inch plywood using screws, washers, and wing nuts, shown in Figure 4.4. A plastic sheet was placed between the plywood and form, the form was then sprayed with WD40 to prevent the cubes from sticking to the forms. The mortar was then placed and trowelled to sufficiently fill the forms. After placing the mortar, a belt sander, protected by a plastic cover, was used to consolidate the mortar in order to guarantee adequate consolidation. The forms were then covered with a wet burlap cloth, which was also covered by a plastic sheet to help maintain the burlap's moisture. After the forms were filled, 2-in. cube specimens were made in accordance with ASTM C 109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*. All equipment and procedures met the requirements specified in ASTM C 109. The 2-in. mortar cubes were stored in the moist curing room covered with a burlap cloth for a period of 24 hours, after which they were stripped from the form and placed into a lime bath until testing. The 2-in. cubes were tested in a 400-kip Forney compression machine at an age of 28 days. After 24 hours from the time of mixing, the 1/2 in. mortar cubes were stripped from their forms, shown in Figure 4.5, and placed into 5-gallon buckets and stored in the moist curing room for 28 days. The buckets had 3/16-in. diameter holes drilled into the bottom and sides of the bucket to allow any standing water to drain. Twenty-eight days after mixing, the compressive strength of the 2-in. cubes was determined, and the 5-gallon buckets with the 1/2-in. cubes were placed into dry storage.

Figure 4.3: Polystyrene light diffuser panel used for mortar cube form

Figure 4.4: Screw, washer and wing nut configuration used to anchor mortar cube form

Figure 4.5: Colored 1/2 in. mortar cubes

4.4 FRESH PROPERTY TESTING

The fresh properties of the concrete were tested in order to quantify the rheological performance of each mixture. The slump flow, slump flow retention, segregation column, unit weight, air content, and setting times were used to determine the fresh properties of the SCC. The J-Ring test was also performed, but the dimensions of the J-Ring were modified to represent a reinforcement spacing more suitable for drilled shaft projects; therefore, for the remainder of this report, it will be referred to as the Modified J-Ring to differentiate from the J-Ring specified in ASTM C 1621 (2005).

4.4.1 WATER SLUMP

The water slump was measured in accordance with ASTM C 143 (2005), *Standard Test Method for Slump of Hydraulic-Cement Concrete*. The water slump was taken before the addition of the HRWR admixture for each SCC mixture. The water slump was performed to determine the consistency of the concrete before the addition of the HRWR admixture. Materials used to perform the test met all specifications and are shown below in Figure 4.6.

Figure 4.6: Water slump testing equipment and setup

4.4.2 SLUMP FLOW

As discussed in Chapter 2, the slump flow test characterizes the filling ability of SCC. The test was done in accordance with ASTM C 1611 (2005), *Standard Test Method for Slump Flow of Self-Consolidating Concrete*. The slump flow was taken before and after the 50-minute transportation period for the first batch of concrete mixed; the slump flow test was only taken at the end of the mixing period for the second batch of concrete. The SCC mixtures tested for this project were all performed with the slump cone in the inverted position, as illustrated in Figure 4.7. Per the specifications, all surfaces were moistened before the concrete was placed into the cone in one lift using a 5-gallon bucket. The cone was then lifted 9 ± 3 in. from the base plate, allowing the concrete to flow into a circular spread. The diameter of the spread was measured in two perpendicular directions, and the average of the two was recorded as the slump flow. The required slump flow after the transportation period was 21 ± 3 in. The testing equipment and setup are shown in Figure 4.7.

Figure 4.7: Slump flow testing equipment and setup

The slump flow test was performed by one person, but a second person was needed to determine the T_{50} time. The second individual started the stopwatch once the cone was lifted and stopped it once the concrete reached a diameter of 20 in. The time required for the concrete to flow from the initial position to a 20 in. diameter was recorded as the T_{50}. It should be noted that there was not a required range for the T_{50} time, but it was recorded as a means to compare the viscosity of different mixtures.

The Visual Stability Index (VSI) rating was also determined from the concrete patty obtained after the slump flow test was conducted. The VSI is a measure of the dynamic stability, because the slump flow was performed directly after mixing. The concrete was considered unstable and was rejected if the VSI rating was greater than 2.0. When moistening the slump flow table precaution was made to remove as much excess water from the table, because if standing water remained on the table the VSI rating would appear higher. The criteria for the VSI rating are shown in Figure 2.3.

4.4.3 SLUMP FLOW RETENTION

The workability of SCC is important, but it is just as critical to maintain workability when placing deep foundations. Deep foundations can take multiple hours to complete and there can also be delays while placing due to difficulties, which is why the concrete must maintain its workability. To do so, the slump flow, described in Section 4.3.2, was performed every 30 minutes for a total of 6 hours after completing the mixing process, which is referred to as the Slump Flow Retention. The last two tests, 5.5 and 6 hours after mixing, were performed by the water slump test methods described in Section 4.4.1.

4.4.4 MODIFIED J-RING

As mentioned in the introduction to Section 4.4, the J-Ring specified in ASTM C 1621 (2005) was modified, as permitted by PCI (2003), to simulate the reinforcement in deep foundations. The J-Ring specified in ASTM C 1621 (2005) uses a 12-in. diameter ring with sixteen 5/8-in. diameter smooth dowels to obstruct the concrete's flow. This creates a 1.74-in. clear spacing between the dowels. This was considered too congested to accurately represent drilled shaft applications. The dowel spacing was modified based on a maximum spiral pitch of 3 in. required for the portion of concrete below the pile cap in a Zone 2 seismic area (AASHTO 2005). It is also important to note that the ring and dowel diameter were held constant at 12 in. and 5/8 in., respectively, for the Modified J-Ring. In doing so, the number of dowels was reduced from 16 to 13, which increased the clear spacing from 1.74 in. to 2.27 in.

Sizing requirements for spiral reinforcement are based on the minimum volumetric spiral reinforcement ratio (ρ_s) for compression members as defined in ACI 318 (2005) by Equation 4.1. Equation 4.1 can be modified to determine the minimum size of reinforcing bar required based on concrete and steel properties, shaft geometry, and pitch spacing as shown by Equation 4.2 and Equation 4.3. Utilizing Equations 4.2 and 4.3, a 5.5-ft diameter shaft designed in a Zone 2 seismic area (i.e. spiral spacing less than or equal to 3 in.) with 4,000 psi concrete and transverse steel with a yield strength of 60,000 psi would require No. 5 (5/8-in. diameter) spiral reinforcing bars, which are the bars specified for both the ASTM C 1621 (2005) J-Ring and the Modified J-Ring.

$$\rho_{s,req'd} = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_{yt}}$$ **Equation 4.1**

Where, A_g is the gross area of the concrete shaft in in.^{2},

A_{ch} is the area of concrete confined by the spiral core in in.^{2},

f'_c is the compressive strength of the concrete in psi, and

f_{yt} is the yield strength of the transverse reinforcement in psi.

And $\rho_{s,\,req'd}$ can also be written as,

$$\rho_{s,req'd} = \frac{(\pi D_c)A_{sp}}{\left(\frac{\pi D_c^2}{4}\right)l_{sp}} = \frac{4A_{sp}}{D_c l_{sp}}$$ **Equation 4.2**

Where, D_c is the diameter of the spiral core, in., measured out to out,

l_{sp} is the spiral pitch, in., and

A_{sp} is the cross-sectional area of the spiral reinforcement, in^2.

Therefore, substituting Equation 4.2 into Equation 4.1 and solving for the area of the spiral,

$$A_{sp} = \frac{0.45 D_c l_{sp}}{4}\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_{yt}}$$ **Equation 4.3**

The procedure used for the Modified J-Ring test was similar to the slump flow test. The base board and slump cone were moistened with a damp sponge. The Modified J-Ring was placed in the middle of the base board and the slump cone was placed, in the inverted position, in the middle of the ring. The concrete was placed into the cone, using a 5-gallon bucket, in one lift. The cone was then lifted straight up 9 ± 3 in. and the diameter of the spread was measured in two directions perpendicular from each other. The average of the two diameters was recorded for the Modified J-Ring reading. The difference between the slump flow and the Modified J-Ring flow was used as an indication of the concrete's passing ability, where a difference less than 1 in. was considered good passing ability and a value greater than 2 in. was poor passing ability (ASTM C 1621 2005).

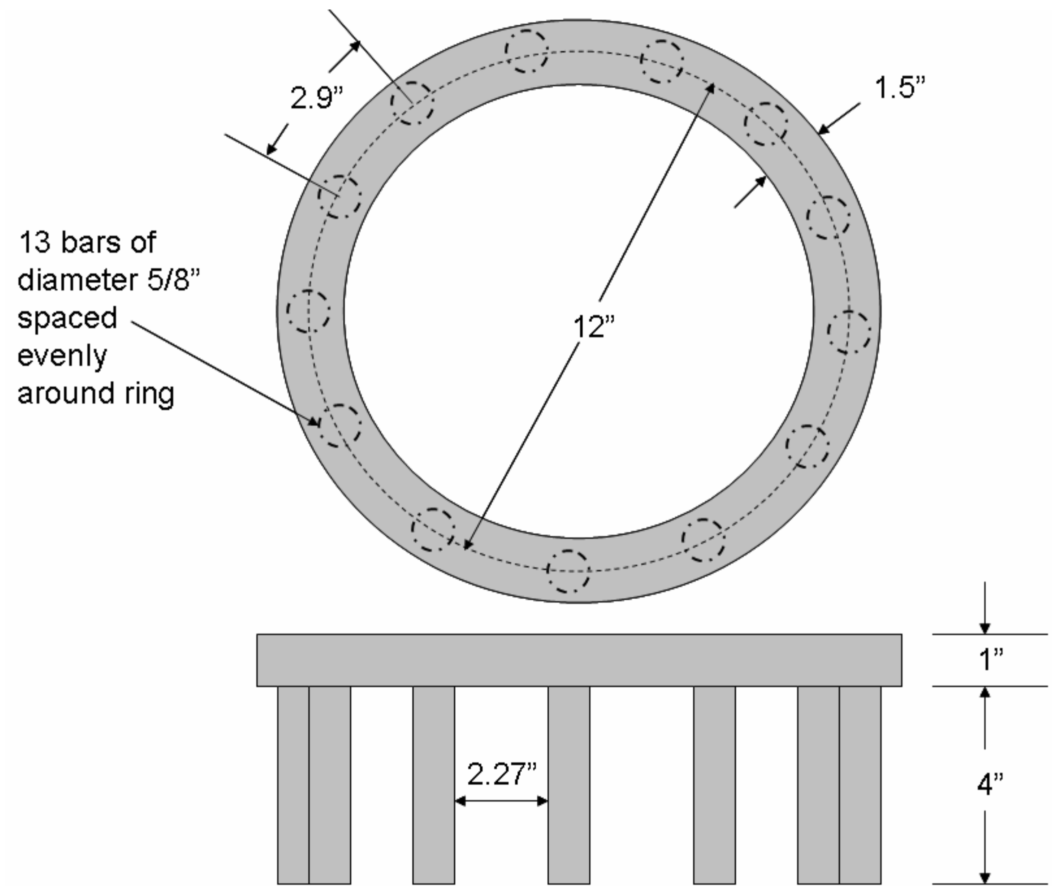


Figure 4.8: Modified J-Ring

4.4.5 SEGREGATION COLUMN

As the name suggests, the segregation column test determines the concrete's resistance to segregation. The procedure was performed in accordance with ASTM C 1610 (2005), *Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique*. The equipment used for the segregation column test is shown in Figure 4.9.

Figure 4.9: Segregation column equipment and setup (Bailey 2005)

The segregation column test was constructed out of schedule 40 PVC pipe 8 inches in diameter and 26-inches tall. The column was divided into four 6.5-inch tall sections. Each section was held together by clamps biting down onto L-brackets attached in four locations around the outside of each section. The column is attached to a rigid non-absorbent base plate. A collection plate was also constructed out of a rigid non-absorbent square plate with a semi-circular cutout in the middle of the plate measuring 8.5 inches across.

The test was performed by first assembling the segregation column and placing it on a level surface, as shown in Figure 4.9. Fresh concrete was placed in the column using a 5-gallon bucket. Once full, the excess concrete at the top was removed by using a strike-off bar. The concrete was left, undisturbed, in the column mold for 1 hour. ASTM C 1610 (2005) specifies the concrete be left, undisturbed, for only 15 minutes. The extended period of time used for this project was selected to more closely match the lengthy placement times associated with deep foundations. After the resting period, the top and bottom sections were removed and placed in separate 5-gallon buckets using the collector plate; the two middle sections were discarded. The top and bottom sections were then washed over a No. 4 sieve to remove all the fines. The remaining coarse aggregates were brought to a saturated-surface-dry state and then each section was weighed to the nearest 0.1 pound. The percent static segregation was then calculated using Equation 2.1. If the mass of the coarse aggregate happens to be greater in the top than the bottom, then there is considered to be no static segregation.

4.4.6 UNIT WEIGHT AND AIR CONTENT

The total air content and the unit weight of the concrete was tested in accordance with the procedure listed in ASTM C 138 (2005), *Standard Test Method for Unit Weight, Yield, and Air Content*. The test was performed to determine the weight per cubic foot and the percentage of air voids within the concrete. All equipment, shown in Figure 4.10, used was within specifications described in ASTM C 138 (2005). The procedure was followed as closely as possible for SCC mixtures with some modifications to account for SCC fresh property characteristics. The 1/4-ft^3 container was filled in three lifts using a 5-gallon bucket, and each lift was tapped, using a rubber mallet, 10-15 times around the outside of the container. This was done in order to reduce the possibility of any large voids that might form around the edge of the container while maintaining minimal consolidation. The excess concrete on the top was then removed using a strike-off plate, and the container was weighed to determine the weight of the concrete per cubic foot. The air content was then determined immediately after the container was weighed.

Figure 4.10: Air content and unit weight equipment

4.4.7 SETTING TIME

Setting time of the concrete was tested in accordance with the procedure listed in ASTM C 403 (2005), *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. The test was performed in order to determine the initial and final setting times of the concrete mortar by measuring its resistance to penetration. All equipment, shown in Figure 4.11, was within specifications described in ASTM C 403 (2005). ASTM C 403 (2005) specifies that when determining the setting time of concrete, the sample must be taken by placing concrete over a No. 4 sieve and placing it on a vibration table in order to remove the mortar from the concrete. It is not acceptable to use prepared mortar that is intended to represent the mortar portion of the concrete mixture. The concrete mortar was placed and sealed in an aluminum container and was tested as needed, using a penetration resistance apparatus, to ensure at least six penetrations from the time of initial to final set. A hole, 3/16 inches in diameter, was drilled into the side of the aluminum container and a thermocouple wire, connected to a maturity meter, was placed inside the concrete so that the temperature could be recorded at the time of each reading. Prior to taking each penetration reading, the container was lifted at a slight angle and the excess bleed water was removed. Initial and final set times were specified as the time it took for the concrete mortar to reach a resistance of 500 and 4,000 psi, respectively. For the use of this project, the final set time was targeted to be no earlier than 18 hours after placement. The construction of deep foundations may take many hours, and it is necessary that the concrete remain viscous until the shaft is completed; therefore, it is required that the concrete not reach final set until 18 hours after mixing. This ensures that the concrete in the shaft does not set in layers, causing weak planes throughout the shaft.

The setting time of the concrete was also monitored by the use of semi-adiabatic calorimetry. A 6-in. diameter by 12-in. high cylinder was placed into a semi-adiabatic calorimeter, and the temperature change in the concrete was recorded. The data collected from the calorimeter were used to generate semi-adiabatic temperature profiles for estimation of the initial and final setting times of the concrete. The setting times of the concrete were estimated using the "Derivatives" method, which defines final set as the time of the maximum first derivative and the initial set as the time of the maximum second derivative of the temperature versus time profile (Sandberg and Liberman 2007). The data could then be compared to the results from the penetration test.

Figure 4.11: Setting test equipment

4.5 HARDENED CONCRETE PROPERTIES

4.5.1 MAKING AND CURING SPECIMENS IN THE LABORATORY

The concrete specimens were made and cured in accordance with the procedure listed in ASTM C 192 (2005), *Standard Test Method for Making and Curing Concrete Test Specimens in the Laboratory*. After the concrete was made in the laboratory many specimens were created for testing. The specimens used for testing consisted of 6-in. diameter by 12-in. high cylinders, 4-in. diameter by 8-in. high cylinders and 3 in. by 3 in. by 12 in. prisms. The procedures were followed as closely as possible for SCC mixtures with some modifications to account for SCC fresh property characteristics. The 6-in. diameter by 12-in. high cylinders were cast in three separate lifts and tapped, using a rubber mallet, 10-15 times around the outside of the cylinder for each lift. The 4-in. diameter by 8-in. high cylinders and 3 in. by 3 in. by 12 in. prisms were cast in two lifts and tapped, using a rubber mallet, 10-15 times around the outside of the molds. Once the cylinders were created they were securely capped, in order to retain all moisture, and stored in the laboratory until the concrete reached an age of 24 hours or twice that of the initial set. Once the concrete reached the appropriate age, the specimens were demolded and placed into the moist curing room. The moist curing room had a constant temperature and humidity of 73 ˚F and 100%, respectively. The cylindrical specimens were left in the moist curing room until testing. Once the prism molds were filled, they were covered in moist burlap and promptly placed into the moist curing room to ensure the burlap remained wet. The prisms were then demolded after they reached an age of 24 hours or twice initial set and placed into a lime bath. The concrete prisms remained in the lime bath for 7 days and were then removed and placed into air storage during the testing period.

4.5.2 COMPRESSIVE STRENGTH

The compressive strength, f'_c, was determined in accordance with the procedure listed in ASTM C 39 (2005), *Standard Test Method for Compressive Strength of Cylindrical Specimens*. The equipment used to determine the compressive strength of the concrete met all the requirements specified by ASTM C 39 (2005). The compressive strength was tested at ages of 7, 28 and 56 days using a Forney compression machine capable of applying 600,000 pounds of force, shown in Figure 4.12. The specimens were tested using unbonded caps that met the requirements of ASTM C 1231 (2005), *Standard Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders*. Each 6-in. diameter by 12-in. high cylinder was loaded at a rate of 35 psi/s, which corresponds to 60,000 lbs/min, and loaded until failure. The ultimate load applied was recorded in pounds and divided by the surface area of the cylinder to give the ultimate compressive stress in units of psi. The ultimate compressive stress was determined for three specimens, and the average was recorded to the nearest 10 psi.

Figure 4.12: 600-kip Forney compression machine (Bailey 2005)

4.5.3 MODULUS OF ELASTICITY

The modulus of elasticity, E_c, was determined in accordance with the procedure listed in ASTM C 469 (2005), *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. The equipment used to determine the elastic modulus of the concrete met all the requirements specified by ASTM C 469 (2005). The modulus of elasticity of the concrete was tested at the same ages as the compressive strength using unbonded caps specified by ASTM C 1231 (2005). A Humboldt compressometer with a digital gauge was used to determine the modulus of elasticity. The compressometer was securely placed onto the middle of the concrete cylinder and then placed into the Forney compression machine, as shown in Figure 4.13. The specimen was loaded to 40% of its compressive strength, without recording any data, in order to properly seat the equipment. The specimen was then reloaded at a rate of

60,000 lbs/min; the data was recorded, and the modulus of elasticity was determined using Equation 4.2. After an initial seating load cycle, the modulus of elasticity test was performed three times for each specimen and the average of the three readings was recorded. The test was performed on two of the three cylinders used during compressive strength testing and the average of the two specimens was recorded to the nearest 50 ksi.

$$E = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.00005)} \qquad \textbf{Equation 4.4}$$

Where, E is the Chord Modulus of elasticity, psi,

S_2 is the stress corresponding to 40% of the compressive strength, psi,

S_1 is the stress corresponding to a longitudinal strain of 50 millionths, psi, and,

ε_2 is the longitudinal strain produced by S_2.

Figure 4.13: Concrete cylinder with compressometer attached (Bailey 2005)

4.5.4 DRYING SHRINKAGE

The drying shrinkage was determined in accordance with the test procedure outlined in ASTM C 157 (2005), *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. The equipment used to determine the drying shrinkage met all the requirements specified by ASTM C 469 (2005). The test was run using 3 in. by 3 in. by 12 in. prisms described earlier. After the prisms were removed from the lime bath and placed into air storage, their lengths (relative to a reference bar) were measured at 1, 2, 3, 7, 14, 28, 56, 91, 180 and 365 days from their removal. The lengths were measured using a Humboldt length comparator with a dial gauge, shown in Figure 4.14, and the drying shrinkage was calculated using Equation 4.3. The test was performed on three specimens for each mixture, and the average of the three readings was calculated.

$$\Delta L = \frac{(CRD - initialCRD)}{G} \qquad \textbf{Equation 4.5}$$

Where, ΔL is the length change of specimen at any age, microstrain,

CRD is the difference between comparator reading of specimen and reference bar, and

G is the gage length, 10 in.

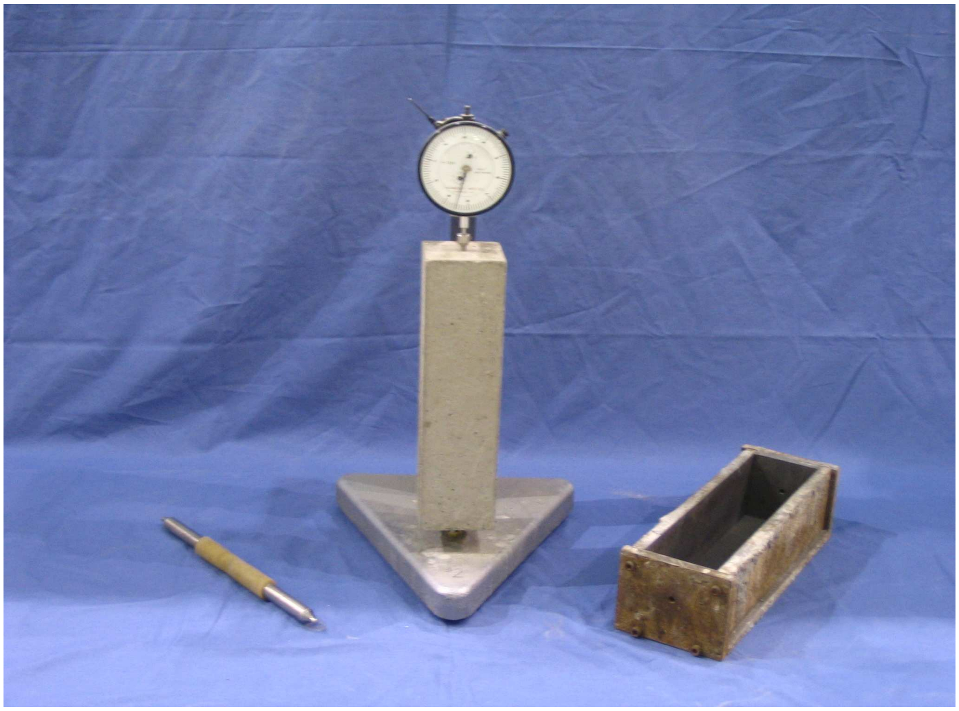


Figure 4.14: Humboldt length comparator with concrete specimen and prism mold

4.5.5 PERMEABILITY

The permeability of the concrete was determined in accordance with the test procedure outlined in ASTM C 1202 (2005), *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. The equipment used to determine the permeability met all the requirements specified by ASTM C 1202 (2005). The test was performed on 4-in. diameter by 2-in. high concrete specimens cut from 4-in. diameter by 8-in. high cylinders described earlier. The specimens were cut from the top 2 inches of the concrete cylinder. Two specimens, cut from two different cylinders of the same concrete batch, were tested for each concrete mixture at ages of 91 and 365 days. Proove' It cells and a Model 164 Test Set with LED readouts, automatic shut off, and automatic processing equipment, shown in Figure 4.15, were used to determine the permeability of the concrete specimens.

The test specimens had to be properly prepared before the permeability test was performed. The specimens were cured in the moist curing room until the day before testing, at which point they were removed, cut and prepared for testing. Once the specimens were cut, they were placed into a vacuum desiccator for a three-hour period. At the end of the three-hour period, the container was filled with de-aerated water while the pump continued to run. The specimens were left submerged in the de-aerated water for another hour, at which point the vacuum was turned off and the top was removed from the vacuum desiccator. The specimens were left submerged for 18 hours, then placed into the Proove' It cells. One side of the Proove' It cell was filled with NaOH while the other was filled with NaCl. The cells were hooked up to the Model 164 Test Set and tested for a 6-hour period. The test results were printed out and the average of the two test specimens was determined.

Figure 4.15: Model 164 test set and Proove' It cells (Bailey 2005)

CHAPTER 5

PRESENTATION AND ANALYSIS OF LABORATORY RESULTS

5.1 INTRODUCTION

As so often stated, this research compares SCC to that of conventional-slump concrete for drilled shaft application. The following chapter will report and discuss the results obtained from the laboratory study of both the conventional-slump and SCC mixtures. The mixtures include a conventional-slump concrete currently used in drilled shafts, which will be referred to as the 'Control mixture'. The remaining mixtures are SCC with varying water-to-cementitious and sand-to-aggregate ratios; resulting in a total of nine SCC mixtures as shown in Table 3-2. In addition, one SCC mixture was made with limestone powder, which will be referred to as 'Mix 2 (LP)'.

The results include data from fresh property testing as well as hardened property testing. All tests and data was performed and collected at Auburn University's Harbert Engineering Center laboratory. The data are presented along with conclusions formed and trends recognized throughout the experimental study. The chapter also includes results documented from SCC mixtures that were produced at a concrete plant in

Scottsboro, Alabama. The results are compared to laboratory data collected from equivalent mixtures. The chapter concludes with a summary of the results presented from SCC and conventional-slump concrete testing.

5.2 FRESH PROPERTIES

The fresh properties that were tested include the slump flow and slump flow retention, modified J-Ring, setting time, and segregating column data. The tests were performed in accordance with the procedures described in Chapter 4.

5.2.1 SLUMP FLOW

The target slump flow value for SCC mixtures prior to the 50-minute transportation period was approximately 26 inches. The values were tested from the first batch of concrete and were recorded between 26 and 28 inches with Mix 3b having an apparently low value of 22.5 inches, see Figure 5.1. This apparent low value could have been adjusted by the use of additional HRWR admixture. However, these values were not used for quality control measures and strictly used as an indicator in order to obtain adequate indication of flow at time of placement.

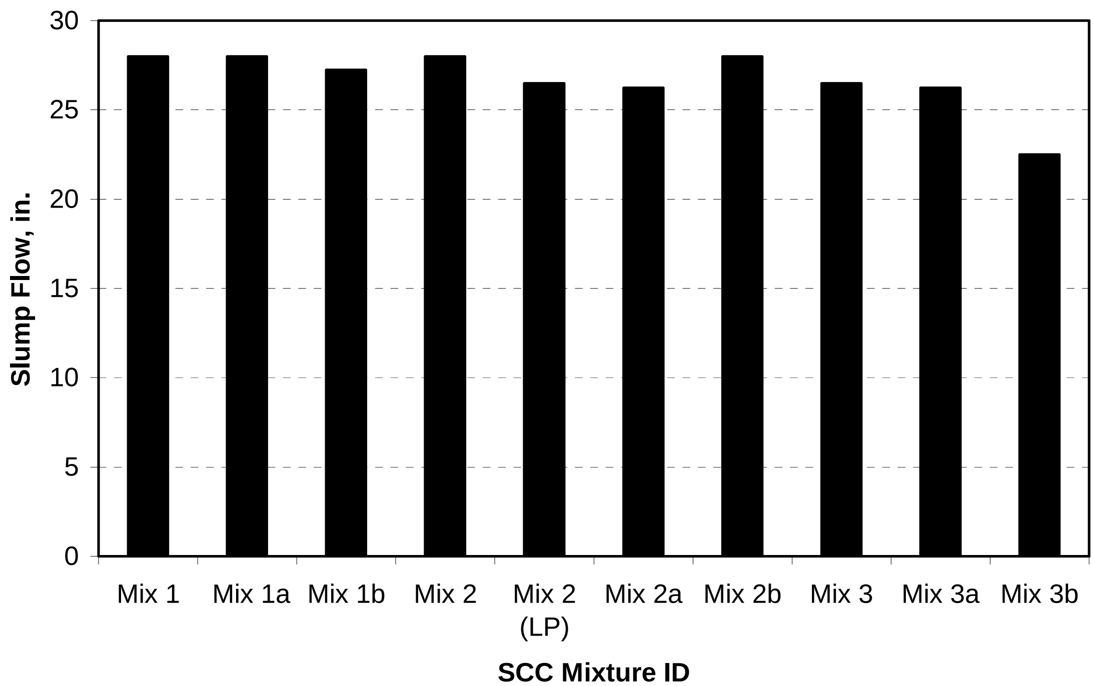


Figure 5.1: SCC slump flow values at plant (before 50-minute transportation period)

The slump flow values were measured from both batches of concrete after the 50-minute transportation period to represent the concrete at the time of placement. The values provided in Figure 5.2 were above the lower limit of 18 inches; however, the mixtures with a HRWR admixture dosage of 12 oz/cwt were higher than the proposed upper limit of 24 inches. Despite the higher slump flow values, the concrete remained stable, therefore allowing the mixture to be used for testing. As long as the concrete was stable and of good quality, the higher slump flow values will be beneficial for drilled shaft applications. The stability of the concrete will be discussed later in this section.

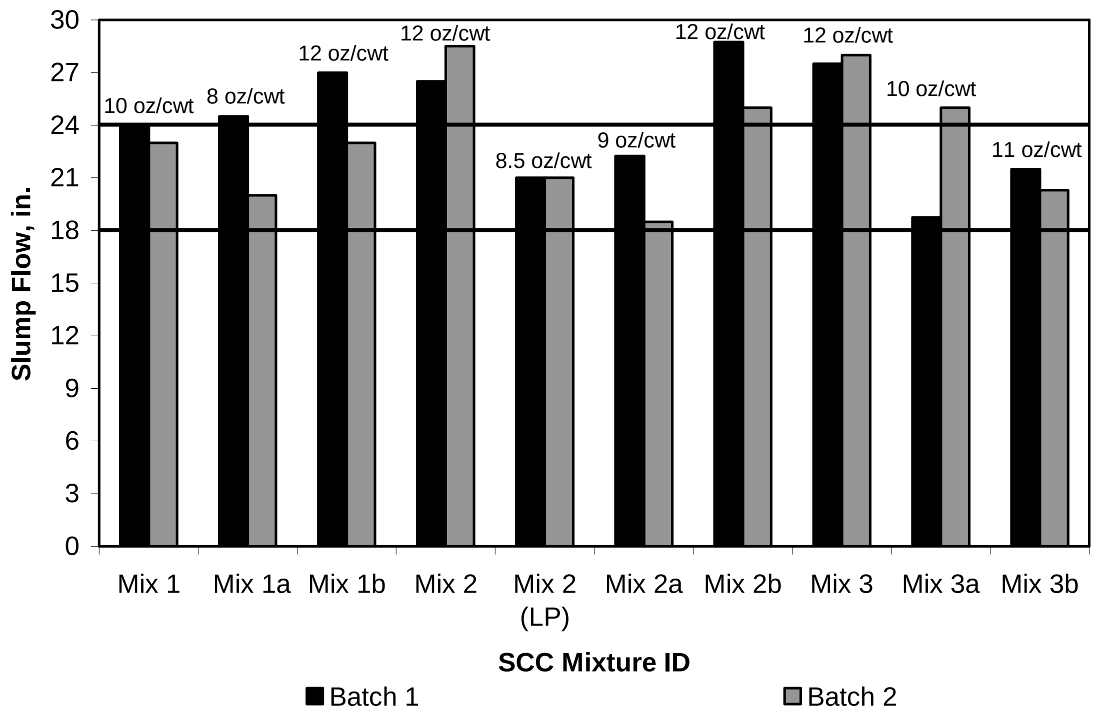


Figure 5.2: Slump flow and corresponding HRWR admixture dosage for SCC mixtures at placement

T_{50} times were recorded with each slump flow, and the values are plotted in Figure 5.3 and Figure 5.4 for the first and second batch, respectively. Slump flow values greater than 22 inches have low T_{50} times except for the SCC mixture containing the limestone powder. This may be a result of the powder absorbing excess water and ultimately increasing the viscosity of the mixture, which would increase the T_{50} time. It should also be noted that a T_{50} time was not recorded for Mix 3a from the first batch and Mix 2a from the second batch because the slump flow was less than 18 inches and the flow patty must reach a diameter of 20 inches for a T_{50} time to be recorded. Mix 3b had significantly higher T_{50} values for both batches of concrete. This high value could be attributed to the low w/cm of 0.38 and the high S/Agg of 0.55 creating a thicker more viscous paste and increasing the T_{50} time.

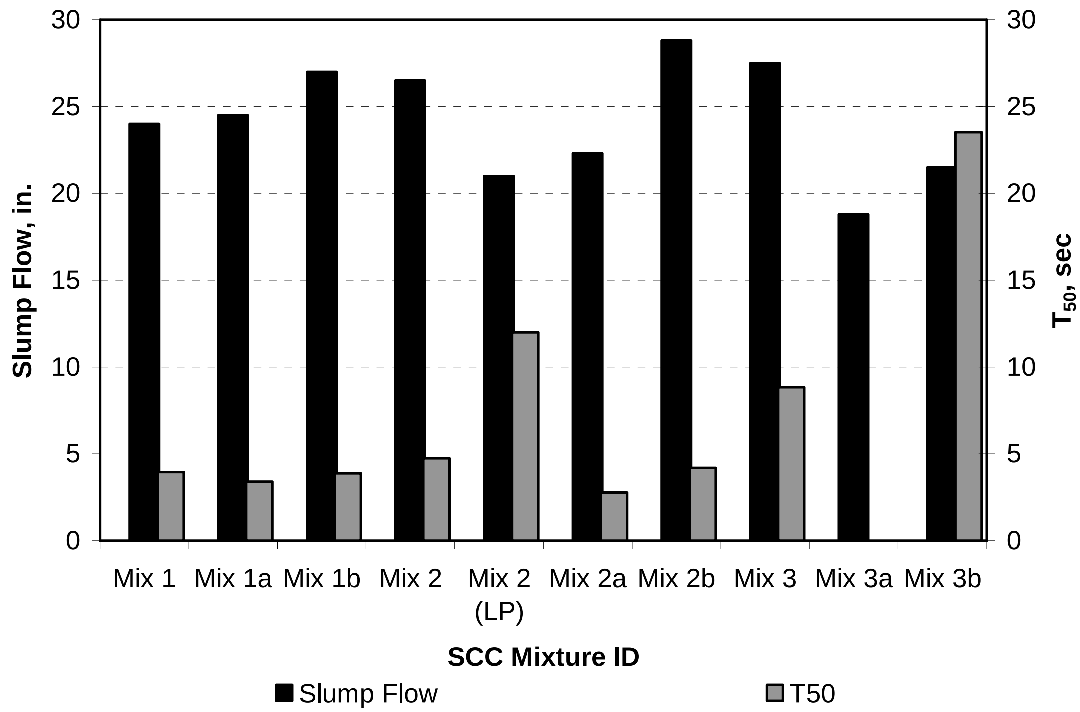


Figure 5.3: Slump flow and T_{50} values recorded at jobsite for first batch

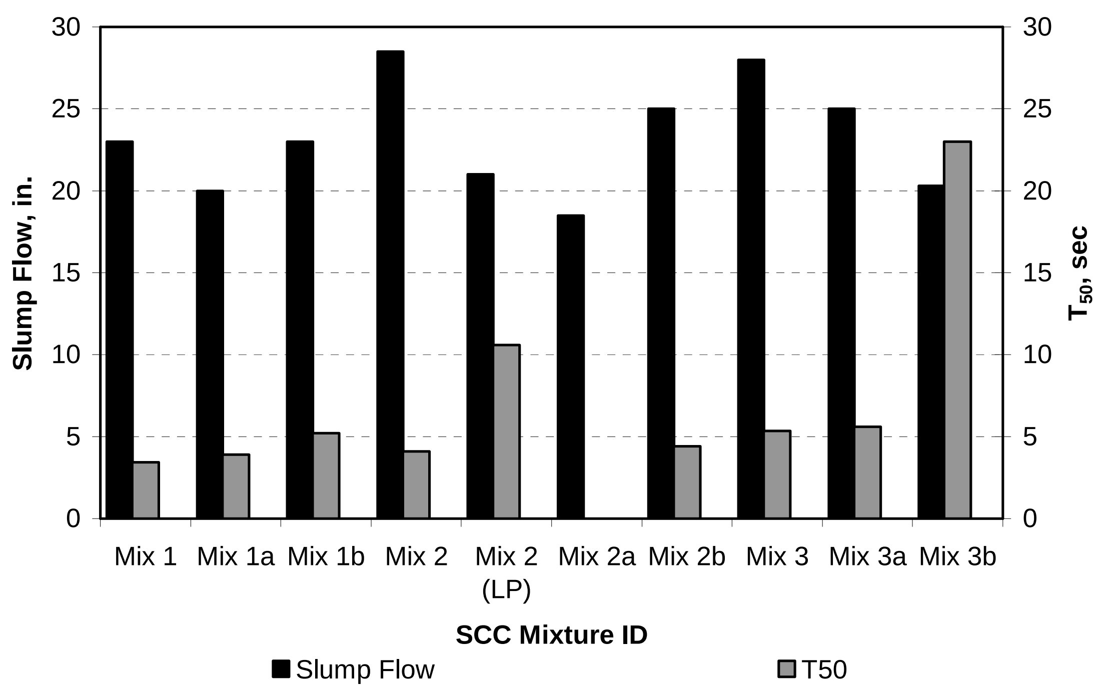


Figure 5.4: Slump flow and T_{50} values recorded at jobsite for second batch

The VSI was also determined for each slump flow performed in order to determine the stability of each mixture. The rating method is very subjective and is based on the visual observation of the technician. The SCC mixtures were stable with VSI ratings ranging from 0.0 to 1.5. These values were well within the requirements set forth at the beginning of the project.

The slump flow retention was also recorded for each SCC mixture to determine each mixture's ability to maintain workability. The slump flow retention was determined from the first batch of concrete. The slump flow retention data for each of the concrete mixtures is shown in Figure 5.5.

Each SCC mixture had better slump values after 6 hours than the conventional-slump concrete; in fact most of the SCC mixtures, except Mix 1a, Mix 2 (LP), and Mix 3b, exhibited greater slump values 6 hours after mixing than the Control at the time of placement. These values clearly fall within the recommendations of the FHWA Drilled Shaft Manual that states a slump of at least 4 inches must be maintained for 4 hours after mixing (O'Neill and Reese 1999). All SCC mixtures, excluding Mix 1a, averaged a slump of 8 inches 6 hours after placement. Mix 1a was slightly lower at a slump of 4.5 inches 6 hours after placement, but still well within the requirements of the FHWA Drilled Shaft Manual. It should also be noted that the SCC mixtures only used 2.5 oz/cwt of hydration-stabilizing admixture compared to the Control at 4.0 oz/cwt, given in Table 3-3.

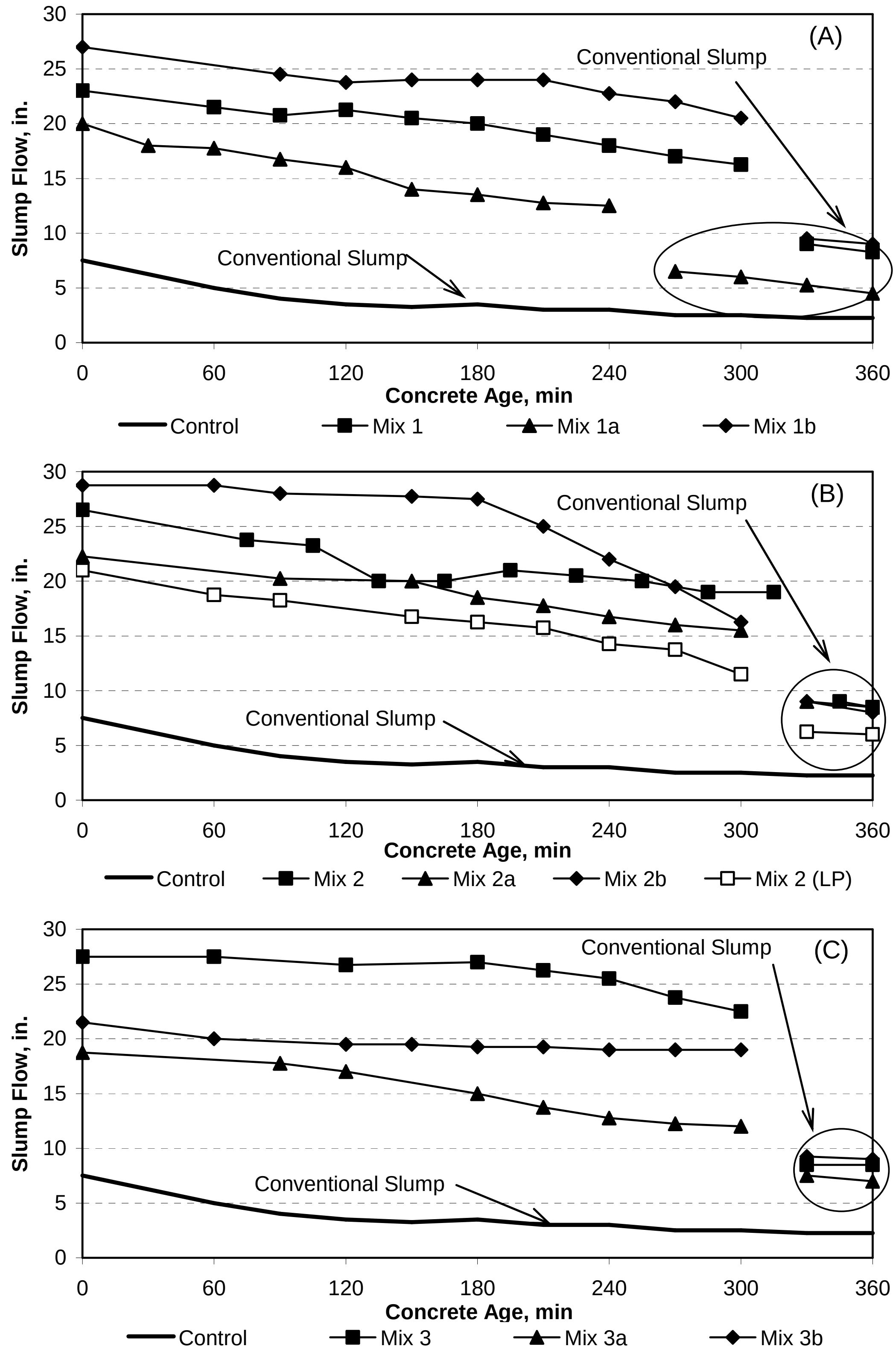


Figure 5.5: Slump flow retention of SCC mixtures with (A) w/cm = 0.42, (B) w/cm = 0.40, (C) w/cm = 0.38

5.2.2 TOTAL AIR CONTENT AND UNIT WEIGHT

The total air content and unit weight of the concrete was measured at the plant as well as the jobsite for quality control measures. The quality control limits for the total air content ranged from 2-6% once the concrete arrived to the jobsite. The values recorded for the total air content and the unit weight are given in Table 5-1. When tested at the jobsite, all concrete mixtures were within the requirements set forth at the beginning of the program. The total air content increased within the 50-minute transportation period for all SCC mixtures from the first batch of concrete. Originally all SCC mixtures were designed using an air-entraining admixture. Early in the laboratory mixing program it was discovered that the total air content significantly increased during the transportation period to the point at which the total air content of the concrete was no longer acceptable. It was believed that air was being entrapped in the concrete from the extra mixing occurring during the transportation period, thereby increasing the total air content. Because of this observation, the air-entraining admixture was removed from the design and more acceptable concrete resulted.

The unit weight of all concrete mixtures was determined and these values are also shown in Table 5-1. The average unit weight of SCC mixtures at the plant and jobsite were 147.4 pcf and 145.7 pcf for the first batch of concrete, respectively. This was a 1.0% decrease in unit weight for the SCC mixtures, which can be attributed to the increase in total air content. The second batch for the SCC mixtures had an average unit weight of 145.5 pcf at the jobsite, but the values were not recorded at the plant. However, the Control mixture experienced a 2.0% increase in unit weight from the plant to the jobsite. Similarly, the average unit weight of SCC at the plant was approximately

3% higher than the Control mixture; whereas, the unit weight for both batches of SCC was less than a percent lower than that of the Control mixture at the jobsite. The relatively low difference between the unit weight of the SCC and Control shows a consistency of the unit weight of SCC with that of conventional-slump concrete.

Table 5-1: Air content and unit weight of all concrete mixtures

Item		First Batch				Second Batch	
		Plant Values		Jobsite Values		Jobsite Values	
		Air Content (%)	Unit Weight (pcf)	Air Content (%)	Unit Weight (pcf)	Air Content (%)	Unit Weight (pcf)
Mixture ID	Control	5.50	143.4	3.50	146.4	3.00	145.6
	Mix 1	2.25	147.5	5.25	142.8	4.00	145.2
	Mix 1a	1.75	145.9	3.50	145.6	4.00	143.9
	Mix 1b	2.50	145.4	4.50	143.0	6.00	140.4
	Mix 2	2.00	146.4	3.25	145.9	2.00	147.1
	Mix 2 (LP)	1.25	147.8	2.00	147.4	2.00	147.5
	Mix 2a	2.75	146.9	6.00	142.2	6.00	142.6
	Mix 2b	1.50	147.2	2.00	146.6	4.00	143.8
	Mix 3	1.00	150.5	1.75	150.8	2.00	148.0
	Mix 3a	1.00	148.3	3.50	145.2	2.00	148.9
	Mix 3b	2.50	148.0	2.50	147.2	2.50	147.0

5.2.3 MODIFIED J-RING TEST

The Modified J-Ring test was performed at the end of the transportation period for each SCC mixture. The difference between the slump flow and the Modified J-Ring flow provided an indicator of the passing ability of the concrete, and these results are shown in Figure 5.6. Based on the difference between the slump flow and the J-Ring flow, ASTM C 1621 (2005) assigns a “blocking assessment” to the SCC. A difference in flow greater than 2.0 inches is considered “noticeable to extreme blocking” as shown in Table 2-1 (ASTM C 1621 2005). Most of the SCC mixtures for the second batch of concrete exhibited a difference in flow of 2.50 in. or less, the exceptions being Mix 2 (LP) and Mix 3b that had blocking assessments of 3.50 in. and 3.55 in., respectively. These two mixtures had high viscosities which were indicated by the high T_{50} times of 10.6 and 23.0 seconds, respectively. However, the first batch of concrete exhibit much larger differences between the slump flow and the Modified J-Ring flow, but it is not apparent if these mixtures will exhibit acceptable passing ability under actual field conditions.

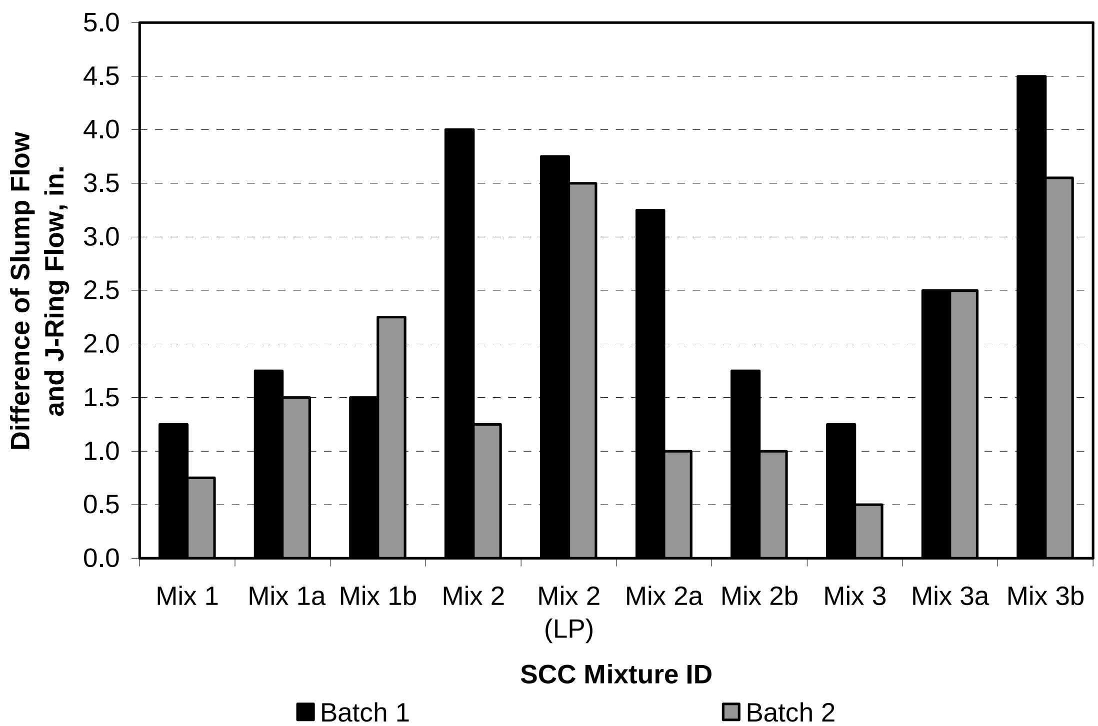


Figure 5.6: Difference in slump flow and Modified J-Ring values for SCC mixtures

5.2.4 SETTING TIME

The concrete was specified to not reach final setting before 18 hours after placement. The setting time was determined using the concrete produced from the first batch. In ASTM C 403 (1999) initial and final setting corresponds to a penetration resistance of 500 and 4,000 psi, respectively. This requirement ensures the concrete remain in a fresh state until the drilled shaft is completed. The results of the setting test are given in Figure 5.7. Of the mixtures shown in Figure 5.7, final setting times were recorded beyond 18 hours after mixing except for Mix 2 (LP), which reached final set around 14 hours. The use of the limestone powder significantly decreased the setting time by approximately 40%. This early setting time is similar to the results of Khayat et al. (2006) that found the addition of limestone powder accelerated the hydration of the cement. The same dosage of hydration-stabilizing admixture, 2.5 oz/cwt, was used for both Mix 2 and Mix 2 (LP), Table 3-3; therefore further, testing should be performed in order to determine the correct dosage to provide an adequate setting time.

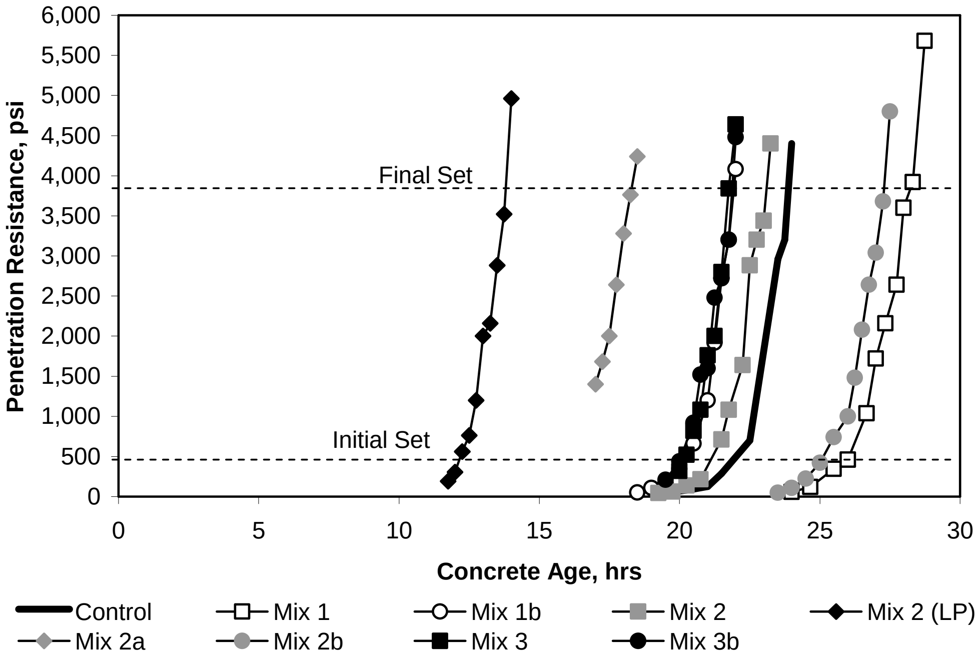


Figure 5.7: Setting times for all concrete mixtures

Two SCC mixtures, Mix 1a and Mix 3a, experienced early setting and the data were not recorded. Based on previous setting time results, the author returned to perform the first penetration test for these three mixtures at an age of approximately 15 hrs, but at this stage these samples had already past final setting. However, the concrete temperature data was also recorded using semi-adiabatic calorimetry in an effort to estimate setting times using the “Derivative” method discussed in Section 4.4.7. The results from the semi-adiabatic calorimeter are presented along with the results from the penetration test in Table 5-2. The first derivative of the semi-adiabatic temperature profile, used to estimate the final setting time of the concrete, gave an obvious maximum value; however, the maximum value of the second derivative, used to estimate the initial setting time, was not as distinct. The results from the semi-adiabatic calorimeter did produce relatively close values to those recorded from the penetration test, with the exception of Mix 3. Also the data shows that Mix 1a and Mix 3a experienced early setting times of 16.0 and 15.7 hours, respectively.

Mix 2a reached final set at approximately 18.5 hrs, which was early compared to the other mixtures, but still above the target setting time of 18 hrs. The three mixtures that experienced early setting times each had S/Agg of 0.45 compared to the remaining mixtures which had S/Agg of 0.50 and 0.55. Likewise, the Control had a relatively low S/Agg of 0.36 which required a higher amount of hydration-stabilizing admixture compared to that of the SCC mixtures. Due to the early setting times of Mix 1a, Mix 2a, and Mix 3a, the dosage of the retarding admixture will also need to be increased. This leads to the conclusion that as the S/Agg decreases, the apparent setting time of the concrete will decrease, which may be a result of a lower sand content in the mortar sieved from the concrete. Further testing should be performed to determine the proper dosage for these three SCC mixtures in order for the concrete to remain fresh for at least a period of 18 hours.

Table 5-2: Initial and final setting times from the penetration test and semi-adiabatic calorimeter

Item	Standard Setting Times		Calorimeter Setting Times		Difference	
	Initial (hr.)	Final (hr.)	Initial (hr.)	Final (hr.)	Initial (hr.)	Final (hr.)
Control	22.0	23.9	20.0	23.8	2.0	0.1
Mix 1	26.0	28.2	*	*		
Mix 1a	*	*	14.0	16.0		
Mix 1b	20.2	21.9	20.5	20.5	-0.3	1.4
Mix 2	21.3	23.0	19.8	22.3	1.6	0.8
Mix 2a	*	18.5	16.3	16.8		1.8
Mix 2b	25.3	27.2	26.3	26.5	-1.0	0.7
Mix 3	20.2	21.8	16.3	25.3	3.9	-3.5
Mix 3a	*	*	15.0	15.7		
Mix 3b	20.1	21.8	22.3	23.5	-2.2	-1.7
Mix 2 (LP)	12.3	13.7	13.3	18.0	-1.0	-4.3

* Data not recorded

5.2.5 SEGREGATION COLUMN

The static segregation of the concrete from the first batch produced was determined using the segregation column test. As previously mentioned in Chapter 4, the concrete remained in the column for a period of 1 hour to better represent drilled shaft conditions. The percentage of static segregation was compared with the corresponding S/Agg and w/cm shown in Table 5-3. It was previously stated that all SCC mixtures had relatively low VSI rating, which indicated good dynamic stability.

Table 5-3: Static segregation with corresponding S/Agg and w/cm for concrete mixtures

Item	Value		
	S/Agg	w/cm	Static Segregation, %
Control	0.36	0.40	4
Mix 1a	0.45	0.42	3
Mix 1	0.50	0.42	6
Mix 1b	0.55	0.42	0
Mix 2a	0.45	0.40	3
Mix 2	0.50	0.40	6
Mix 2 (LP)	0.50	0.40	7
Mix 2b	0.55	0.40	3
Mix 3a	0.45	0.38	10
Mix 3	0.50	0.38	8
Mix 3b	0.55	0.38	0

All mixtures showed a low percentage of static segregation; the values ranged from 0.0 to 10.3% with an average of 4.7% static segregation for the SCC mixtures. These values were considered acceptable by the standards determined by ACI Committee 237 (2007) which stated that the percentage of segregation of SCC should be less than 10%. The mixture that produced the highest percentage of segregation was Mix 3a at 10.3%, a value slightly above the general requirements of ACI Committee 237 (2007). The higher values could be a result of the mixture's low S/Agg of 0.45, which indicates it has the most coarse aggregate. However, the fresh properties indicated the mixture was quite viscous and stable from the low slump flow, T_{50}, and VSI values, suggesting that error may have occurred during separating, sieving, or washing of the aggregates. Nonetheless, the mixtures with a S/Agg of 0.55 showed lower potential for segregation. This may be attributed to the decreased coarse aggregate content which improves the mixture's stability. Mix 3b revealed no potential for segregation indicating a highly viscous mixture, which corresponds to the high T_{50} values reported during the slump flow test.

5.3 HARDENED CONCRETE PROPERTIES

The hardened properties that were tested include the compressive strength, modulus of elasticity, drying shrinkage, and permeability of the concrete. The tests were performed on all concrete mixtures produced from the second batch of concrete and tested in accordance with the procedures described in Chapter 4.

5.3.1 COMPRESSIVE STRENGTH

The compressive strength results for the conventional-slump concrete and the SCC are presented in Figure 5.8. As discussed in Chapter 3, the average compressive strength was to be at least 5,200 psi at an age of 28 days. All mixtures were well above the required strength; in fact most mixtures had strengths greater than 6,000 psi at 28 days. The Control mixture had a w/cm = 0.40, which was identical to Mix 2, Mix 2a, and Mix 2b of the SCC mixtures. Figure 5.8b illustrates the similarities between the compressive strength of the mixtures with w/cm = 0.40. Mix 2 (LP) exhibited an average decrease of about 7.0% in compressive strength compared to Mix 2. This reduction in strength was a result of a 10% replacement of the cementitious material with a limestone powder, thus creating Mix 2 (LP). As shown in Table 3-3, the water-to-powder ratio remains constant for both Mix 2 and Mix 2 (LP), but due to the cementitious replacement by the limestone powder, a non-cementitious material, the w/cm increased to 0.44. The reduction of cementitious material, which increased the w/cm, resulted in a decrease in strength.

However, the compressive strength of Mix 2 (LP) was still approximately 1,000 psi greater than required.

Neville (1996) stated that the most influential factor of a concrete's compressive strength is the w/cm; the two are inversely proportional to one another. This trend was evident in Figure 5.8 as the w/cm of the SCC mixtures decrease from Figure 5.8a to Figure 5.8c the compressive strength of the concrete increases. On average the data showed about an 11.0% increase in strength from w/cm = 0.42 to w/cm = 0.40 and a 16.0% increase from w/cm = 0.40 to w/cm = 0.38. There were no significant differences in the strength of the concrete as S/Agg varied while the w/cm remained constant. The largest difference, approximately 20.5%, occurred between Mix 3 and Mix 3b at a maturity of 7 days; however, this difference between the mixtures decreased to 10.4% and 2.3% at ages of 28 and 56 days, respectively. The remaining SCC mixtures experienced a difference in strength at varying S/Agg of less than 10%. This was consistent with Bailey (2005), who stated that the strength of SCC mixtures containing fly ash were not influenced by changes in S/Agg.

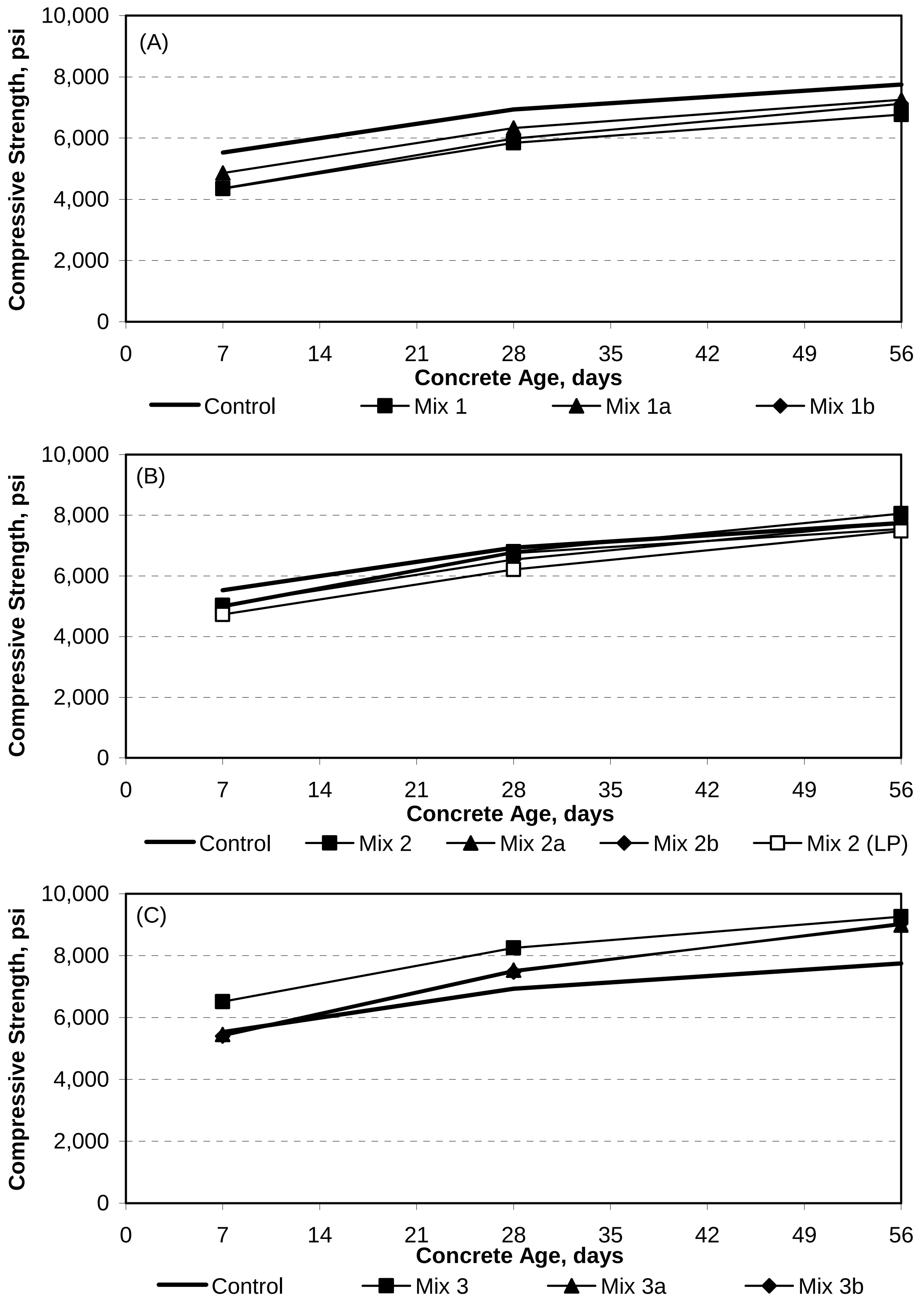


Figure 5.8: Compressive strength of SCC mixtures with (A) w/p = 0.42, (B) w/p = 0.40, (C) w/p = 0.38

5.3.2 MODULUS OF ELASTICITY

The modulus of elasticity of the concrete was calculated from the same cylinders used during compressive strength testing. The data are presented in Figure 5.9 according to w/cm of the SCC mixtures. The modulus of elasticity for the mixtures increases with respect to age, similar to that of the compressive strength. This should be expected since the stiffness of the concrete is a function of the compressive strength. However, stronger concrete does not necessarily imply a stiffer concrete. For instance the Control mixture had a higher modulus of elasticity compared to the SCC mixtures at all ages, whereas the Control mixture was not the strongest concrete. The difference is clearly shown when comparing the compressive strengths and modulus of elasticity of the Control mixture to Mix 3, Mix 3a, and Mix 3b from Figure 5.8c and Figure 5.9c, respectively.

The stiffness of the concrete did not show much of a trend with varying w/cm at the early ages. As the concrete matured the stiffness increased as the w/cm decreased. At a maturity of 56 days the concrete stiffness increased by an average of 2% from w/cm = 0.42 to w/cm = 0.40, but when the w/cm was lowered from 0.40 to 0.38 the stiffness increased by an average of 11%. Furthermore, the addition of the limestone powder decreased the modulus of elasticity by an average of 7%. This loss of stiffness would be expected due to the decrease in cementitious material to be hydrated. The data also showed that the modulus of elasticity was not significantly affected by a variation of S/Agg. These results match the trends found by Bailey (2005).

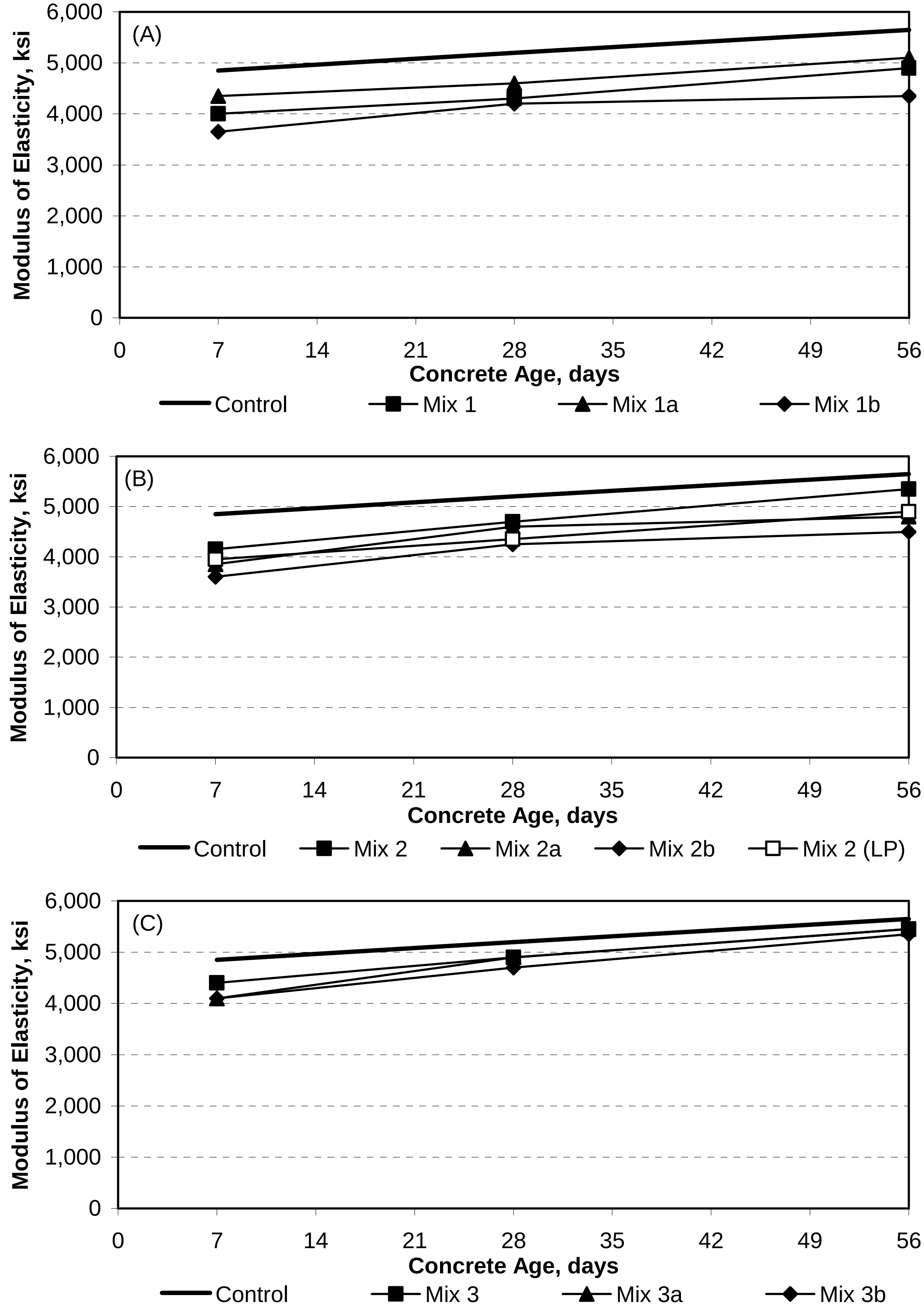


Figure 5.9: Modulus of elasticity of SCC mixtures with (A) w/p = 0.42, (B) w/p = 0.40, (C) w/p = 0.38

The modulus of elasticity at different ages was also estimated using ACI 318 (2005) in order to compare its applicability to SCC. Equation 2.4 from Chapter 2 was used to estimate the concrete's modulus of elasticity based on the unit weight and compressive strength of the concrete. The results of the comparison are given in Figure 5.10. The results show that the equation provided by ACI 318 (2005) accurately predicts the modulus of elasticity of the SCC mixtures developed in this research and therefore is sufficient to be used for design.

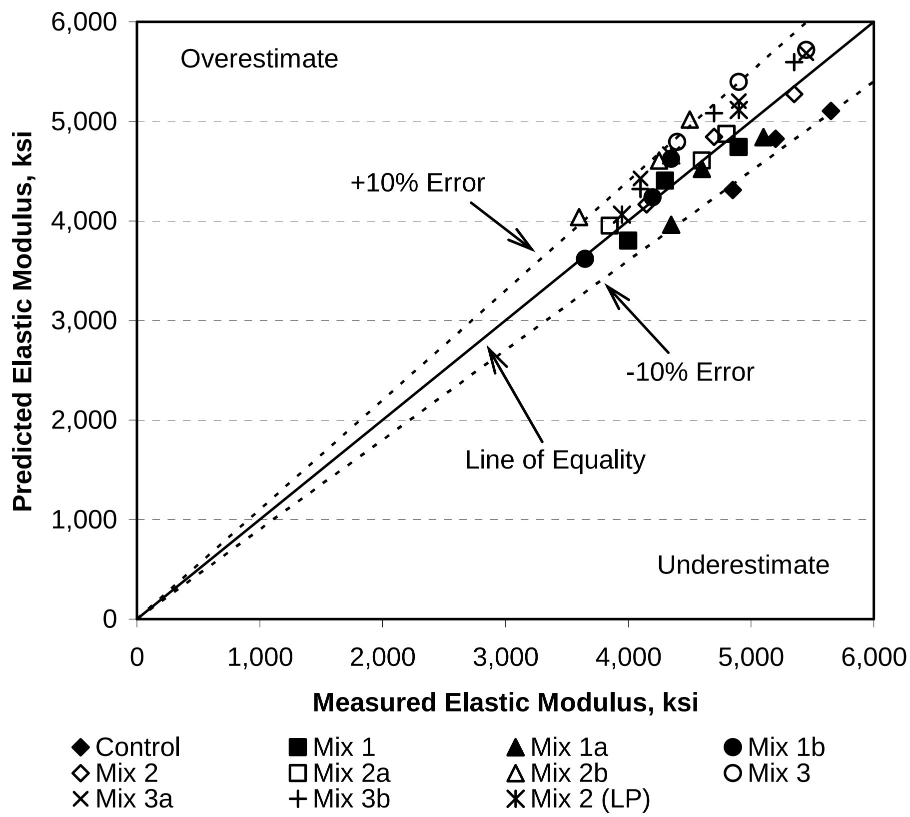


Figure 5.10: Predicted versus measured modulus of elasticity according to ACI 318 (2005)

5.3.3 DRYING SHRINKAGE

The drying shrinkage was measured for each concrete specimen and the results are given in Figure 5.11. The data clearly show the amount of drying shrinkage is decreased as the w/cm is lowered. As the w/cm decreased from 0.42 to 0.38, the 180-day shrinkage dropped about 30% from an average of 810 to 560 microstrains. A variation of S/Agg did not show any significant trends for a constant w/cm. However, the shrinkage was slightly reduced for Mix 2 by replacing 10% of the cementitious material with a limestone powder. The 91-day shrinkage was reduced approximately 17% by using the powder replacement. This reduction in shrinkage is not intuitive because by replacing a portion of the cementitious material with a non-cementitious powder the w/cm was effectively increased. The studies by Khayat et al. (2006) and Omya (2007) did not look at the effects of limestone powder on drying shrinkage for comparison. It should also be noted that all SCC mixtures, with the exception of Mix 1a, exhibited less drying shrinkage compared to the Control mixture. This result is also counterintuitive due to the higher paste volume provided by the SCC mixtures, which is where shrinkage occurs (Mindess 2003). However, the SCC mixtures contained a larger dosage of Class F fly ash, and this pozzolan is effective in reducing the porosity of the concrete over time (Manmohan and Mehta 1981). This reduction in porosity may explain the reduced drying shrinkage measured for the SCC mixtures.

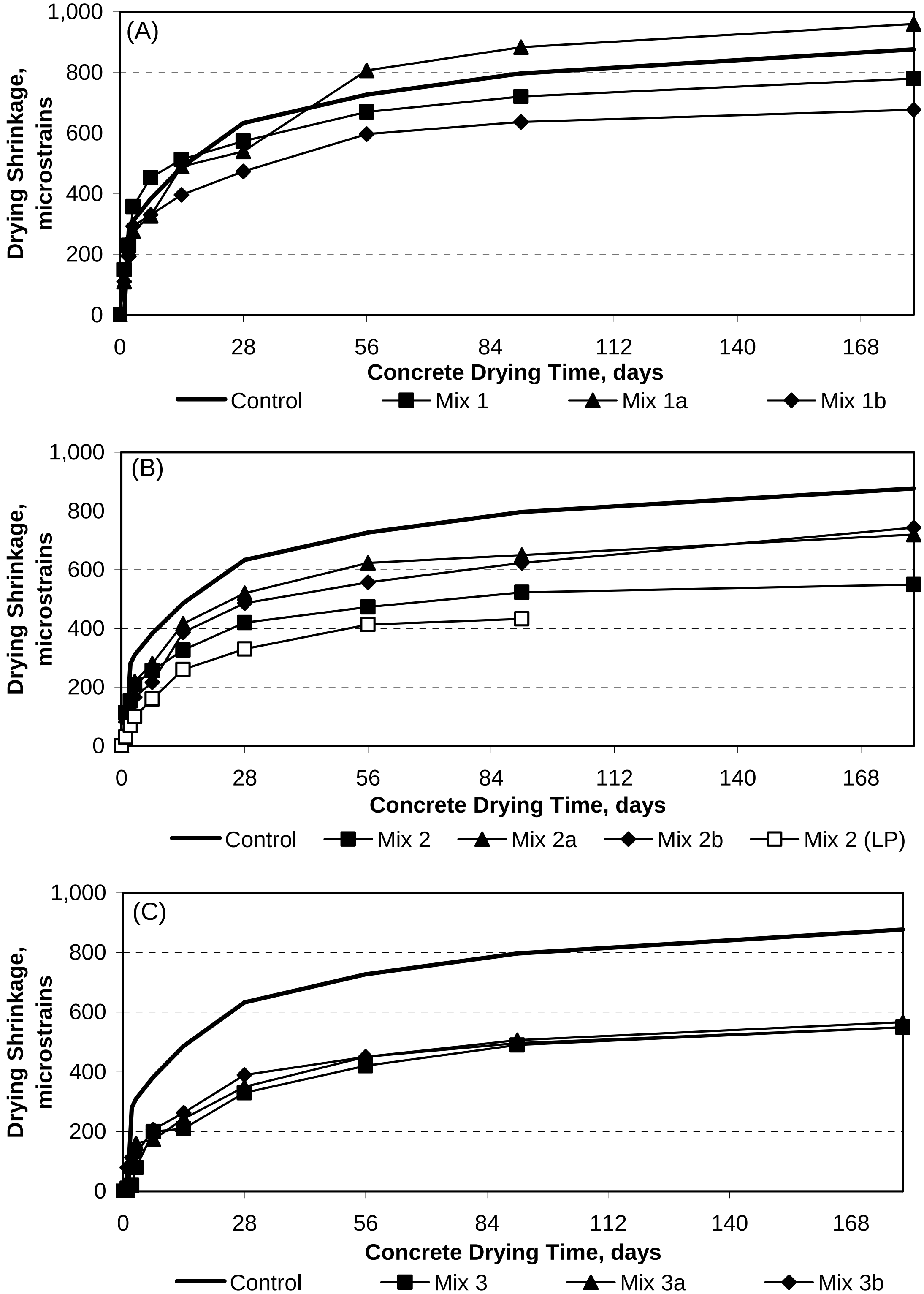


Figure 5.11: Drying shrinkage of SCC mixtures with (A) w/p = 0.42, (B) w/p = 0.40, (C) w/p = 0.38

5.3.4 PERMEABILITY

The permeability of concrete was estimated by measuring its resistance to chloride ion penetration. This test was performed in accordance with the procedure listed in Chapter 4, and the results are given in Figure 5.12. The two lowest results were recorded for Mix 1 and Mix 1a at 450 and 490 coulombs, respectively. The remaining results ranged from 640 to 850 coulombs with an average of 770 and a standard deviation of 90 coulombs. It should be noted that there was a 44% increase in permeability between Mix 2 and Mix 2 (LP). According to ASTM C 1202 (2005) two concrete samples obtained from the same batch may vary up to 42% from one another, which provides a means to compare differences between results. However, all concrete samples recorded results less than 1,000 coulombs, which indicates a very low permeability (ASTM C 1202 2005). According to the results in Figure 5.12, all mixtures should provide sound, durable concrete for design.

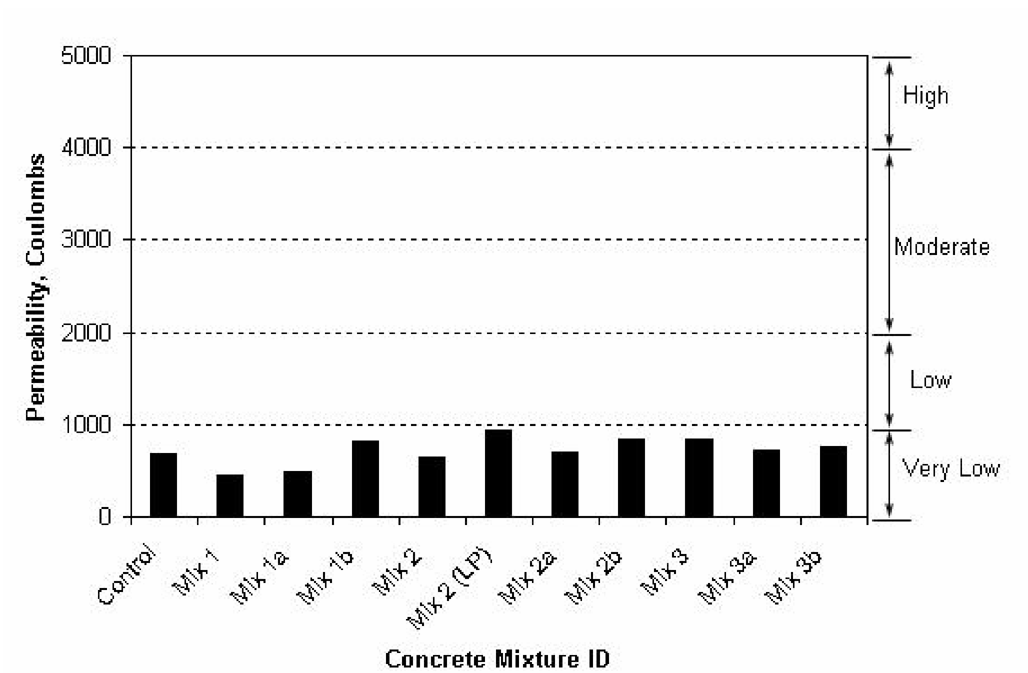


Figure 5.12: 91-day permeability results

5.4 COMPRESSIVE STRENGTH OF MORTAR CUBES

As mentioned in Chapter 4, 2 x 2 x 2 in. colored mortar cubes were made and the compressive strength was determined at 28 days. The compressive strength was determined to assure that the cubes are strong enough to withstand any abuse that may occur during the placement of the concrete. To make sure the cubes are strong enough, they were designed to be much stronger than the concrete to be placed. Table 5-4 gives the results of the compressive test and shows that the cubes should be strong enough to not be damaged during placement in the shafts.

Table 5-4: 28-day compressive strength of colored mortar cubes

Cube Color	28-day Compressive Strength, psi
Red	14,720
Blue	7,950
Yellow	10,930
Green	11,880
Orange	13,060

5.5 COMPARISON OF LABORATORY AND FIELD MIXTURES

Of the ten SCC mixtures developed in the laboratory, two are to be compared to the conventional-slump drilled shaft concrete in a field study that will be discussed in the following chapter. Mix 2 and the Mix 2 (LP) were the two SCC mixtures chosen. Mix 2 was chosen because the w/p was identical to the Control mixture, see Table 3-3. The SCC mixture containing the limestone powder, Mix 2 (LP), was chosen to compare its effects on bleeding under full-scale application to its counterpart, Mix 2.

To prepare for the placement of the concrete in actual drilled shafts in the field study, the SCC mixtures were first prepared and tested at a concrete plant located close to the proposed field site. A 3-yd^3 concrete batch was prepared at a ready-mix concrete plant in order to ensure the dosage of the chemical admixtures resulted in concrete similar to that which was created in the laboratory. The proportions of a concrete mixture often do not transfer from small production, such as in a laboratory, to larger production, such as field work, and adjustments may be needed. This process helps to alleviate any problems associated with the concrete during full-scale testing.

The coarse and fine aggregates were first loaded from the stock pile into a bin shown in Figure 5.13. The aggregates were then loaded into the truck from the bin using a conveyor belt, and the cementitious materials were loaded from overhead silos as shown in Figure 5.14. Initially the truck was loaded with cement, fly ash, hydration-stabilizing admixture, water, and the coarse and fine aggregate. The truck was allowed to mix for a few minutes as it pulled away from the loading dock to a platform used as a wash station. The high-range water-reducing (HRWR) admixture required for an SCC mixture was not initially added with the raw materials because the plant did not have access to the admixture for automated dispensing. However, this allowed for a concrete sample to be obtained from the truck and tested before introducing the HRWR admixture. After the concrete was tested, the HRWR admixture was poured into the truck using the wash station platform shown in Figure 5.15. Once the HRWR admixture was added, the truck mixed the material for five minutes before a sample was taken for testing. The batching process for Mix 2 (LP) was identical except that the limestone powder was introduced into the truck along with the HRWR admixture, shown in Figure 5.16. After initial testing was done, the truck continued to mix for 50 minutes at a mixing speed typically used during transport, approximately 5-7 rpm. At the conclusion of the transportation period, the concrete was once again discharged and sampled to test the fresh and hardened properties.

Figure 5.13: Loading aggregate from stockpile

Figure 5.14: Loading of concrete truck with raw materials

Figure 5.15: Concrete truck at wash station platform

Figure 5.16: Addition of HRWR admixture and limestone powder into concrete truck

The fresh properties from the field and laboratory tests are shown in Table 5-5 for comparison. The HRWR admixture dosage for Mix 2 in the field was initially 11 oz/cwt, which resulted in a slump flow of 17 inches. The slump flow was unsatisfactory, therefore an additional 2 oz/cwt was immediately added and mixed for 5 minutes resulting in a slump flow of 23.3 inches. It should be noted that the air content for the mixtures are comparable for the laboratory and field tests. The mixing speed during transportation was different between the laboratory mixer and the concrete truck. Typical mixing speeds for a concrete truck during transportation were approximately 6 rpm, but the lowest speed for the laboratory mixer was 18 rpm. Therefore, the laboratory mixing drum was raised to approximately 5˚ from vertical in order to reduce agitation of the concrete and simulate lower mixing speeds, as discussed in Section 4.2. Even though the laboratory mixing process was altered there was still concern of entrapping air due to constant mixing. However, this was not a problem, and the air content was acceptable. The difference in mixing procedures may have also resulted in the lower slump flow values recorded in the field compared to the laboratory. The continuous mixing of the concrete truck may have caused more agitation compared to the laboratory procedure which incorporated periods of rest. However, this cannot be officially concluded without more information to assess the amount of agitation provided from each mixing procedure. The air temperatures for the field and laboratory are shown in Table 5-5. The higher temperatures during the field study of Mix 2 (LP) can have adverse effects on the concrete, such as lower slump flow values and earlier setting times.

Table 5-5: Fresh properties from laboratory and field testing

Item		SCC Mixtures: Mix 2 (Lab)	Mix 2 (Field)	Mix 2 (LP) (Lab)	Mix 2 (LP) (Field)
Avg. air temperature, ˚F		75	46	75	78
HRWRA dosage, oz/cwt		12	12	8.5	8.5
Before HRWRA	Wet slump, in.	0.50	1.75	0.50	3.25
	Air content, %	2.5	2.2	2.0	2.0
Plant	Slump flow, in.	28.0	23.3	26.5	24.0
	VSI	1.0	0.5	1.0	0.5
	T_{50}, sec	4.62	3.78	6.94	1.50
	Air content, %	2.0	2.7	1.3	1.2
Jobsite	Slump flow, in.	26.5	20.0	21.0	20.5
	VSI	1.0	0.5	0.0	0.5
	T_{50}, sec	4.75	7.31	12.00	2.50
	Air content, %	3.3	4.0	2.0	1.5
	Unit weight, pcf	145.9	145.6	147.4	151.2
	Modified J-Ring, in.	22.5	18.0	17.3	19.0

Note: HRWRA = high range water reducing admixture

The slump flow retention was also tested at the batch plant and compared to the laboratory results, see Figure 5.17. Mix 2 followed a similar trend in slump flow loss between the laboratory and field mixture, which resulted in an 8.5 in. and 7.0 in. slump after 6-hours for the respective mixtures. Despite the fact that Mix 2 produced in the field began the 6 hour period at a much lower slump flow, the mixture only lost 2.75 inches of slump flow in 4 hours. This was not the same case for the field mixture containing the limestone powder. The slump flow loss for this mixture was 6 inches in the 3 hours after placement, compared to the 4.75 inches lost in the laboratory. The concrete continued to stiffen, and a 2-inch conventional slump was measured 4.5 hours from the time of placement. These values for Mix 2 (LP) were unacceptable and may be attributed to the high temperature experienced throughout the day. This mixture was prepared midday in the month of May, at which point the temperatures reached into the mid 80's. These are higher temperatures than compared to the constant temperature of 75˚ F in the laboratory; whereas, Mix 2 was tested at the batch plant in the middle of February when the temperatures were much lower. If produced again in temperatures above 80˚ F, it is recommended that the dosage of the hydration-stabilizing admixture be increased to compensate for the higher temperatures.

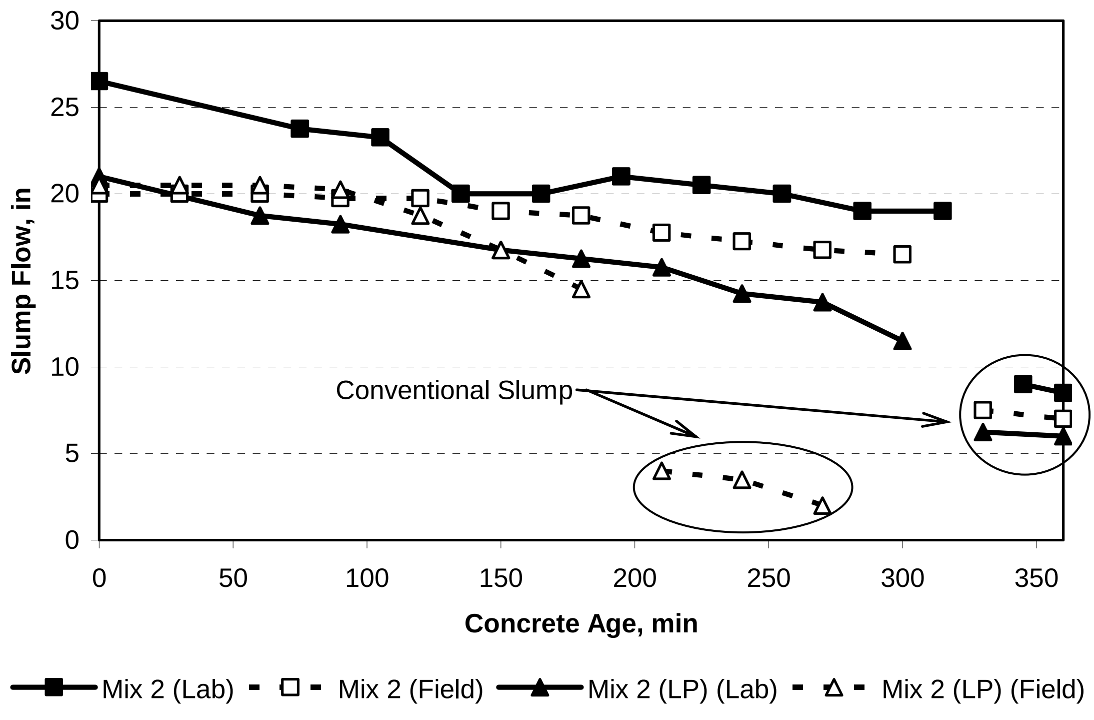


Figure 5.17: Slump retention for laboratory and field mixtures

The segregation column was also taken to the concrete batch plant to test each mixture's resistance to segregation. The laboratory and field results are presented in Table 5-6. There were no signs of segregation for the field mixtures. The mixtures appeared to have a higher viscosity compared to the concrete produced in the laboratory, which might look apparent when comparing the VSI results in Table 5-5. However, the lower T_{50} results suggest a loss in viscosity between the laboratory and field mixtures.

Table 5-6: Static segregation of laboratory and field mixtures

Item	SCC Mixtures			
	Mix 2 (Lab)	Mix 2 (Field)	Mix 2 (LP) (Lab)	Mix 2 (LP) (Field)
Static Segregation, %	6	0	7	0

Lastly, the compressive strength of the concrete mixtures was tested, and the results are given in Figure 5.18. The field batch of Mix 2 clearly showed higher strengths, an increase of approximately 11%, compared to the results from the laboratory. However, Mix 2 (LP) showed significantly lower results compared to the laboratory, with an average decrease of 27.6%. The mixture was below the required strength of 5,200 psi at a concrete age of 28 days, which was unacceptable. The increased water slump and low T_{50} values of this mixture produced in the field as compared to when it was produced in the laboratory both suggest increased water content. The rapid loss in filling ability also suggests an increase in water content because as the excess water evaporates the concrete will loose its filling ability. An increase in water content will lead to an increased w/cm, which would explain why this mixture's field trial produced low strengths. It is thus plausible that this mixture was batched with too high a water content. Due to the unsatisfactory results returned from the slump flow retention and the compressive strength tests, further large-scale testing should be performed in order to understand and correct the problems encountered with the field production of Mix 2 (LP).

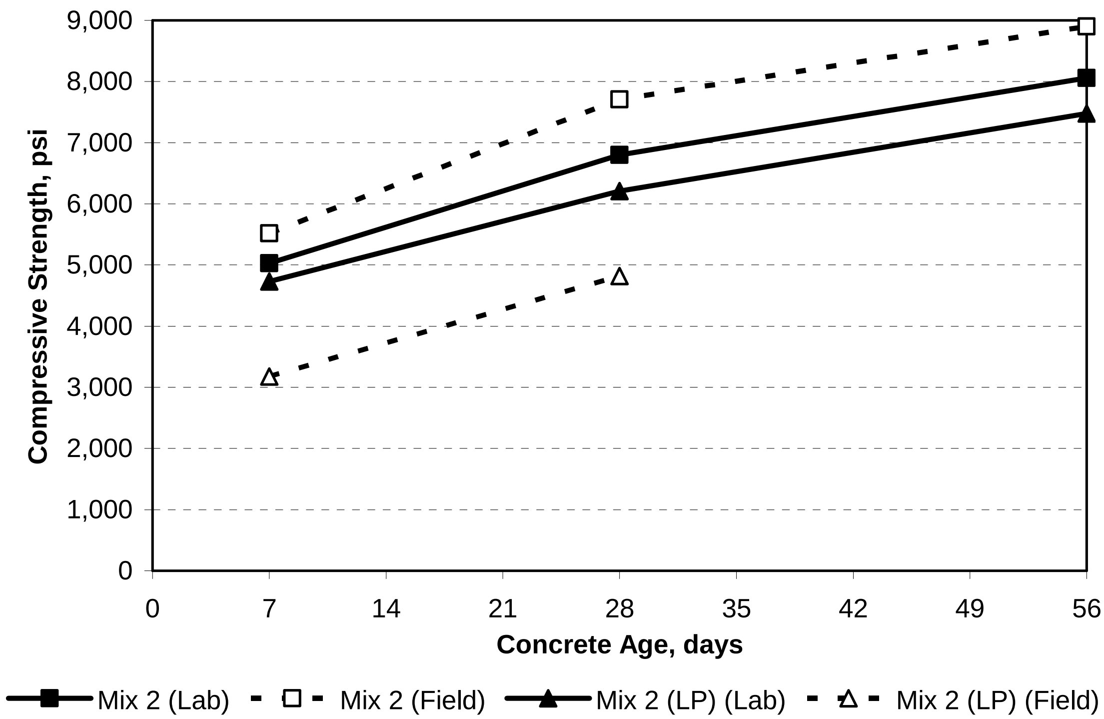


Figure 5.18: Compressive strength comparison of laboratory and field batches

5.6 SUMMARY OF RESULTS

Based on the laboratory work performed, the following results were found:

- The average slump flow for the SCC mixtures at the plant was 26.5 inches, and this value can be used as a reference, but not for quality control measures.
- All slump flow values recorded were above the lower limit of 18 inches, but most mixtures with HRWR admixture dosage of 12 oz/cwt yielded slump flows greater than 24 inches at the time of placement.

- The use of the limestone powder significantly increased the viscosity, which may be a result of the powder absorbing excess water.
- Due to the low slump flow of Mix 3a for the first batch of concrete and Mix 2a for the second batch, a T_{50} time was not recorded which may be attributed to the lower w/cm and the higher S/Agg creating a thicker, dryer mortar.
- All SCC mixtures appeared to be stable with VSI ratings ranging from 0.0 to 1.0.
- Except for Mix 1a, Mix 2 (LP), and Mix 3b, the SCC mixtures had a higher slump after 6 hours from the time of placement compared to the Control mixture at the time of placement. All SCC mixtures were within the FHWA Drilled Shaft Manual requirement by maintaining a slump greater than 4 inches after 4 hours from the time of placement.
- The total air content was within the requirement of 4 ± 2% for all mixtures. No air-entraining admixtures were used in the SCC mixtures in order to minimize the increase in total air content due to agitation over the transportation period.
- The unit weight of the SCC mixtures was consistent with the unit weight of the Control mixture.
- SCC mixtures had a difference between the slump flow and Modified J-Ring flow of 2.25 inches or less for the second batch of concrete produced, except for Mix 2 (LP) and Mix 3b which experienced extreme blocking due to their high viscosity. The first batch of concrete showed much larger differences, but it is not apparent that these mixtures will not provide adequate passing ability in actual field conditions.

- Most mixtures reached final set after 18 hours, except for Mix 2 (LP), which had a final setting time of 14 hours. Additional hydration-stabilizing admixture will be required to extend the setting time of this mixture.
- Setting time significantly decreased for sand-to-aggregate ratios below 0.50, which caused the SCC mixtures with a sand-to-aggregate ratio of 0.45 to experience earlier setting times.
- The SCC mixtures had an average static segregation of 5%, which was below the acceptable value of 10%. These mixtures should thus remain stable after placement in a deep foundation. The mixtures with a sand-to-aggregate ratio of 0.55 showed a lower potential for segregation due to a thicker, more stable mortar.
- All mixtures recorded compressive strengths greater than 5,200 psi at 28 days; in fact, most mixtures had strengths that exceeded 6,000 psi at 28 days.
- Replacing 10% of the cementitious material with limestone powder reduced the strength of the concrete by an average of 7%, but the concrete's strength was still well above the required strength.
- The strength of the concrete increased as the water-to-cementitious ratio decreased, however there was no influence from the sand-to-aggregate ratio on the strength of the concrete.
- The Control mixture recorded higher modulus of elasticity values than all of the SCC mixtures, indicating a higher stiffness despite the higher compressive strengths recorded by many of the SCC mixtures.

- The replacement of cementitious material with a limestone powder resulted in a 7% decrease in the modulus of elasticity, a reduction similar to that measured for the compressive strength.
- Like that of the compressive strength, the modulus of elasticity of the concrete was not affected by variations of sand-to-aggregate ratios.
- Results show that the modulus of elasticity of the SCC was accurately predicted using the equation provided in ACI 318 (2005).
- Drying shrinkage decreased approximately 30% as water-to-cementitious ratio decreased from 0.42 to 0.38 at an age of 180 days; however, there was no significant change due to varying sand-to-aggregate ratios.
- With the exception of Mix 1a, all SCC mixtures experienced less shrinkage than the Control mixture, which could be attributed to the higher percentage of Class F fly ash used in the SCC mixtures
- The 91-day drying shrinkage was reduced approximately 17% by replacing a portion of the cementitious material with a limestone powder.
- All mixtures had very low rapid chloride ion permeability values, indicating that these mixtures should be durable.

Based on batching and testing two mixtures in the field, the following results were found:

- The HRWR admixture dosage was increased in the field test batch of Mix 2 from 11 oz/cwt to 13 oz/cwt to increase the slump flow from 17 to 23.3 inches prior to transportation.
- Both field mixtures showed no signs of static segregation.

- The field trial of Mix 2 showed an approximate 11% increase in compressive strength compared to the laboratory mixture.
- The field trial of Mix 2 maintained a 7 inch slump after 6 hours and only lost 2.75 inches of slump flow in 4 hours.
- It is suspected that the field trial of Mix 2 (LP) was batched with an increased water content, which led to the following results:
    - The water slump significantly increased from the laboratory to the field for Mix 2 (LP), and
    - Mix 2 (LP) had lower T_{50} results between the laboratory and field mixtures.
    - Mix 2 (LP) was unsatisfactory with a 2-inch slump 4.5 hours from the time of placement. This may have been attributed to excess water evaporating from the warmer weather experienced at the batch plant, causing loss in filling ability.
    - Unsatisfactory compressive strengths at 28 days, which were caused by higher water-to-cementitious ratios from the excess water.

CHAPTER 6

PROPOSED EXPERIMENTAL FIELD STUDY

6.1 INTRODUCTION

The primary purpose of the field study is to evaluate the use of SCC as a viable material for use in drilled shaft construction. This field study will provide a means to compare the fresh and hardened properties of self-consolidating concrete and ordinary drilled shaft concrete under actual field conditions. A brief discussion of the proposed field study is presented in this chapter. This discussion includes detail of the test shafts, fresh concrete property testing, hardened concrete property testing, placement monitoring, temperature measurement, cross-hole sonic logging testing, exhuming of shafts and testing of exhumed shafts. The proposed site for this field study is located in Scottsboro, AL on the north side of the B.B. Comer Bridge on AL-35 shown in Figure 6.1. All testing procedures listed in this chapter should be conducted using current ASTM or AASHTO standards.

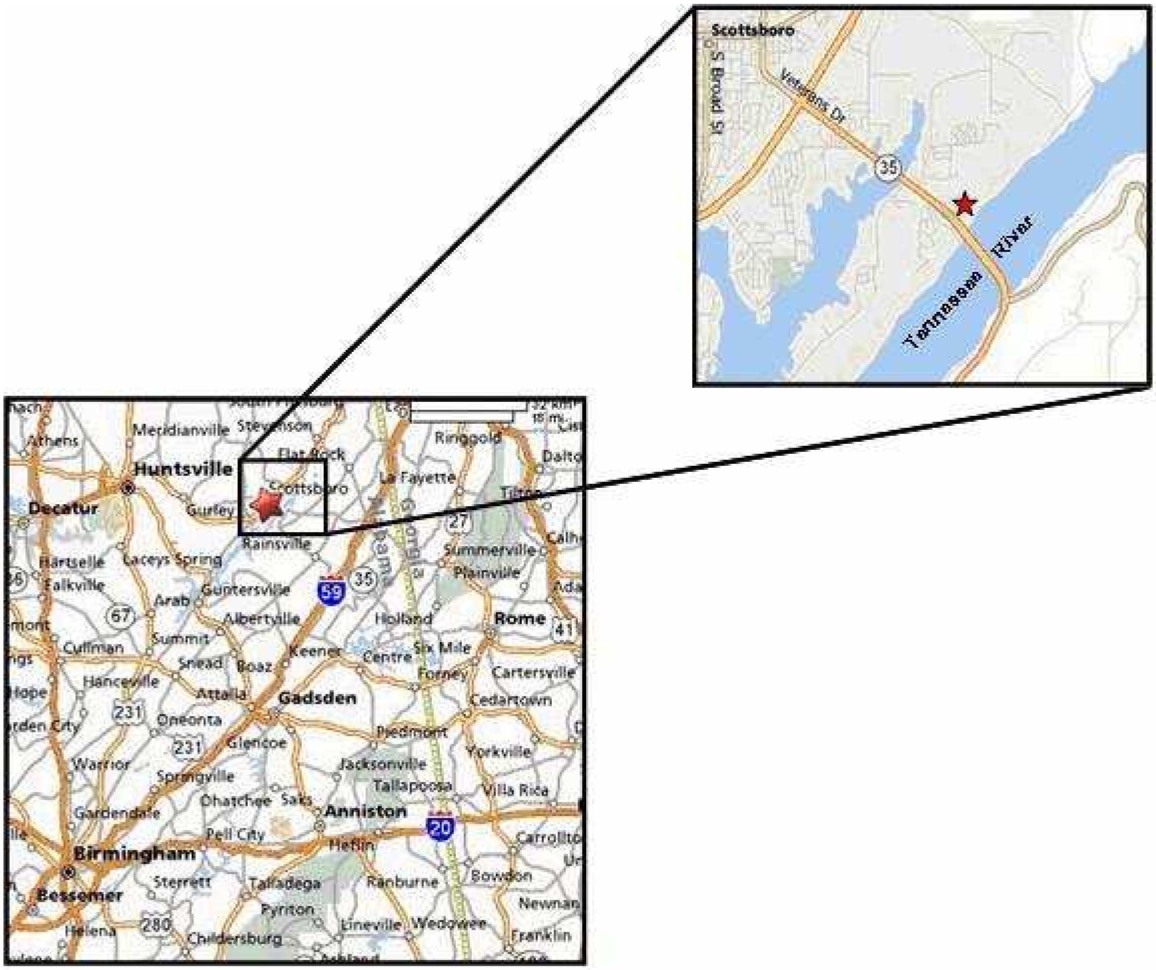


Figure 6.1: Proposed field site (adapted from Mapquest 2008)

6.2 TEST SHAFTS

Three test shafts will be constructed and exhumed. All test shafts shall be exhumed at 28 days, or later, after placement for visual inspection and testing. The shafts are to be reinforced as shown in Figure 6.2. Each shaft is to be constructed using a sono tube for casing with sand fill around the outside of casing. The casing is to be filled with polymer slurry. In addition a fine sand should be added to the slurry to act as contaminant to help evaluate the performance of the concrete mixtures. A schematic of the shafts is given in Figure 6.3. The three shafts are as follows:

- Ordinary Drilled Shaft Concrete (ODS): One - 6.0 ft Ø x 25 ft test shaft made with ordinary drilled shaft concrete with w/cm = 0.40, S/Agg = 0.36 and No. 4 hoops at 4 in. on center.
- SCC Mixture 1 (SCC-1): One - 6.0 ft Ø x 25 ft test shaft made with SCC with w/cm = 0.40, S/Agg = 0.50, and No. 4 hoops at 4 in. on center.
- SCC Mixture 2 (SCC-2): One - 6.0 ft Ø x 25 ft test shaft made with SCC with a limestone powder resulting in a w/cm = 0.44, w/p = 0.40, S/Agg = 0.50 and No. 4 hoops at 4 in. on center.

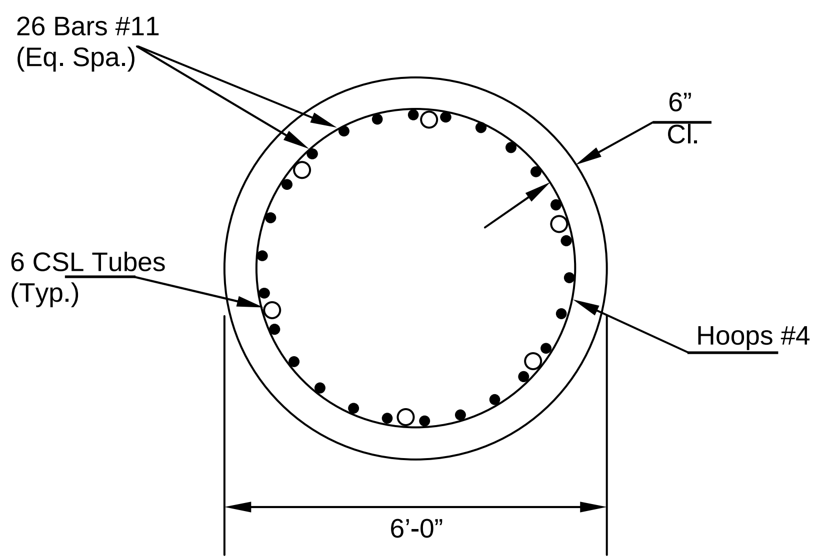


Figure 6.2: Cross section of shaft

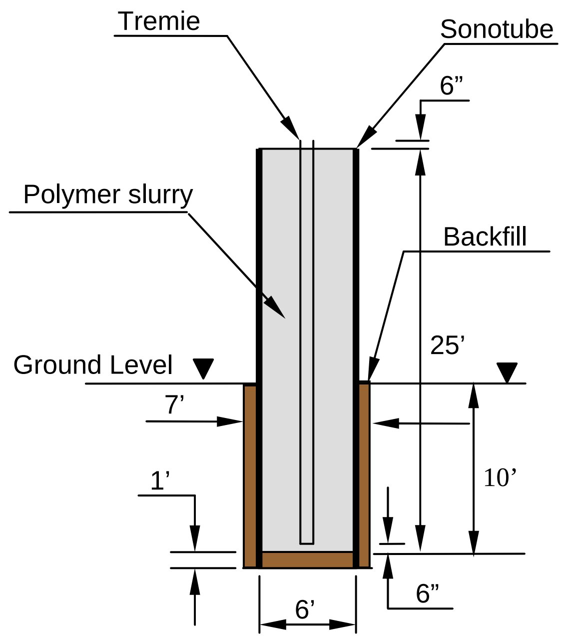


Figure 6.3: Longitudinal section of shaft

6.3 FRESH CONCRETE PROPERTY TESTING

The fresh properties of the concrete shall be tested upon arrival to the jobsite by the following test methods: slump test, slump flow test, total air content and unit weight, Modified J-Ring, segregation column, and setting by penetration resistance.

The slump of the concrete shall be tested in accordance with ASTM C 143 (1999) and be performed on all ODS concrete batches at time of placement. The slump of the ODS concrete batches, at the time of placement, shall be 6 to 9 inches. The ODS concrete’s ability to maintain slump will be monitored for 6 hours after the time of placement. To do so, an ODS sample shall be taken from the first truck, and the slump test will be performed every 30 minutes for a duration of 6 hours after placement. The slump shall be no less than 4 inches after 6 hours from the time of placement.

The slump flow test shall be performed in accordance with ASTM C 1611 (2005) on all SCC batches at the concrete plant and the time of placement. The slump flow of the SCC mixtures, at the time of placement, shall be 21 ± 3 inches. The filling ability of the SCC will also be monitored for 6 hours after placement from a sample taken from the first concrete truck. The slump flow test shall be performed every 30 minutes for a duration of 6 hours after placement. The slump flow reading shall be no less than 6 inches after 6 hours from the time of placement.

The total air content and unit weight shall be tested for all concrete mixtures and batches upon arrival to the construction site. The tests are to be performed in accordance with ASTM C 138 (2001). The air content shall be 4% ± 2% for all mixtures.

The passing ability of all SCC mixtures shall be tested according to ASTM C 1621 (2006). However, the dimensions of the J-Ring specified in ASTM C 1621 (2006) are too confining for drilled shaft applications. A J-Ring that has been modified to better simulate drilled shaft applications shall be provided by Auburn University and used for testing. The Modified J-Ring test shall be performed on all SCC batches at the time of placement.

The concrete's ability to resist segregation shall be tested using the segregation column test specified in ASTM C 1610 (2006). The segregation column test is to be performed on most SCC batches at the time of placement. The concrete shall be allowed to stand undisturbed in column mold for one hour. Because of this extended testing period, it is assumed that all SCC batches will not be tested, but the test shall be performed on as many batches as possible.

Finally, the setting time for all concrete mixtures shall be determined by ASTM C 403 (1999), *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. The test shall be performed for each of the three mixtures from a concrete sample taken from the first truck of each shaft. The mortar of the concrete sample shall be obtained by wet sieving the concrete through a No. 4 sieve. The mortar shall then be placed in a 7.5 inch Ø x 6.0 inch cylindrical container for testing.

6.4 HARDENED CONCRETE PROPERTIES

The compressive strength, modulus of elasticity, drying shrinkage, and permeability are the hardened properties to be tested in the experimental field study. The following section details these tests.

Three 6 Ø x 12 inch molded specimens shall be cast per testing age for each concrete mixture. The specimens are to be demolded no earlier than 2 x initial set and cured in accordance with ASTM C 31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field*. The compressive strength and modulus of elasticity shall be determined for the specimens by the procedures listed in ASTM C 39 (2005) and ASTM C 469 (2002). These tests shall be performed at ages of 7, 28, 56 and 91 days.

Three 3 x 3 x 12 inch molded specimens shall be cast per mixture, and the drying shrinkage of the concrete shall determined by the testing procedure listed in ASTM C 157 (2004). A wet burlap cloth shall be placed over the specimens until they can be demolded, no earlier than 2 x initial set. At which point the specimens are to be placed in a lime-saturated bath for a period of 7 days. Afterwards, the specimens shall be removed from the lime bath and placed in air storage. The specimens shall be tested at 1, 2, 3, 7, 14, 28, 56, 91, 180, and 365 days after removal from lime-saturated bath.

Lastly, the permeability of the concrete mixtures will be determined by testing the concrete's resistance to chloride ion penetration outlined in ASTM C 1202 (1997). Cylindrical specimens measuring 4 inch Ø x 2 inch are to be cut from the top of 4 inch Ø x 8 inch concrete molds cast in the field. 3 specimens shall be cast per testing age for each mixture and tested at ages of 91 and 365 days. The curing of the specimens shall be done in accordance with ASTM C 31 (2003) and demolded no earlier than 2 x initial set.

6.5 PLACEMENT MONITORING

During concrete placement for each shaft, the elevation difference between the inside and outside of the reinforcing cage shall be determined by the use of plumb-bobs attached to a nylon measuring tape. The elevations shall be recorded for comparison of the concrete's flow through the reinforcing cage. Also during concrete placement, 1/2-inch colored mortar cubes shall be added to the concrete in all shafts at different times during the placement for all shafts. The cubes are to be placed at the specific concrete heights shown in Figure 6.4. The shafts will be exhumed at a later date and cut to examine the final placement of the colored mortar cubes. The final location of the cubes will be recorded and compared to the initial placement given in Figure 6.4. The final placement of the mortar cubes was also predicted based on the initial placement of the cubes and the placement of the tremie throughout the pour. The predicted final location of the mortar cubes is shown in Figure 6.5 and will also be used for comparison.

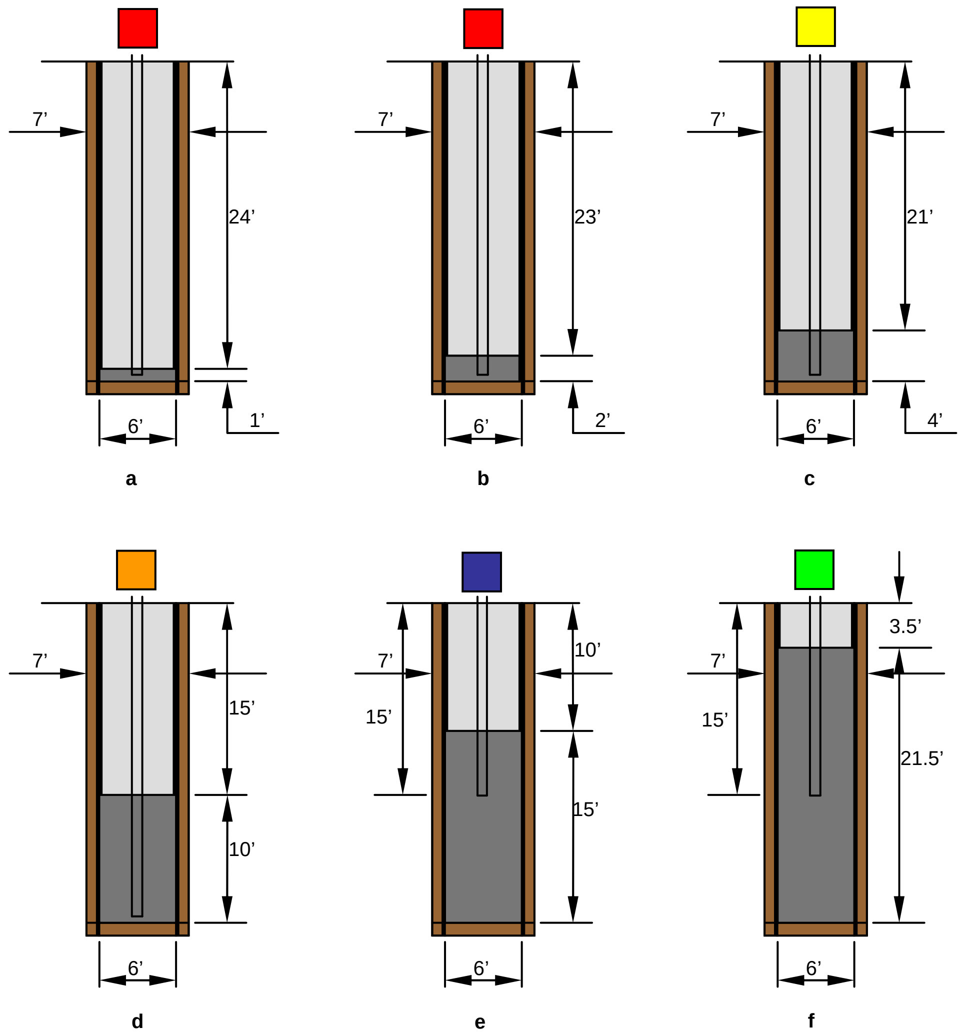


Figure 6.4: Cube placement in shaft

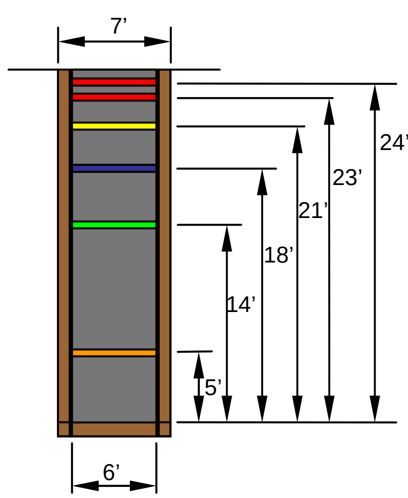


Figure 6.5: Reference for final configuration of mortar cubes

6.6 TEMPERATURE MEASUREMENT

Temperature probes are to be placed in each shaft in order to monitor the temperature development at different areas of the shaft. The temperature will be monitored by data loggers referred to as iButtons. The iButtons are attached to a two-wire 20-gauge telephone wire that is connected to a computer by an RJ11 telephone jack attached at the other end. The iButton are encapsulated with an epoxy to protect and waterproof the data logger. The temperature development will be monitored along the cross section of the shaft by placing the iButtons at the edge of the shaft, at longitudinal steel inside the rebar cage, and close to the center of shaft. Due to the location of the tremie, the iButton will not be able to be placed in the middle of the shaft and should be placed as close to the middle as possible. To keep the iButtons securely placed throughout the concrete placement, the iButtons should be fixed firmly to horizontal steel bars that will be attached to the reinforcing cage prior to the installation of the cage. The horizontal bars should be located 3-feet below the surface of the shaft, at mid-depth of the shaft, and 3 feet from the bottom of the shaft as shown in Figure 6.6. There shall be 3 iButtons per bar and 9 iButtons per shaft, making a total of 27 iButtons used for the field study. The temperature data shall be sampled at 30-minute intervals for the first 28 days after placement.

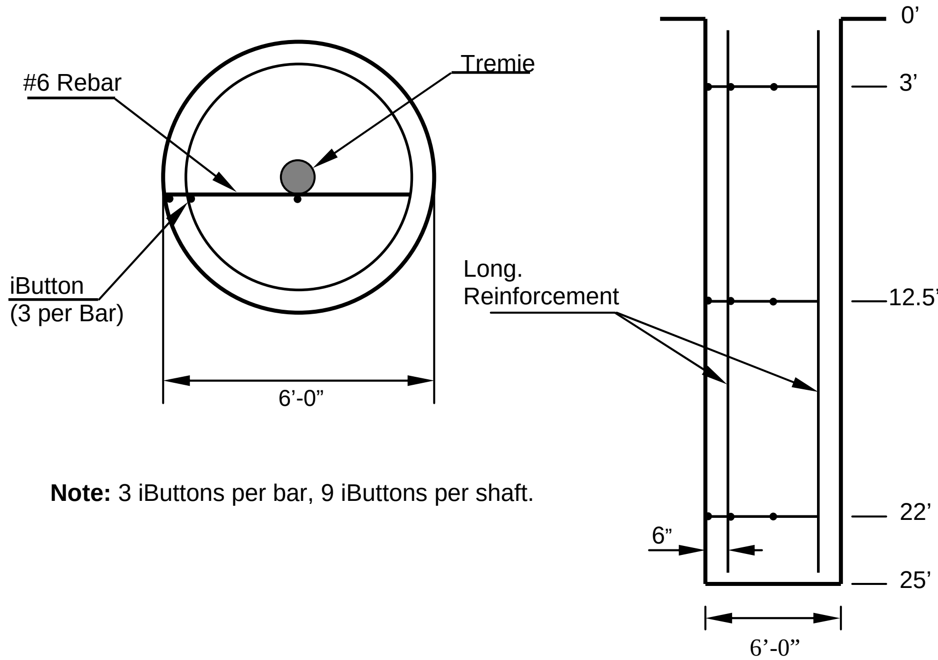


Figure 6.6: Location of temperature sensors

6.7 CROSS-HOLE SONIC LOGGING (CSL)

The concrete will be tested for voids and irregularities within the cross section of each shaft by cross-hole sonic logging. Six metal CSL tubes shall be used and attached to the transverse reinforcement for testing concrete soundness along shaft height. Cross-hole sonic logging shall be performed when concrete has exceeded a maturity of seven days.

6.8 EXHUMING OF SHAFTS

All shafts shall be exhumed at an age no earlier than 28 days after placement. Each shaft shall be pressure washed and cleaned of all debris and prepared for testing. The testing procedure of the shaft is discussed in the following section.

6.9 TESTING OF EXHUMED SHAFTS

Once exhumed and cleaned, each shaft will be cut using a wire-saw in order to inspect aggregate distribution, locate any possible bleed channels, evaluate any voids and/or debris entrapments, and to locate the final placement of the colored mortar cubes. Each shaft will be cut longitudinally for initial inspection. After making the longitudinal cut, two cross-sectional cuts shall be made horizontally at locations determined from initial inspection. The horizontal cuts are predicted to be made approximately 7 ft and 20 ft from the top of the shaft as shown in Figure 6.7.

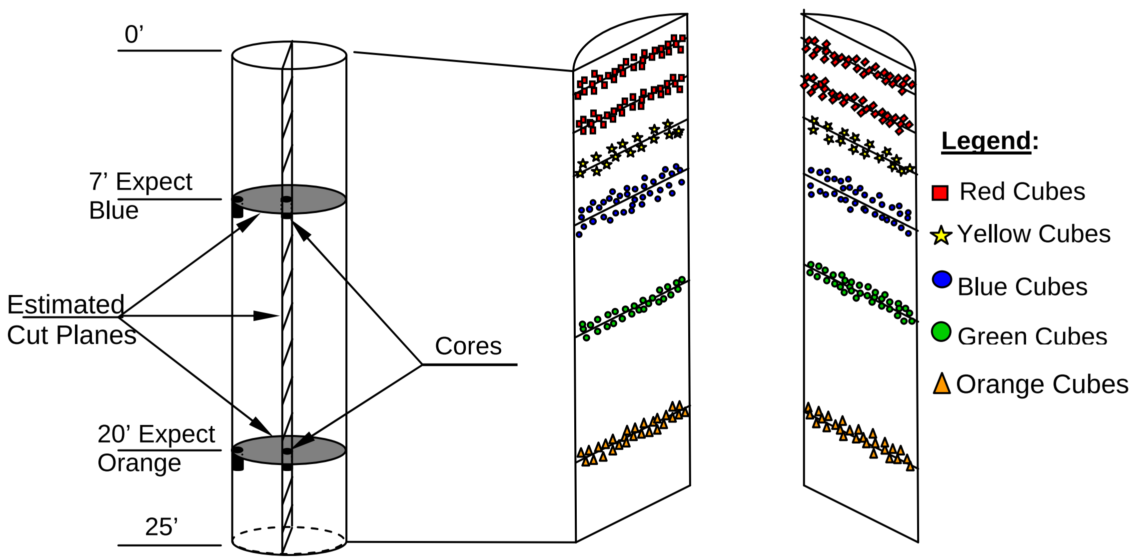


Figure 6.7: Cutting and coring of exhumed shafts

Cores shall be taken at each cut cross section previously determined from visual inspection. The cores shall be extracted between the shaft surface and rebar cage (area of concrete cover) as well as at the center of the cross-section. Three cores shall be tested for compressive strength, modulus of elasticity, and permeability. Three 4 inch Ø x 10 inch cylindrical specimens, cut to a testing size of 4 inch Ø x 8 inch, shall be cored from each of the locations described and tested to determine the compressive strength and modulus of elasticity according to ASTM C 39 (2005) and ASTM C 469 (2002). These specimens are to be tested at an age of 56 days. Likewise, three 4 inch Ø x 4 inch cylindrical specimens, cut to a testing size of 4 inch Ø x 2 inch, shall be cored from each of the locations described and tested to determine its permeability by ASTM C 1202 (1997). The specimens are to be tested at an age of 91 days. There are to be 12 cores per horizontal cut at the locations shown in Figure 6.8, giving a total of 24 cores per shaft.

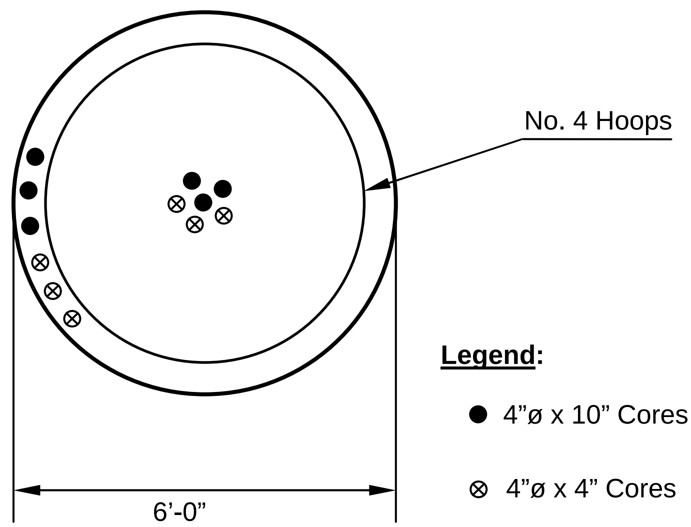


Figure 6.8: Coring detail of exhumed shafts

CHAPTER 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 SUMMARY OF EXPERIMENTAL PROGRAM

This research was funded by the Alabama Department of Transportation (ALDOT) to determine the effectiveness of self-consolidating concrete (SCC) in deep foundations relative to the conventional-slump concrete currently being used. The experimental program took place at Auburn University, where several SCC mixtures were developed and tested. There were a total of 10 SCC mixtures that varied between 3 water-to-cementitious ratios and 3 sand-to-aggregate ratios. The water-to-cementitious ratios used were 0.42, 0.40, and 0.38 and the sand-to-aggregate ratios were 0.45, 0.50, and 0.55. Nine mixtures were created by pairing each of the 3 water-to-cementitious ratios with each of the 3 sand-to-aggregate ratios. The tenth mixture was derived from one of the 9 mixtures such that 10% of the cementitious material was replaced by a non-cementitious limestone powder. Three experimental test shafts are to be constructed in north Alabama where one of the original 9 SCC mixtures was chosen along with the mixture containing the limestone powder to be compared with the conventional-slump concrete. From the results of the test shafts it will be decided if the SCC is acceptable for the construction of the middle two piers of the B.B. Comer Bridge in Scottsboro, Alabama.

All ten SCC mixtures and the conventional-slump concrete were developed in the laboratory, and the fresh and hardened properties were tested and compared. Fresh properties were determined from the following tests: the slump flow, which included the T_{50} and VSI, slump flow retention, air content, unit weight, Modified J-Ring, setting time, and segregation column. The hardened properties tested included the compressive strength, modulus of elasticity, drying shrinkage, and permeability. Once the tests were completed, two mixtures were chosen for a field study. However, the two mixtures were first tested at a concrete batch plant to assure that the concrete produced at the ready-mix plant was comparable to the concrete produced in the laboratory.

Another study incorporated in this program was the flow of concrete within the shaft during tremie placement. To do so, thousands of different colored 1/2-in. mortar cubes were fabricated. These cubes are to be inserted into each shaft at different stages of the placement. The shafts are to be exhumed later and cut open to expose the mortar cubes along with any deformities. The initial and final location of the cubes will be compared and any assumption and hypothesis will be made.

7.2 CONCLUSIONS FROM RESULTS

The following sections summarize the conclusions determined in Chapter 5. Conclusions were drawn from the fresh and hardened properties of the concrete, as well as conclusions from the test mixtures performed at the concrete batch plant.

7.2.1 FRESH PROPERTIES

The following conclusions were drawn from the fresh property tests conducted in the laboratory:

- High-range water-reducing (HRWR) admixture dosage of 12 oz/cwt produced slump flow values beyond the maximum requirement of 24 in., but the stability of the mixtures was not compromised.
- The use of a limestone powder significantly increased the viscosity of the concrete, indicated by an increase in T_{50} time, which may be a result of the powder absorbing excess water.
- The VSI ratings for the SCC mixtures ranged from 0.0 to 1.0, indicating that the mixtures were stable and showed no signs of segregation.
- The SCC mixtures used less hydration-stabilizing admixture than the Control mixture, but most SCC mixtures were able to maintain a slump value 6 hours from the time of placement equal to or greater than the Control mixture's value at the time of placement.
- All SCC mixtures had slump values significantly higher than the 4 in. after 4 hours that is required by the FHWA Drilled Shaft Manual (1999), but the Control mixture was unsatisfactory, yielding a 3 in. slump 4 hours from the time of placement. Therefore, more hydration-stabilizing admixture is needed for the conventional-slump drilled shaft concrete.
- A 50-minute mixing period was designed to simulate the transportation period from the concrete plant to the jobsite. It was discovered at the laboratory that air was being entrapped in the concrete during this period due to high amounts of

agitation; therefore, the mixing procedure at the laboratory was altered and the air entraining admixture was removed from all SCC mixtures to meet the required air content of 2-6%.

- Higher T_{50} times could potentially reduce the concrete's passing ability.
- The SCC mixtures required lower dosages of hydration-stabilizing admixture in order to keep the concrete in a fresh state for the duration of construction. The use of a limestone filler significantly reduced the setting time of the concrete.
- Setting times decreased significantly for mixtures with sand-to-aggregate ratios of 0.45 relative to higher sand-to-aggregate ratios.
- Mixtures with a higher sand-to-aggregate ratio showed less potential for segregation.

7.2.2 HARDENED PROPERTIES

The following conclusions were drawn based on the hardened property results determined in the laboratory:

- Results indicated that the compressive strength was inversely related to the water-to-cementitious ratio of the concrete mixture; however, the sand-to-aggregate ratio provided no influence on the compressive strength of the concrete.
- Replacing 10% of the cementitious material with a limestone powder reduced the concrete's strength and modulus of elasticity by an average of 7%.
- The concrete's modulus of elasticity was related to the strength of the concrete and followed a progression similar to that of the compressive strength.

- The modulus of elasticity was not influenced by changes in the sand-to-aggregate ratio.
- The modulus of elasticity of SCC can be predicted accurately by the equation used for conventional-slump concrete in ACI 318 (2005).
- Drying shrinkage for SCC was decreased with lower water-to-cementitious ratios, but no significant change was indicated by variations in sand-to-aggregate ratios.
- The use of a limestone powder reduced the effects of drying shrinkage.
- All mixtures produced highly durable concrete indicated by very low rapid chloride ion permeability results.

7.3 RECOMMENDATIONS

Further research is needed to better understand and introduce SCC in the U.S. construction industry. The following are recommendations and suggestions based on experiences from the author for future research of SCC in drilled shaft applications.

- Increase the dosage of the hydration-stabilizing mixtures for sand-to-aggregate ratios below 0.50.
- When testing for specific construction situations, consider the time required for transportation and possible delays in order to obtain mixtures in the laboratory comparable to what would be placed in the field.
- A pressurized bleeding test should be performed on all mixtures to simulate high concrete pressures of drilled shafts.
- All mixtures should be produced and tested at the concrete batch plant to correct any problems associated with the mixture prior to construction.

- SCC Mix 2 and Mix 2 (LP) should be used for the proposed field study outlined in Chapter 6. It is strongly recommended that Mix 2 (LP) be reproduced at the batch plant to obtain better fresh and hardened properties. There is reason to believe that Mix 2 (LP) created in the field was batched with more water than specified.
- Increased hydration-stabilizing admixture dosage should be considered when placing concrete at higher temperatures.
- If there is an excess of compressive strength, a finely ground limestone powder may be used to reduce the amount of bleed water, drying shrinkage, and setting time of the concrete.
- Further research should be conducted on the permeability of SCC for varying water-to-cementitious and sand-to-aggregate ratios.

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