Assessment of Stability Test Methods
for Self-Consolidating Concrete

by

Samuel Deiter Keske

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 9, 2011

Keywords: Visual Stability Index, segregation, top-bar factor, ultrasonic pulse velocity

Approved by

Anton K. Schindler, Chair, Associate Professor of Civil Engineering
Robert W. Barnes, James J. Mallett Associate Professor of Civil Engineering
Justin D. Marshall, Assistant Professor of Civil Engineering

Abstract

Self-consolidating concrete (SCC) is a highly fluid, nonsegregating concrete that can spread through reinforcement and completely fill formwork without the use of mechanical consolidation. Resistance to segregation, also known as stability, is difficult to measure in fresh samples, and few test methods are available to quantify this vital property during production. The objectives of this study were to identify and assess several fresh stability test methods for SCC and recommend the stability testing protocol the Alabama Department of Transportation should implement when using SCC to produce precast, prestressed bridge girders.

The following stability test methods were evaluated: Visual Stability Index, Column Segregation Test, Rapid Penetration Test, Sieve Stability Test, Surface Settlement Test, and the Multiple-Probe Penetration Test. These six tests were performed while placing SCC in four walls of heights of 36, 54, 72, and 94 inches, and the fresh concrete stability test results were compared to the results of in-situ uniformity testing conducted on the hardened concrete walls.

The wall uniformity testing program included through-wall ultrasonic pulse velocity (UPV) tests that were conducted at multiple heights within each wall. Also, pullout tests were performed on groups of deformed steel bars embedded at the top, middle, and bottom of each wall.

The strongest correlations between stability test results and in-situ uniformity were established with the surface settlement test. The results of the sieve stability test and VSI showed reasonable correlations with in-situ uniformity and with each other. The surface settlement test should be the primary stability test used to assess SCC mixture stability during mixture prequalification, and a rate of settlement less than 0.15 percent per hour determined between 10 and 15 minutes should ensure that the tested SCC will exhibit acceptable in-situ uniformity.

The sieve stability test should be the primary fresh stability test used to assess SCC mixture stability during production, and a sieved fraction less than 15 percent should ensure that the tested SCC will exhibit acceptable in-situ uniformity. Also, the VSI should be used first to assess SCC mixtures during production, and a VSI less than 2.0 should ensure that the tested SCC will exhibit acceptable in-situ uniformity. If the VSI result is greater than 1.0, though, the sieve stability test result should be used to accept or reject the batch.

Acknowledgements

I am indebted to the people that regularly got covered up to their wrists in self-consolidating concrete to help me in the laboratory: Wes, Eric, Ben, Kevin, Emily, Philip, Adam, Kaylor, Matt, John, and Scott, as well as to the men that I am proud to consider my coworkers, as well as friends: Dr. Anton Schindler, Dr. Robert Barnes, and Mr. Billy Wilson. For their unwavering support and encouragement, I would like to thank my First Baptist Church of Columbus family, my Auburn family, and the family that didn't get a choice in the matter: Old Man, Momma, and Bucko. I give God the credit for all things past and future, and I have a special note for Katie and everybody else that I envision in that future: what the future holds may not be black and white...

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Background

Self-consolidating concrete (SCC) is a highly fluid, nonsegregating concrete that can spread through reinforcement and completely fill formwork without the use of mechanical consolidation (ACI 237 2007). Pioneered in Japan during the late 1980's, this technology is now rapidly developing in the United States. Because it is a high-performance concrete in the fluid state, SCC can often best be used in heavily reinforced or irregularly shaped structural elements that would be difficult or impossible to properly consolidate with traditional vibratory techniques. Knowing this, contractors, architects, and engineers continue to push the bounds of concrete construction by using SCC in applications that require the greatest efficiency of time, energy, and labor, including architecturally exposed concrete, mass concrete, and precast members.

One increasingly popular implementation of SCC is in the production of precast, prestressed bridge girders, where narrow forms and congested reinforcement make proper filling and consolidation using conventional concrete difficult and labor-intensive. The demanding configuration of formwork and reinforcement needed to produce thin-web precast, prestressed girders make internal vibratory consolidation of the bottom flange difficult. The prevalent method of consolidation when using conventional concrete is to combine extremely loud, high-impact external vibration of the lower flange and web with slow, labor-intensive internal vibration of the upper flange and web. Afterwards, the finished product still frequently needs to be resurfaced and patched to be given a durable and attractive finish. Formwork that is typical of precast, prestressed bulb-tee girders is shown in Figure 1.1. An example of the surface finish typically resulting from the use of conventional concrete in precast, prestressed bulb-tee construction is shown in Figure 1.2.

Figure 1.1: Formwork and reinforcement of a typical precast, prestressed bulb-tee girder

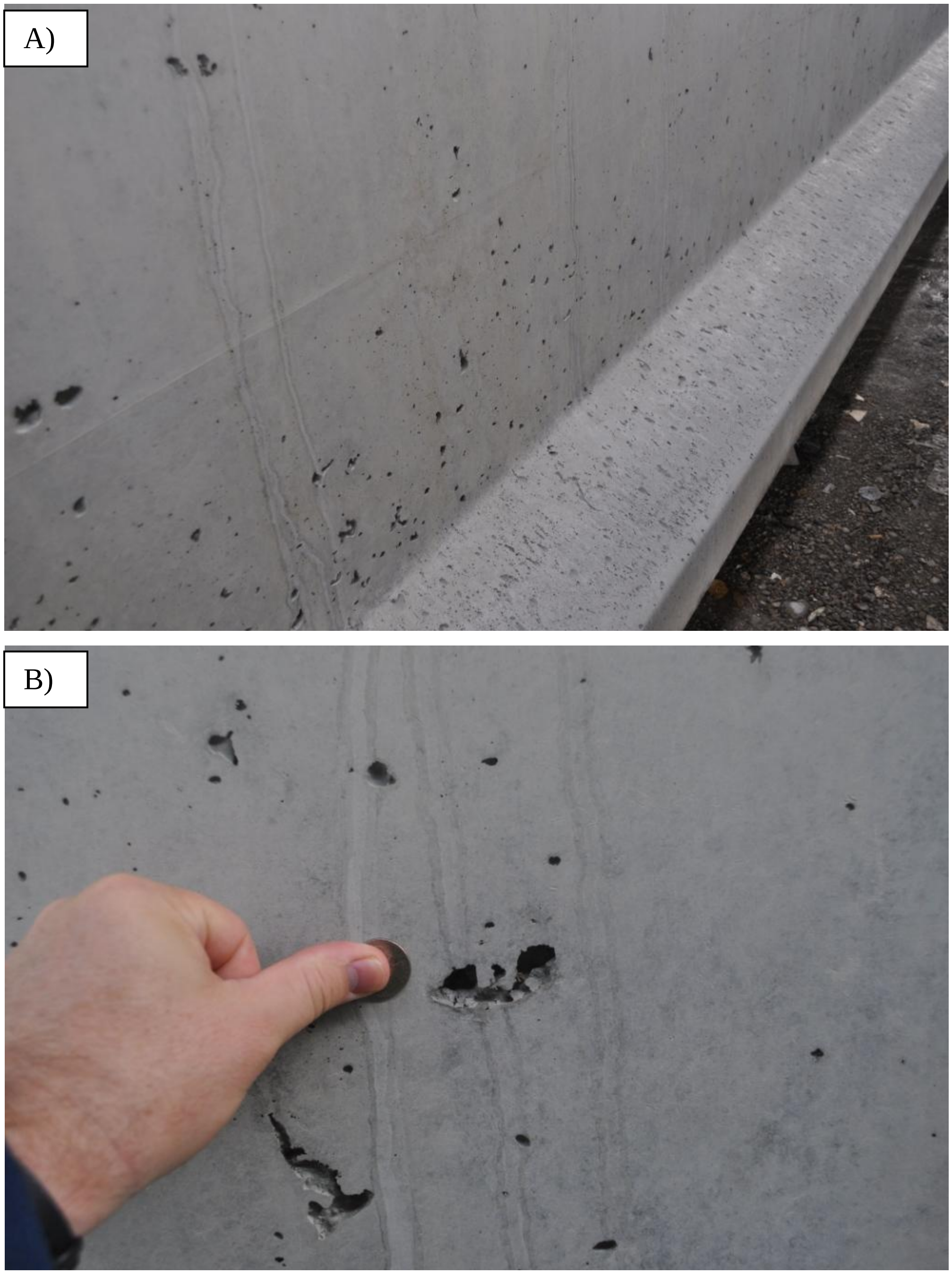

Figure 1.2: A) Typical surface finish achieved when using conventional concrete to produce precast, prestressed bulb-tees, and B) a bug hole in the beam surface

SCC completely fills the forms and encapsulates reinforcement under its own flow, and the finished product may not require any resurfacing or patching to achieve an attractive, durable finish. Thus, the precast, prestressed industry is eager to use SCC in order to reduce construction time, energy, and, ultimately, cost.

Accompanying the advantages associated with the fluid nature of SCC are several disadvantages. Joints in formwork must be completely sealed in order to prevent leaking of the paste, and the forms must be able to safely resist the high hydrostatic pressures that are possible with fluid SCC. Also, the concrete is given its fluid nature by changing the mixture proportions and adding chemical admixtures, and the effects of these mixture changes and chemical additions on the fresh and hardened properties of the concrete are not always clear. For these reasons, these potential effects of SCC implementation are still being actively studied.

One potential concern with SCC is the fresh mixture's stability, which refers to its ability to avoid segregation, primarily in the forms of constituent sedimentation and/or excessive bleeding. Severe segregation can have detrimental effects on the structural capacity of members in which it occurs and must be avoided before, during, and after placement. Thus, SCC stability is an important material property of fresh SCC.

As important as controlling stability is, accurately assessing this property by testing the fresh concrete has proven difficult, and few tests are currently available to quantitatively measure it. Of the tests developed to assess the stability of SCC, the most widely used in the U.S. is the Visual Stability Index (VSI), which is based on a visual inspection of a patty of fresh SCC as shown in Figure 1.3. The VSI is a rapid and simple test, but, because it is visually assessed, it is subjective.

Figure 1.3: Patty of fresh SCC as it is visually assessed during the VSI test

Very recently, more tests have been proposed that can potentially offer a more quantitative and less subjective assessment of SCC stability. NCHRP Report 628 (Khayat and Mitchell 2009) recommended the surface settlement test, in which the settlement of a thin acrylic plate into the top surface of a sample of SCC is measured. This test is shown in Figure 1.4. Shown below the surface settlement test in Figure 1.5 is the column segregation test method, which is defined by ASTM C 1610 (2006) and involves weighing the coarse aggregate found in the top and bottom sections of a column of SCC that has been left at rest for fifteen minutes.

Figure 1.4: Settlement of a clear acrylic plate into SCC during the surface settlement test

Figure 1.5: Filling of a column mold during the column segregation test

Other recently proposed fresh stability test methods include the sieve stability test (EPG 2005), rapid penetration test (ASTM C 1712 2009), and multiple-probe penetration test (El-Chabib and Nehdi 2006). The sieve stability test is recommended by a European consortium of concrete producers as the primary stability test for SCC in Europe (EPG 2005), and it involves pouring a sample of SCC onto a sieve and pan from a height of 20 in. to determine the amount of laitance that passes through the sieve. This test is shown in Figure 1.6.

Figure 1.6: Pouring of SCC onto a sieve during the sieve stability test

The rapid penetration and the multiple-probe penetration test methods are each used to assess the stability of SCC by measuring the penetration depth of a specified apparatus as it settles into a sample of SCC. The rapid penetration test method involves measuring the settlement of a weighted hollow penetration cylinder over 30 seconds, and the test is shown in Figure 1.7. The multiple-probe penetration test involves measuring the settlement of four cylindrical probes over 30 seconds to determine an average settlement, and the test is shown in Figure 1.8.

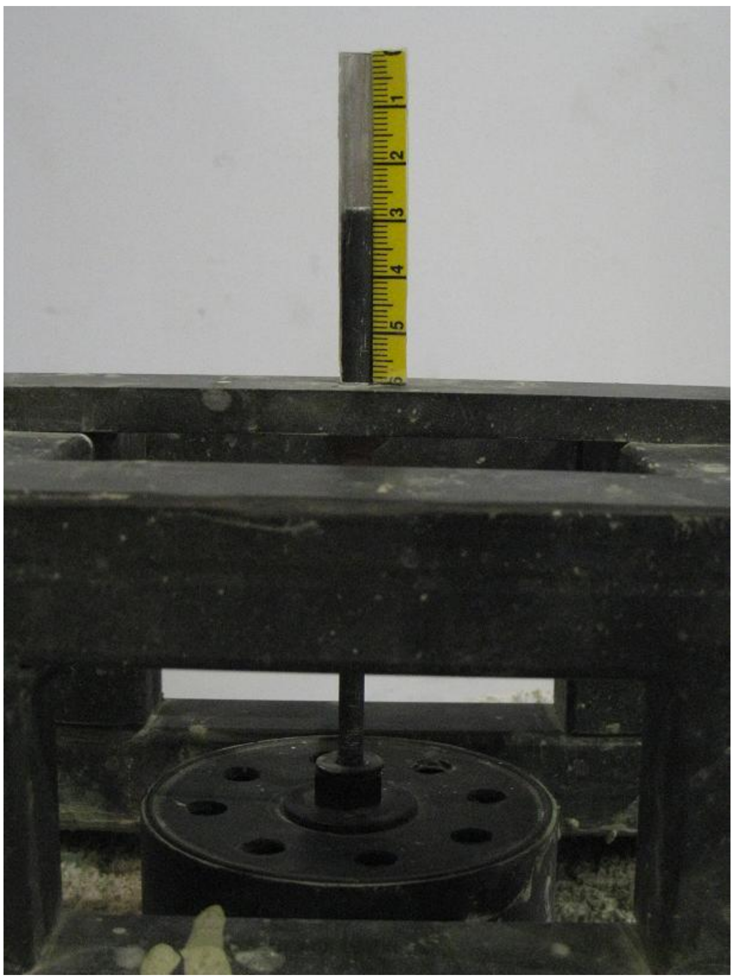

Figure 1.7: Settlement of a hollow penetration cylinder into SCC during the rapid penetration test

Figure 1.8: Settlement of four cylindrical penetration probes into SCC during the multiple-probe penetration test

Other researchers have created, studied, or recommended other fresh stability test methods, but all of these advancements in the methodology to assess SCC stability have been very recent, and their relevance to assess in-situ uniformity of SCC is unclear.

1.2 Research Objectives

This project was undertaken to address concerns about the methodology of assessment of fresh SCC stability. The primary objectives of this research were thus to

- Identify fresh test methods that provide a quantitative assessment of the degree of stability of SCC, and

- Recommend the testing protocol that the Alabama Department of Transportation (ALDOT) should implement to address SCC stability during the production of precast, prestressed elements.

Several secondary objectives were established for this research that would help the research team meet the two primary objectives. These secondary objectives required the team to

- Evaluate the effects of segregation on hardened concrete elements,
- Evaluate the accuracy and technician-friendliness of the various fresh stability test methods identified, and
- Determine the correlations that exist between the various fresh stability test methods.

1.3 Research Methodology

After reviewing the available literature, six fresh stability test methods were selected for evaluation: Visual Stability Index (ASTM C 1611 2005), Column Segregation Test (ASTM C 1610 2006), Rapid Penetration Test (ASTM C 1712 2009), Sieve Stability Test (EPG 2005), Surface Settlement Test (Khayat and Mitchell 2009), and Multiple-probe Penetration Test (El-Chabib and Nehdi 2006). The research team decided to study these six test methods by preparing nine SCC mixtures that would be acceptable for precast, prestressed implementation and then conducting the fresh stability test methods simultaneously and in conjunction with placement of the concrete in walls 36 in., 54 in., 72 in., and 94 in. tall. Two conventional concrete mixtures were also prepared as controls to assess the uniformity of the walls when cast with conventional concrete typical of precast, prestressed construction.

Each of the concrete placements required a volume of concrete that could not be batched at Auburn University, so the materials were stored at a nearby ready-mix concrete plant, and ready-mix concrete trucks were used to deliver the concrete to the Auburn University Structural Engineering Laboratory. Upon arrival, the research team then added additional water and chemical admixtures to intentionally induce varying levels of stability before conducting the fresh stability tests and placing the concrete in the four walls.

The four wall heights were representative of three precast, prestressed bridge sections commonly employed by ALDOT and one precast segmental bridge section. The 36 in. height represented the minimum height above which segregation might be easily identified, the 94 in. height represented the maximum section height ALDOT is likely to encounter in precast, prestressed construction, and 54 in. and 72 in. represented the heights of common ALDOT sections that would provide approximately equal height increments between 36 in. and 94 inches. This allowed the research team to study the accuracy of the fresh stability tests as they would be needed for a variety of SCC implementations ALDOT is likely to encounter. It also allowed the study of any relationships present between wall height and the effects of segregation.

To establish the level of segregation experienced by each mixture, two types of hardened concrete tests were conducted on each wall: nondestructive through-wall ultrasonic pulse velocity (UPV) tests and destructive pullout tests of deformed steel reinforcement cast into each wall. Because the UPV method is nondestructive, many

UPV measurements were conducted at various heights to create a uniformity profile within each wall. Then, pullout tests were performed on deformed bars embedded horizontally near the top, bottom, and middle of each wall to determine the extent of bond strength variation experienced with increasing depth of concrete cast below each group of bars.

The levels of UPV and bond strength variation were then compared to each other to define the degree of in-place uniformity exhibited by each wall and mixture. The levels of uniformity for each mixture were then compared to the fresh stability test results for that mixture in order to assess the accuracy of the fresh stability test methods.

Once acceptable levels of uniformity were determined from the hardened concrete test measurements, acceptable fresh stability test values could be identified in those fresh stability tests that showed a strong correlation to the in-situ uniformity measurements. Recommendations were then made for the use of the most relevant fresh stability tests and SCC acceptance criteria that ALDOT should adopt for these tests during precast, prestressed applications.

1.4 Report Outline

The existing literature concerning all aspects of this research project is summarized in Chapter 2 of this report. First, mixture proportioning of SCC, as well as the fresh and hardened properties of concrete affected by this proportioning, are discussed. Stability of fresh SCC and the hardened properties affected by it are defined, followed by a summary of the methods used to assess stability in the fresh state and uniformity in the hardened state. Lastly, the acceptance criteria previously established for these methods are reviewed.

The experimental plan developed for this research project is documented in Chapter 3, beginning with a general order of the activities performed on each mixture. A detailed description of the mixing and placement procedure is given, followed by descriptions of the fresh and hardened concrete tests that were considered for further study. Testing procedures for the six fresh concrete tests and two hardened concrete tests are defined, as are the construction procedures and dimensions of the walls cast from each mixture. Finally, the SCC mixtures used are described, and their mixture proportions are defined.

The most relevant results of the fresh and hardened concrete tests are presented in Chapter 4. Production flaws and circumstances unique to each mixture, as well as trends in the construction and testing process, are also elaborated upon in this chapter. Statistical comparisons between datasets and discussion of their implications are then discussed, complete with tables summarizing the correlations established between all fresh stability tests and hardened tests. All conclusions and recommendations derived from the research performed in this study are then summarized in Chapter 5.

Chapter 2

Literature Review

2.1 Introduction

The primary factor distinguishing self-consolidating concrete (SCC) from conventional concrete is that no vibration is required to consolidate SCC. Fresh SCC uniformly fills formwork and encapsulates reinforcement under its own flow, a mechanism that is practically described by three properties: filling ability, passing ability, and stability. ACI 237 (2007) defines these properties as follows:

- Filling ability (or unconfined flowability) refers to SCC's ability to fill formwork under its own weight,
- Passing ability (or confined flowability) refers to SCC's ability to pass through constricted spaces and around obstacles without blockage, and
- Stability (or segregation resistance) refers to SCC's ability to maintain a uniform distribution of its constituents during flow and setting.

These three properties, and some of the test methods used to study them, are described in Section 2.3.1. The properties are controlled through changes in the constituent materials of SCC and in the mixture proportions thereof, and these changes can affect the hardened properties of SCC. Therefore, hardened properties of SCC are described in Section 2.3.2, after the materials and proportioning used to produce SCC are described in Section 2.2. The objectives of this research project, as outlined in Chapter 1, included identifying and studying the accuracy of test methods used to quantify the stability of fresh SCC. Therefore, the following topics are thoroughly addressed in the remaining sections of this chapter:

- Test methods used to assess the uniformity of hardened SCC (Section 2.4),
- Test methods used to quantify the stability of fresh SCC (Section 2.5), and
- Test criteria used to accept SCC mixtures based on fresh stability or hardened uniformity test results (Section 2.6).

2.2 Materials and Mixture Proportions of Self-Consolidating Concrete

Self-consolidating concrete is a high-performance concrete because of its highly flowable behavior in the fresh state, and it can be proportioned to achieve practically any behavior in the hardened state (Bartos 2005). As with conventional concrete, SCC consists of coarse and fine aggregate, portland cement, supplementary cementing materials, water, air, and chemical admixtures. However, at a particular level of performance, SCC will have differences from conventional concrete in both the materials used and the proportions thereof. These differences, with an emphasis on the proportions of SCC for precast, prestressed applications, are discussed in the following subsections.

2.2.1 Coarse Aggregate and Fine Aggregate

In applications that require high passing and filling ability, such as in the production of precast, prestressed bridge girders, coarse aggregate occupies approximately a third of the SCC mixture volume, with fine aggregate occupying approximately another one-third

(Khayat and Mitchell 2009; Koehler et al. 2007). Because coarse aggregate and fine aggregate represent such a significant portion of the concrete, they significantly affect all three of the concrete's fresh characteristics, particularly filling and passing abilities (Koehler et al. 2007).

Precast, prestressed bridge girders contain very closely spaced steel strands and deformed steel reinforcement, which make filling and passing ability only possible using a relatively small nominal aggregate size (ACI 237 2007). In previous phases of Auburn University's testing of SCC for use in precast bridge girders, No. 78 crushed limestone was used for SCC proportioning (Kavanaugh 2008; Roberts 2005). This No. 78 gradation fits the maximum size aggregate (MSA) of ½ in. recommended in NCHRP Report 628 (Khayat and Mitchell 2009) and is defined by AASHTO M 43 (2003).

SCC for precast, prestressed applications is typically proportioned with a reduced coarse aggregate content in order to increase the mortar phase of the mixture (consisting of fine aggregate, powders, water, and air), which enhances the cohesiveness of the mixture (ACI 237 2007; Koehler et al. 2007). The decrease in total coarse aggregate content also ensures adequate passing ability and promotes filling ability, as a reduction in the total coarse aggregate content increases the average size of inter-aggregate voids that must be filled with mortar (Koehler et al. 2007).

The selection of fine aggregate is not as restrictive as the selection of coarse aggregate, but ACI 237 (2007) recommends using well-graded natural sand or a blend of natural and manufactured sand. SCC is typically proportioned with a higher sand-to-total- aggregate ratio (*s/agg*) than conventional concrete, as fine aggregate helps suspend coarse aggregate and increase filling ability (Bonen and Shah 2005; Kwan and Ng 2009).

Fang, Jianxiong, and Changhui (1999) and Khayat and Mitchell (2009) recommend using a *s/agg* of 0.40–0.50, but the exact ratio is dictated by the application (ACI 237 2007).

2.2.2 Portland Cement and Supplementary Cementing Material

The powder phase consists of portland cement, ground inert fillers, and supplementary cementing materials. As in conventional concretes, an increased powder phase and relatively low water-to-cementitious-material ratio are used in precast, prestressed SCC to ensure the high early-age strength that is desired for the application (Koehler et al. 2007). While the water-to-cementitious-material ratio is further discussed in Section 2.2.3, the types and proportions of cement and supplementary cementing materials that are commonly used in precast, prestressed SCC are discussed in this section.

PCI (2004) recommends selecting the type of cement based on the overall requirements of the individual application, including strength, durability, and appearance. Although any of the five primary types of portland cement can be used in SCC, Type III cement is preferred for precast elements because of its high early-age strength characteristics (Khayat and Mitchell 2009). With mostly the same chemical composition as standard Type I cement, Type III cement varies mainly in that it is more finely ground than Type I (Mehta and Monteiro 2006). The extra grinding increases particle surface area, which increases the cement's rate of early-age strength gain, a property that is conducive to the manufacturing process for precast members (Mindess, Young, and Darwin 2003).

Because Type III cement hydrates quickly, it loses workability more quickly, which needs to be accounted for during placement of SCC. To reduce this risk and also decrease the cost of the relatively larger amount of cementitious material, supplementary cementing materials are frequently used (Khayat and Mitchell 2009; Mehta and Monteiro 2006). Hydration-stabilizing admixtures may also be used to regulate setting and promote prolonged workability. These admixtures are discussed in Section 2.2.4.2.

2.2.2.1 Fly Ash

Fly ash is a glassy, spherical waste product of coal-fired power plants. It is divided into two classes based largely on calcium oxide content: Class C, which is typically 15–40 percent calcium oxide, and Class F, which is less than 10 percent calcium oxide (Mehta and Monteiro 2006). Typically used to decrease the cost and heat of hydration associated with Type III cement, fly ash can also increase workability of conventional concrete (ACI 232 2003).

Fly ash may also enhance workability and slump flow of SCC (ACI 237 2007), particularly when using Class F fly ash (Khayat and Mitchell 2009). Although other replacement rates can be used, workability of SCC can be most efficiently increased and maintained when fly ash replaces 20–40% of the portland cement by volume (Fang, Jianxiong, and Changhui 1999; Khayat and Mitchell 2009).

Because of the difference in calcium oxide content, the two classes of fly ash have different effects on the fresh properties of SCC. While both classes improve workability, Class F, with its reduced initial reactivity, has been shown to better retain fluidity of SCC (Khayat and Mitchell 2009). However, early strength gains at three and seven days are reduced more when using Class F fly ash than when using Class C (Mehta and Monteiro 2006). The choice of which type of fly ash to use, or to use slag cement (see Section

2.2.2.2), is frequently determined by regional availability and the strength-gain needs of the application. Class C fly ash has been used in previous SCC production for research in Alabama (Kavanaugh 2008; Roberts 2005).

2.2.2.2 Slag Cement

Slag cement is "the nonmetallic product, consisting essentially of silicates and aluminosilicates of calcium and other bases that is developed in a molten condition simultaneously with iron in a blast furnace" (ACI 233 2003). It is a cementitious material whose chemical composition varies widely depending on the source, although the variance between sources is much greater than within one plant (ACI 233 2003). Because of its fineness and chemical composition, it reduces heat of hydration and begins to contribute to early-age strength gains within seven days (Koehler et al. 2007), with its greatest benefits being increased long-term strength and durability (ACI 233 2003). The choice between it and Class C fly ash depends largely on local availability and relative cost, making it a viable supplementary cementing material in SCC.

2.2.2.3 Silica Fume

Silica fume can be used at small cement replacement dosages to greatly increase the quality of concrete: increase early strength, decrease chemical permeability, improve frost durability, and reduce bleeding, in which excess water separates from the hydrating concrete (ACI 234 1996). An industrial byproduct in the production of silicon metal, silica fume is approximately fifty times finer than portland cement (ACI 234 1996). Its fineness and chemical makeup are largely responsible for its effects on concrete, and it is a popular addition in SCC for high-performance applications such as precast, prestressed bridge element production (Fang, Jianxiong, and Changhui 1999).

Because of its extreme fineness, silica fume reduces the fluidity of SCC (ACI 237 2007), which must be offset by increasing dosages of water and water-reducing admixtures (Fang, Jianxiong, and Changhui 1999). The increased demand for water and chemical admixtures is sensitive to the dosage of silica fume and type of chemical admixture (Fang, Jianxiong, and Changhui 1999), so the addition of water and admixtures must be carefully monitored in SCC.

2.2.3 Water

The water-to-cementitious-material ratio (*w/cm*) of concrete is inversely related to the strength of the concrete—as *w/cm* decreases, strength increases (Mehta and Monteiro 2006). The *w/cm* of SCC can be the same as that of a conventional concrete of the same use. As high early-age strengths are desirable for precast concrete, SCC proportioned for that application employs a low *w/cm*, typically between 0.34 and 0.40 (Khayat and Mitchell 2009).

The selection of the *w/cm* used in precast, prestressed SCC is frequently controlled by the demands of early-age release-strength requirements (ACI 237 2007). As stated in Section 2.2.2, large amounts of cementing materials are frequently used in precast, prestressed SCC to increase the mortar fraction, improve cohesiveness, and help suspend the coarse aggregate particles. Although SCC with a higher *w/cm* could attain adequate compressive strength, it would exhibit a reduced early-age compressive strength. Consequently, precast SCC is proportioned with a reduced *w/cm* and is always given its fresh characteristics through the use of chemical admixtures (ACI 237 2007).

2.2.4 Admixtures

Although the fresh characteristics of SCC are influenced by the proportioning of constituents described thus far in Section 2.2, their effects are limited compared to those of chemical admixtures (Fang, Jianxiong, and Changhui 1999). The following frequently used admixtures will be discussed in this section (Mindess, Young, and Darwin 2003):

- Air-entraining admixtures, which increase the microscopic air bubbles present in concrete, making it more resistant to freezing and thawing,
- Hydration-stabilizing admixtures, which affect the setting time of the concrete,
- Water-reducing admixtures, which reduce the amount of water necessary to achieve a particular consistency or increase the workability at a given *w/cm*, and
- Viscosity-modifying admixtures, which increase viscosity, improve cohesiveness, and reduce segregation tendency.

2.2.4.1 Air-Entraining Admixtures

Air, in the form of macroscopic voids and microscopic bubbles, inevitably makes up some percentage of the volume of concrete. Like any porous material, concrete is susceptible to damage by cyclic freezing and thawing of water caught in these voids. When resistance to this damage is important, such as in saturated bridge elements exposed to temperature fluctuations around 32˚ F, a uniform air void structure can prevent excessive damage (Mindess, Young, and Darwin 2003). This uniform structure can be secured with air-entraining admixtures (AEA), thus making their use popular in precast bridge element construction.

AEA are typically used in very small dosages, as air content is sensitive to the admixture. The fluid nature of SCC makes the dispersion of air-entraining admixtures more uniform, allowing for smaller dosages to be used (Khayat and Assaad 2002; Mindess, Young, and Darwin 2003). However, churning of the fluid concrete tends to increase air content (Khayat and Assaad 2002), so the admixture dosage must be adjusted based on the concrete fluidity and production techniques employed.

2.2.4.2 Hydration-Stabilizing Admixtures

Effective not only in SCC, hydration-stabilizing admixtures affect the setting time of concrete, whether for delaying or accelerating purposes. In SCC proportioned with a high cementitious content or low *w/cm*, hydration-stabilizing admixtures are usually used in dosages that allow the SCC to maintain its fresh properties during the batching, transport, and placing process, with the expectation of normal set and curing thereafter (PCI 2004).

Hydration-stabilizing admixtures are less common in precast section construction, as the SCC is mixed in the same location as casting, and rapid set and curing are favorable to the construction process. However, in very low *w/cm* applications, such as in precast, prestressed girder production, hydration-stabilizing admixtures are used to delay setting while additional batches are placed and to slow the potentially damaging heating that results from cement hydration (PCI 2004).

2.2.4.3 Water-Reducing Admixtures

As stated in Sections 2.2.1 and 2.2.3, the flowability of SCC is partially controlled through the proportioning of aggregates and selection of *w/cm*. However, these changes have relatively small influences on the SCC compared to the influence of water-reducing (WR) admixtures. As the name implies, water-reducing admixtures decrease the water necessary to achieve a given workability in a concrete mixture. In fact, WR admixtures, especially high-range water-reducing (HRWR) admixtures, are always used to induce the flowability necessary for creating SCC (Roberts 2005).

Only fresh properties of SCC are directly affected by the addition of HRWR admixtures, while hardened properties, particularly strength, are affected by the reduction in *w/cm* generally accompanying the use of HRWR admixtures. Although specific effects depend on the admixture type and dosage employed, HRWR admixtures generally cause the following (Mindess, Young, and Darwin 2003):

- Increased slump,
- Rapid slump loss once the HRWR admixture is exhausted,
- Increased bleeding, but only when dosages are excessive, and
- Air detrainment, while reducing the amount of air-entraining admixture necessary to achieve a given air content

2.2.4.4 Viscosity-Modifying Admixtures

As a fluid, the yield stress of SCC corresponds to the minimum shear stress required to initiate flow. Below the yield stress, SCC does not undergo any deformation and does not, therefore, flow. The constant of proportionality (slope) of the relationship between shear stress and shear rate is referred to as the plastic viscosity and refers to the resistance of the material to undergo a given flow (ACI 237 2007). Figure 2.1 illustrates a Bingham model of this behavior in which, above the yield stress, shear stress increases linearly as shear rate increases (Koehler et al. 2007).

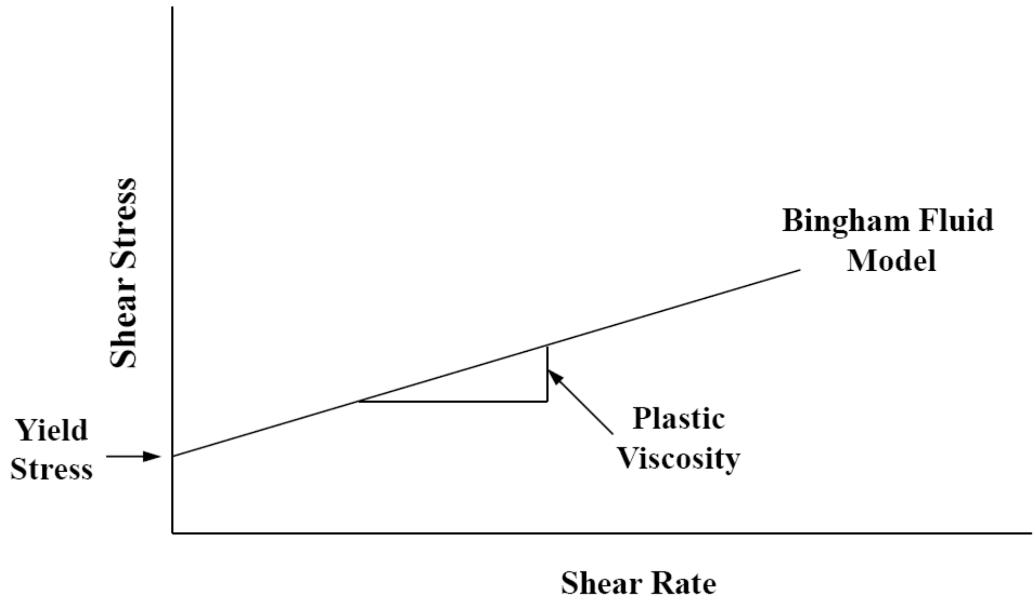

Figure 2.1: Viscosity relationship in a Bingham fluid (Koehler et al. 2007)

In practical terms, SCC that must travel greater distances during placement, or through narrow or congested formwork, requires lower viscosity, as a lower resistance to flow will ensure self-consolidating behavior in those situations (Koehler et al. 2007). The viscosity of a concrete mixture can be controlled through aggregate selection, or by controlling the dosages of WR admixtures and viscosity-modifying admixtures (Khayat, Ghezal, and Hadriche 2000; Koehler et al. 2007). Viscosity-modifying admixtures can also be used to make a mixture more robust, or more easily able to maintain a uniform viscosity between batches despite batching inconsistencies (ACI 237 2007; Khayat, Ghezal, and Hadriche 2000), and they can help maintain a uniform stability at a lower viscosity (Khayat 1999). The use of viscosity-modifying admixtures is, thus, important in SCC with a high *w/cm* or low cementitious content (Khayat and Mitchell 2009).

2.3 Performance of Self-Consolidating Concrete

As shown by the diversity of the materials and proportions used to make it, SCC can be produced to achieve almost any target performance in both the fresh and hardened states. As with any concrete use, SCC produced for precast, prestressed construction follows a particular set of performance targets necessitated by

- The constraints of the construction process,
- The volume and distribution of steel reinforcement, and
- The necessary structural attributes of the concrete.

In this section, fresh and hardened properties of SCC are discussed, as are the ways in which these properties are measured. Emphasis is placed on the requirements for SCC used in precast, prestressed applications.

2.3.1 Fresh Properties

SCC in the fresh state can be defined by three primary characteristics: passing ability, filling ability, and stability (ACI 237 2007). From a fluid mechanics point of view, SCC can also be defined rheologically. Rheology, the study of deformation and flow of a material under loads, defines SCC in terms of its yield stress (minimum stress to induce flow) and plastic viscosity (ACI 237 2007). While these properties are useful for describing the general characteristics of SCC, as in Section 2.2, they are difficult to experimentally quantify. Rheological testing is time-consuming and requires the use of expensive equipment, and the results are not easily grasped (Emborg 1999).

In past research, relationships have been found between the rheology of SCC and its passing and filling abilities (Lange 2007). However, because neither passing nor filling ability was the primary concern of this research, these properties are defined by measurement techniques in lieu of the more fundamental rheological parameters.

2.3.1.1 Filling Ability

Filling ability, otherwise known as unconfined flowability, describes the ability of liquid SCC to flow into and completely fill the shape of the formwork under its own weight (ACI 237 2007). Filling ability is practically defined by the lateral distance the SCC can travel from the point of discharge, and the most common measure of filling ability is the slump flow test (ASTM C 1611 2005). The slump flow test, shown in Figure 2.2 and Figure 2.3, measures the lateral spread of a sample of SCC after it leaves an inverted slump cone. The T50, which is the time it takes for the sample to spread to 50 centimeters (20 in.), can be measured in conjunction with this test.

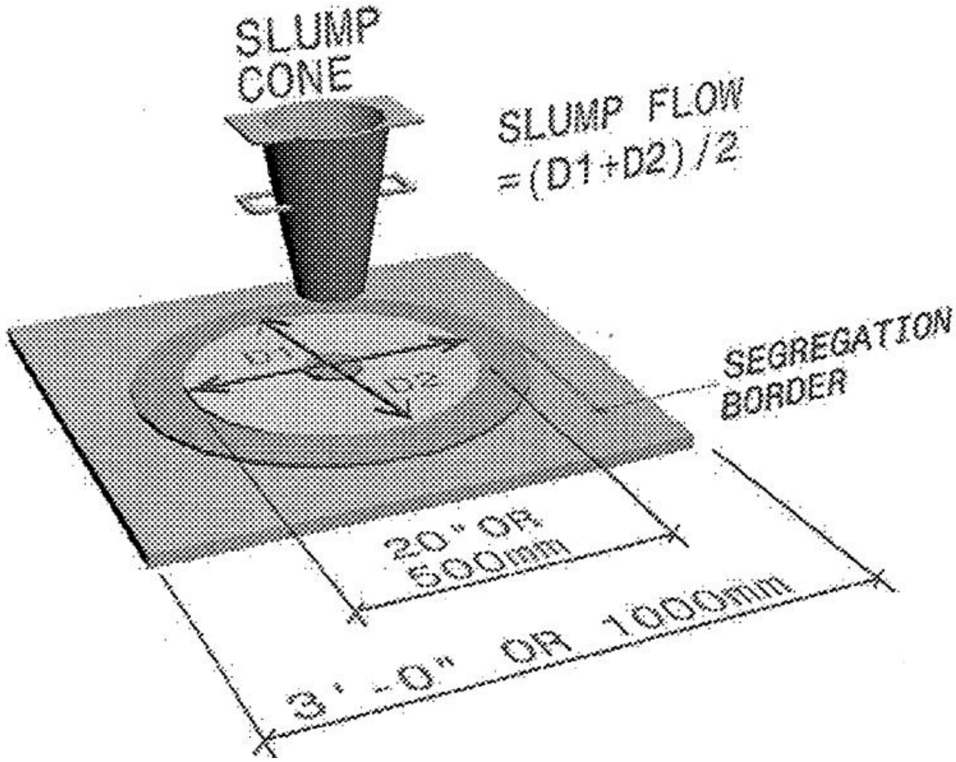

Figure 2.2: Inverted slump cone (PCI 2004)

Figure 2.3: Slump flow test in progress

SCC used in the construction of precast, prestressed bridge girders must possess high filling ability (Khayat and Mitchell 2009). Past research and construction in this field have typically identified a target slump flow of 27 in. ± 2 inches (ACI 237 2007; Roberts 2005; Schindler et al. 2007).

2.3.1.2 Passing Ability

Passing ability, or confined flowability, describes SCC's ability to pass between obstacles and through narrow spaces within the forms without blockage (ACI 237 2007). It is practically defined through the use of mock-up structural elements that attempt to mimic these obstacles and narrow spaces. The most common tests for passing ability are the J-ring test and the L-box test (ACI 238 2008). These two tests, shown in Figure 2.4 and Figure 2.5, assess the restricted flow of SCC around predetermined obstacles. The J-ring test is run similarly to the slump flow test described earlier, except that the laterally flowing concrete must pass through a ring of obstacles as defined by ASTM C 1621 (2009). The test results are given as a restricted slump flow, and precast, prestressed concrete is typically required to have a restricted flow that is reduced by no more than 2 in. from its unconfined slump flow.

Figure 2.4: J-ring apparatus with slump cone (ACI 237 2007)

The L-box consists of vertical and horizontal legs separated by a gate, as shown in Figure 2.5. SCC fills the vertical leg, and, after the gate is raised, flows horizontally around a line of obstacles into the horizontal leg. The height of the SCC at the end of the horizontal leg is compared to the height of the SCC remaining in the vertical leg, with a ratio closer to 1.0 implying that the SCC has a higher passing ability. In SCC for precast construction, Khayat and Mitchell (2009) recommend a ratio exceeding 0.50, while others (ACI 237 2007; EPG 2005) recommend a ratio exceeding 0.80.

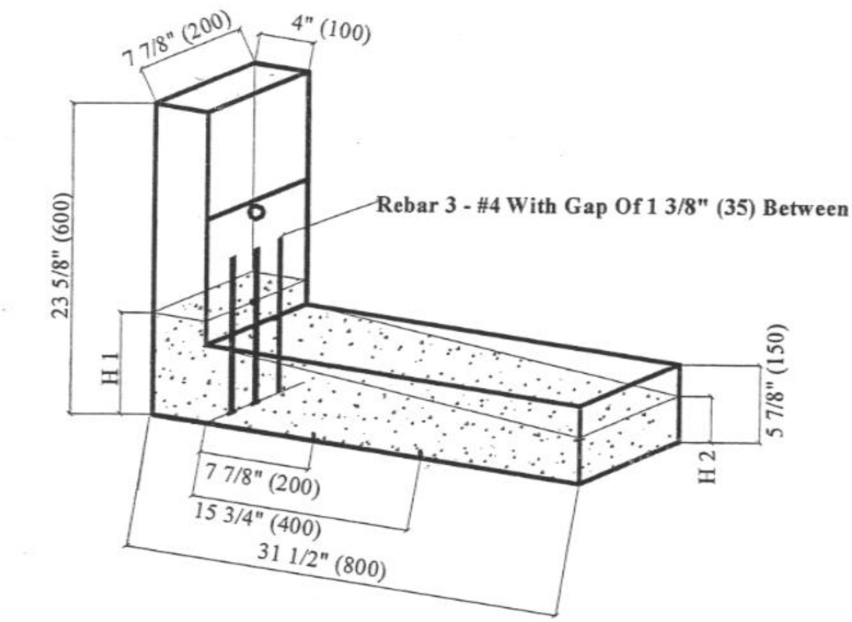

Figure 2.5: Typical L-box configuration (PCI 2004)

2.3.1.3 Stability

Stability, or concrete's ability to remain uniform before, during, and after placement, may be difficult to maintain while also achieving adequate passing and filling abilities. In highly demanding applications, such as in the construction of precast, prestressed beams, passing and filling abilities are increased by reducing coarse aggregate size and content and increasing either *w/cm* or HRWR admixture content. While the reduction in aggregate size helps promote mixture stability during placement (Khayat and Mitchell 2009), the reduction in aggregate content decreases the number of collisions between coarse aggregate particles, which may reduce their ability to resist settlement (Koehler and Fowler 2008). Increasing *w/cm* or HRWR admixture content reduces relative stability, as those increases result in decreased cohesion of the mixture (Khayat and Mitchell 2009; Lemieux, Hwang, and Khayat 2010).

During the construction process, different forms of segregation occur while the SCC is dynamically active than while it is stationary. These forms of segregation, and the different measures taken to resist them, are described in the following subsections.

2.3.1.3.1 Dynamic Stability

Dynamic stability of SCC refers to its ability to resist separation of its constituents while it is moving, primarily during placement into the formwork (ACI 237 2007). Typically, segregation in the dynamic state encompasses any form of forced separation of coarse aggregate from the binder as the concrete flows outward from the point of discharge through closely spaced reinforcement and narrow openings (ACI 237 2007).

Dynamic segregation can be assessed while conducting the tests that assess filling and passing ability, as the SCC is dynamically active during those tests (ACI 237 2007). To that effect, the J-ring, L-box, and slump flow tests can each be used to visually identify any separation of aggregate from the binder resulting from flow during testing. However, none of these tests were intended to quantitatively assess dynamic stability (Koehler and Fowler 2010), and dynamic stability must be tailored to the demands of each application.

Precast, prestressed girder construction requires high dynamic stability because of both the spacing of the reinforcement and the long flow distances the SCC must travel. According to Khayat (1999) and Ng, Wong, and Kwan (2006), cohesiveness of the mortar and choice of coarse aggregate are the most important factors in ensuring adequate dynamic stability. As mentioned in Sections 2.2.1 and 2.2.2, SCC made for precast girder construction accomplishes this through

- Relatively high cementitious content of approximately 600–800 lbs/yd^3 (ACI 237 2007; Khayat and Mitchell 2009),
- Small gradation of coarse aggregate, such as a No. 78 gradation (Koehler et al. 2007; Roberts 2005), and
- Relatively lower total aggregate content and higher *s/agg* (Koehler et al. 2007).

Furthermore, dynamic stability is assured through avoidance of any outside sources of vibration (ACI 237 2007), limitation of free-fall drop height (Khayat and Mitchell 2009), and the use of quick placement rates (Bonen and Shah 2004; Lange 2007). While the PCI Guidelines (2004) suggest determining acceptable free-fall, or the unrestricted dropping of SCC into deep formwork, through the use of mock-up elements, Khayat and Mitchell (2009) recommend limiting free-fall to 6.6 ft. The AASHTO Bridge Construction Specifications (2010) Section 8.7.3.1 requires that free-fall of conventional concrete be limited to 5 ft. Researchers have successfully dropped SCC from greater heights, but only in situations where reinforcement could restrict the fall (ACI 237 2007; Zhu, Gibbs, and Bartos 2001). The limitation is meant to limit the forced sedimentation of the heaviest aggregates upon impact, and more importantly, to limit the entrapment of large air voids.

SCC, because of its fluid nature, benefits from added kinetic energy through “remixing” of the flowing material. As the concrete flows outward from the placement point, increased rate of flow increases fluid drag exponentially, which helps force heavier aggregate to move with the flow (Bonen and Shah 2004; Lange 2007). However, the highly fluid material can entrap air bubbles against forms and within the remixing fluid

(ACI 237 2007; Khayat and Assaad 2002). Proper selection of the placement rate of SCC is necessary to balance these two effects—use a high enough placement speed to ensure uniform filling, but not one so high as to cause air void instability (ACI 237 2007).

2.3.1.3.2 Static Stability

Static stability of SCC refers to its ability to resist separation of its constituents while it is stationary, primarily after placement into the formwork (ACI 237 2007). Forms of segregation experienced in the static state include (PCI 2004)

- Settling of coarse aggregate particles,
- Non-uniform dispersion of lighter constituents, and
- Internal and external bleeding due to excess or uneven accumulation of water.

The above forms of segregation cannot be reduced by using proper construction practices (such as avoidance of vibration or excessive free-fall), so static stability is instead managed through mixture proportioning (Bonen and Shah 2004). As stated by Kwan and Ng (2009), SCC must be proportioned to achieve a desirable fluidity without adversely affecting the hardened properties of the mixture or causing a lack of cohesion of the fresh concrete.

Cohesion affects settling of coarse aggregate, as do aggregate size and density, aggregate content, and mortar density (Bonen and Shah 2005; Lange 2007). Aggregate size affects the ratio of surface area to weight, with smaller aggregate exhibiting a higher surface area for the same mass. This increased surface area allows each particle to be more easily suspended in the mixture. Similarly, incorporating a coarse aggregate of a similar density to that of the mortar phase allows each particle to be more easily suspended in the mixture (Bonen and Shah 2005; Lange 2007).

According to Bonen and Shah (2004) and Koehler and Fowler (2008), coarse aggregate in SCC cannot settle freely through fluid mortar, but instead collides with underlying aggregate particles. This creates an aggregate lattice structure that can help mitigate settlement when mortar viscosity alone cannot prevent it. For the same volume of aggregate, smaller aggregate leaves more, smaller inter-particle voids, increasing the likelihood of inter-particle collisions that prevent settlement (Koehler and Fowler 2008).

Although selection of coarse aggregate can limit aggregate settlement in the static state, air and unbound water still tend to rise. To limit these forms of segregation, cohesiveness and water-demand of the binder material must be considered. Cohesion helps stabilize the air structure of the mixture, as the cohesive mortar prevents the upward migration of air particles through static SCC (Khayat and Assaad 2002). If not prevented, upward-travelling air particles either disperse unevenly over height or become concentrated beneath large aggregate particles, both of which result in a non-uniform product (Khayat and Assaad 2002).

Similarly, water in excess of what is needed to hydrate cementitious materials either escapes (external bleeding) or collects beneath horizontal obstructions such as coarse aggregate and steel reinforcement (internal bleeding) (Mindess, Young, and Darwin 2003). This collection of bleed water is illustrated in Figure 2.6. Reasons for the presence of excess water include overdosing of water or of WRA, miscalculation of water present in batched coarse aggregate and fine aggregate, and other production-related issues such as leaving water in the mixer after washing out a prior batch.

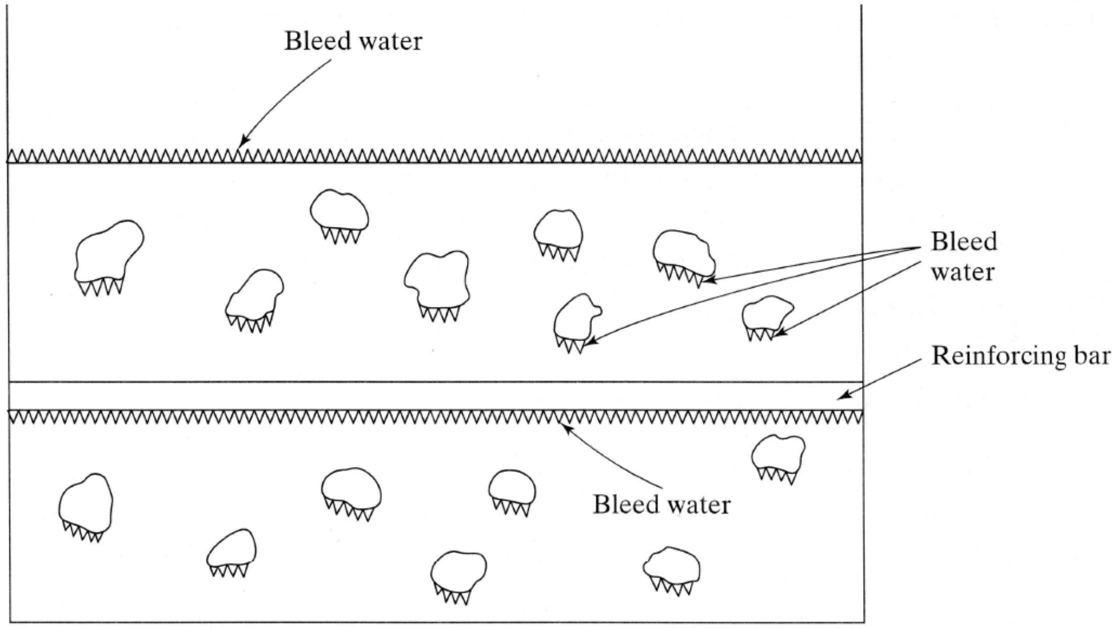

Figure 2.6: Internal and external bleeding (Mindess, Young, and Darwin 2003)

Hydrostatic pressure of the fluid SCC can further aggravate the uneven dispersion of air and water. After placement into forms, still-plastic SCC has been shown to cause self-weight induced pressures that increase with depth (ACI 237 2007; Lange 2007). This pressure results in some forced expulsion of incompressible water and a reduction of the size of compressible air voids (Castel et al. 2006; Khayat and Assaad 2002).

2.3.2 Hardened Properties

General hardened properties of SCC, and the effects static segregation can have on them, are discussed in this section. When SCC is used in place of conventional concrete, its performance should be similar or better than that of the replaced concrete. Concrete used for production of precast, prestressed bridge elements must follow a particular set of performance characteristics, many of which may be directly affected by segregation.

As discussed in Section 2.3.1.3, a lack of static stability results in an uneven distribution of the constituents of SCC, with air and water tending to rise and coarse aggregate tending to sink (Castel et al. 2006; Soylev and Francois 2003). The result, inevitably, is a variation in the mechanical properties of the hardened concrete. This variation can be measured nondestructively with the ultrasonic pulse velocity (UPV) test, which will be described in Section 2.4. This variation is also an underlying cause of strength variation (Khayat, Manai, and Trudel 1997) and bond variation (Mindess, Young, and Darwin 2003). The effects of segregation on these two performance characteristics are described in more detail in the following sections, as are the methods used to assess them.

2.3.2.1 Strength

Concrete used in precast, prestressed applications typically exhibits higher strength than cast-in-place concrete. In previous studies involving precast, prestressed concrete (Khayat and Mitchell 2009; Schindler et al. 2007), compressive strength values ranged from 5,000 psi to 9,000 psi. When stable, SCC can have equal or better strength uniformity than conventional concrete in this strength range (Khayat, Attiogbe, and See 2007; Khayat, Manai, and Trudel 1997; Khayat et al. 2003; Zhu, Gibbs, and Bartos 2001). Khayat, Manai, and Trudel (1997) and Zhu, Gibbs, and Bartos (2001) predict that the uniformity is a result of the semi-automated casting and consolidation process, which removes some user-variability.

Where researchers have attempted to directly study the effect of static stability on strength uniformity, elements were cast using SCCs of varying stability, and the uniformity of strength was determined by testing cores taken along their height. Some found that strength variation was statistically insignificant in SCC showing questionable stability (Daczko 2003; Soylev and Francois 2003), while others concluded that strength variation is directly affected by segregation (Khayat 1998; Khayat, Manai, and Trudel 1997). Although they conclude that strength variation is caused by segregation, Khayat (1998) and Khayat, Manai, and Trudel (1997) note that the variation in strength they measured may have been attributable to the coring process.

Mindess, Young, and Darwin (2003) point out several potential flaws of the coring process, all of which make it a difficult method for studying strength uniformity:

- The drilling process can damage the concrete within the core. The resulting random variation can only be decreased by increasing the number of samples, which requires a much larger specimen,
- The ratio of core strength to companion cylinder strength decreases more rapidly as concrete strength increases. This may lead to an underestimation of the variation in strength actually present, as high-strength concrete cores test disproportionately lower than low-strength concrete, and
- As mentioned in Section 2.3.1.3.2, bleed water and air tend to accumulate on the underside of aggregate, leading to planes of weakness in that direction. Cores loaded parallel to these planes of weakness exhibit compressive strength reductions that do not occur in cylinders loaded normal to planes of weakness.

As illustrated in Figure 2.7, wall elements are cast vertically and cored horizontally, which means core strength may be overly sensitive to these planes of weakness that are caused by segregation.

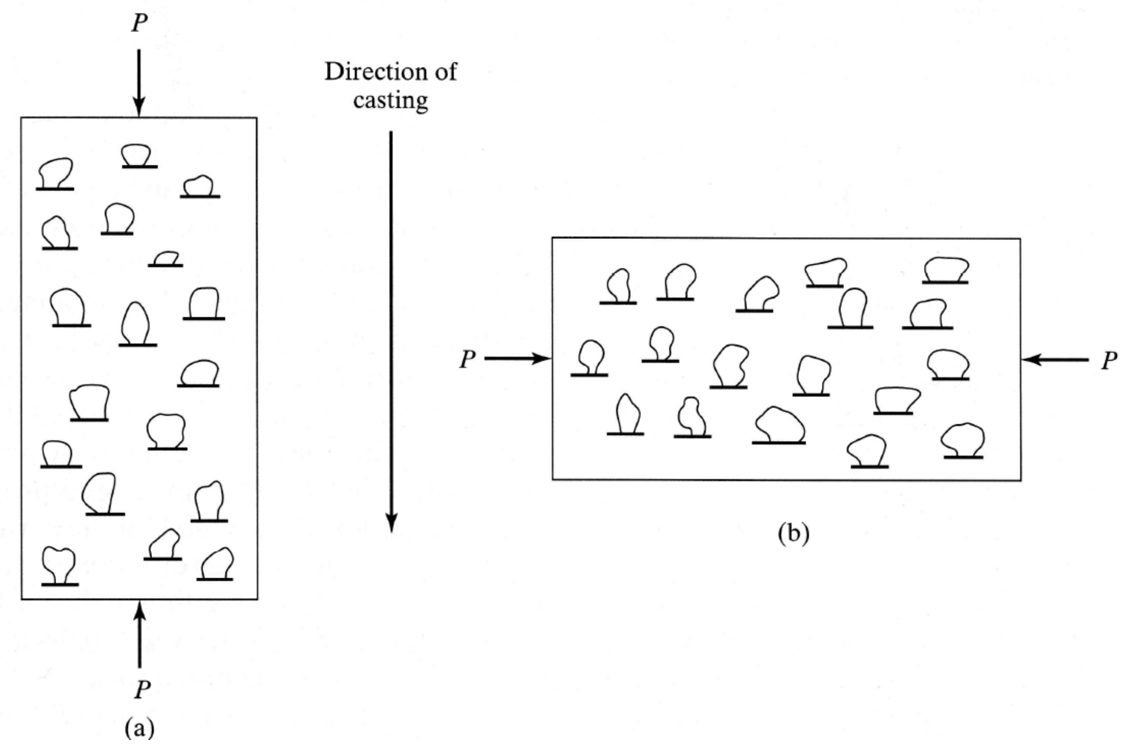

Figure 2.7: Planes of weakness due to bleeding: (a) perpendicular to direction of loading, and (b) parallel to direction of loading (Mindess, Young, and Darwin 2003)

2.3.2.2 Bond with Reinforcement

Another structural characteristic widely studied with respect to SCC is bond with reinforcement. The relationship between concrete quality and strength of bond with reinforcement has been widely documented:

- Bond strength is affected by surface characteristics and size of reinforcement (Stocker and Sozen 1970),
- Bond strength is affected by concrete age at time of testing (Chan, Chen, and Liu 2003; Hassan, Hossain, and Lachemi 2010),

- Bond strength is proportional to the square root of compressive strength (ACI 318 2008; Barnes, Grove, and Burns 2003; Khayat et al. 2003),
- Bond strength is significantly affected by weak bond surfaces caused by the accumulation of air particles and bleed water (Castel et al. 2006; Soylev and Francois 2003).

The effect of concrete age relates specifically to the use of chemical admixtures, as the early-age curing rate of concrete can vary widely based on admixture type and dosage. This can cause two mixtures with the same later-age behavior to exhibit very different early-age behaviors. However, the effect of admixture type and dosage on bond strength seems to stabilize at approximately 14 days (Chan, Chen, and Liu 2003; Hassan, Hossain, and Lachemi 2010).

Several researchers (Almeida Filho, El Debs, and El Debs 2008; Cattaneo 2008; Girgis and Tuan 2005; Hossain and Lachemi 2008) have found that SCC exhibits equal or better bond capacity than equivalent conventional concrete, while others (Esfahani, Lachemi, and Kianoush 2008; Swords 2005) have found that SCC does not have as much bond capacity as equivalent-use conventional concrete. In all cases (Almeida Filho, El Debs, and El Debs 2008; Barnes, Grove, and Burns 2003; Cattaneo 2008; Esfahani, Lachemi, and Kianoush 2008; Girgis and Tuan 2005), the average bond strength was found to be proportional to the square root of average compressive strength.

Chan, Chen, and Liu (2003), Esfahani, Lachemi, and Kianoush (2008), and Hossain and Lachemi (2008) have used this strength proportionality to infer that segregation more seriously affects bond than compressive strength. If an exponential decay in strength should be required to cause a linear decrease in bond, but bond decreases rapidly in segregated concrete despite little strength loss, segregation is most likely the cause of the bond reduction (Esfahani, Lachemi, and Kianoush 2008; Soylev and Francois 2003).

2.3.2.2.1 Effect of Segregation on Bond Quality

As already pointed out in Section 2.3.2.1 and shown in Figure 2.6, both excess bleed water and migrating air tend to pool beneath horizontal obstructions in concrete, which reduces the concrete quality near these surfaces. When reinforcement is cast horizontally within a concrete member, such as longitudinal reinforcement in beams, this weakened surface can develop along the entire underside of the reinforcement. When this occurs, bond to reinforcement is reduced (Castel et al. 2006; Esfahani, Lachemi, and Kianoush 2008; Khayat, Manai, and Trudel 1997).

Because air and water migrate upward, the upward portion of the cast concrete suffers from the greatest reduction in bond. Some researchers (Khayat, Manai, and Trudel 1997; Soylev and Francois 2003) found a linear decrease with height, with the highest bond strength at the bottom of the member. Khayat, Manai, and Trudel (1997) found this relationship during testing of concrete members 59 in. (150 cm) tall, while Soylev and Francois (2003) tested concrete members 79 in. (200 cm) tall.

Other researchers (Castel et al. 2006; Hassan, Hossain, and Lachemi 2010; Jeanty, Mitchel, and Mirza 1988; Stocker and Sozen 1970) suggest that the reduction is stepped, with the most noticeable drop in bond capacity occurring in bars with greater than 10 in. to 12 in. of concrete cast below them. Castel et al. (2006) made this conclusion after testing concrete specimens 59 in. tall, while Jeanty, Mitchel, and Mirza (1988) tested concrete specimens 18 in. tall, and Stocker and Sozen (1970) tested concrete specimens 32 in. tall.

Whether stepped or gradual, this phenomenon, known as the “top-bar effect”, affects the top-cast bars of deep members and has been documented in both conventional concrete and SCC. The effect is typically presented as the nominal bond strength of bottom-cast bars divided by that of top-cast bars, with a value of 1.0 indicating an absence of the top-bar effect.

Research concerning the top-bar effect in SCC (Castel et al. 2006; Hassan et al 2010; Hossain and Lachemi 2008; Khayat, Attiogbe, and See 2007; Khayat, Manai, and Trudel 1997; Khayat et al. 2003) has concentrated on assessing the viability of high-quality SCC. The top-bar effects Khayat, Attiogbe, and See (2007) calculated for conventional concretes and SCC’s used in precast, prestressed construction are identified in Figure 2.8, with effects in conventional concrete identified as 1, 1R, and 2 and effects in SCC identified as 3–6. In that figure, the top-bar effect is calculated by dividing bottom-cast bar pullout strength (Ub) by pullout strength at each other tested location. The top-bar effect varies irregularly with height, but with larger effects (that represent larger reductions in bond capacity) near the top of tested sections.

In studies that tested the top-bar effect in SCC mixtures of questionable stability (Castel et al. 2006; Khayat 1998), the effect was measured to confirm the presence of instability, not to establish a required level of stability. Also, all of the mixtures assessed by Khayat, Attiogbe, and See (2007) were deemed stable but still exhibited the variability shown in Figure 2.8. By selecting a maximum acceptable top-bar effect, though, Khayat and Mitchell (2009) were able to use measured top-bar effects to determine if mixtures exhibited acceptable uniformity. This is further discussed in Section 2.6.2.

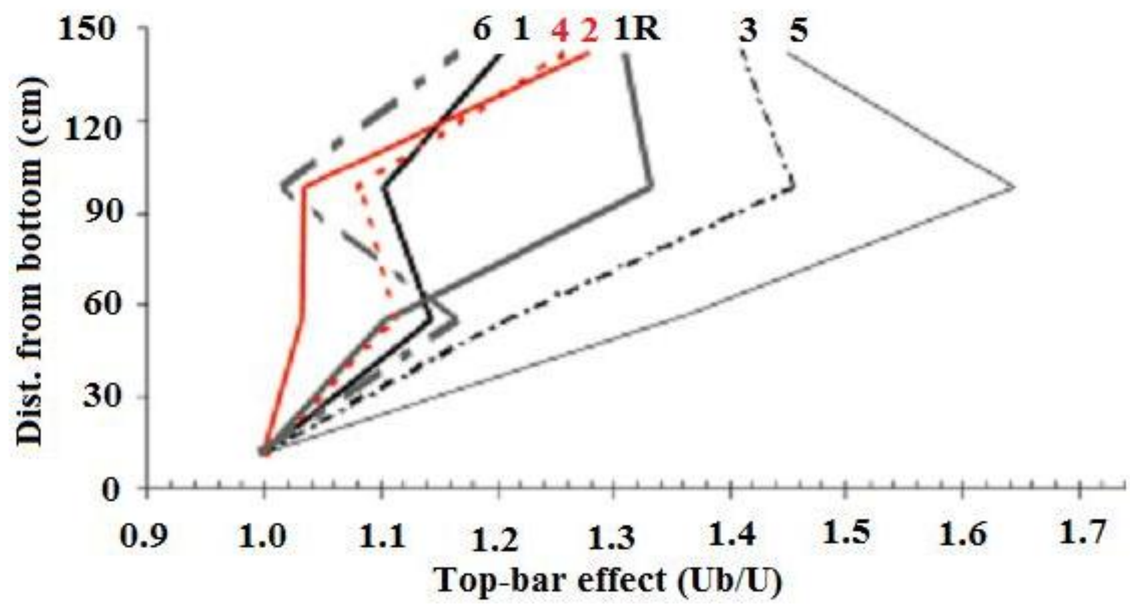

Figure 2.8: Top-bar effect in conventional concrete [1, 1R, 2] and SCC [3–6] for precast construction, by height above bottom of section (Khayat, Attiogbe, and See 2007)

2.4 Assessment of Uniformity of Self-Consolidating Concrete by Hardened Concrete Tests

Of those hardened properties of SCC most frequently affected by segregation, two were selected for observation in this research as benchmarks to assess in-situ uniformity: ultrasonic pulse velocity and bond to reinforcement.   Ultrasonic pulses sent through hardened concrete walls can show changes in elastic properties and composition (Mindess, Young, and Darwin 2003), and bond to reinforcement is affected by aggregate settlement, air migration, and bleeding (Castel et al. 2006; Soylev and Francois 2003). The details of these tests, as well as past research in which they have been employed, are described in the following subsection.

2.4.1 Ultrasonic Pulse Velocity Test

While strength testing and bond testing can show the effects of segregation on hardened performance, nondestructive ultrasonic pulse velocity testing (UPV) can directly measure changes in the overall quality of hardened concrete (Abo-Qudais 2005; Naik, Malhotra, and Popovics 2004; Sahmaran, Yaman, and Tokyay 2007). The test is conducted by placing two metal couplers on flat surfaces of the concrete specimen, initiating rapidly repeating ultrasonic pulses at one coupler, and measuring the average time required for the pulses to reach the other coupler. Once the travel length between couplers is determined, the average speed of pulses through that travel path can be calculated. A typical configuration of this test is shown in Figure 2.9. The speed of the ultrasonic pulse is affected by several factors:

- Density and porosity, in which speeds are higher in denser, less porous material (Lin et al. 2007; Lin, Lai, and Yen 2003; Sahmaran, Yaman, and Tokyay 2007),
- Interface quality between mortar and coarse aggregate, in which a better interface results in better transmission of waves (Abo-Qudais 2005; Soshiroda, Voraputhaporn, and Nozaki 2006),
- Aggregate size, in which presence of larger aggregate results in reduced speed (Abo-Qudais 2005),
- Aggregate content, in which presence of more aggregate results in increased speed (Abo-Qudais 2005; Lin et al. 2007; Lin, Lai, and Yen 2003),
- Moisture content and concrete saturation, in which water fills pores to transmit faster pulses (Abo-Qudais 2005; Mindess, Young, and Darwin 2003), and

- Strength, in which speeds are higher in stronger material (Abo-Qudais 2005; Lin et al. 2007; Soshiroda, Voraputhaporn, and Nozaki 2006).

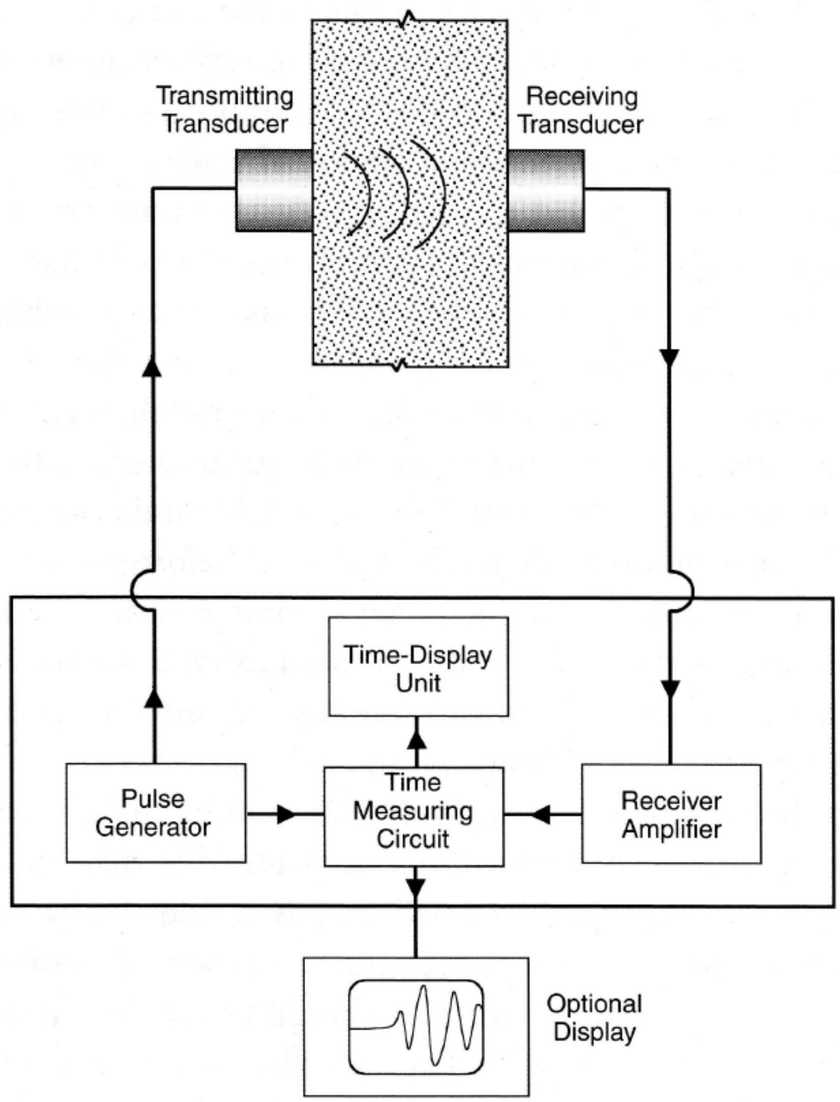

Figure 2.9: Ultrasonic pulse velocity testing equipment
(Naik, Malhotra, and Popovics 2004)

The factors that affect UPV results are all related to SCC uniformity: strength relates to *w/cm* ratio, density relates to distribution of constituents and mortar quality, and interface quality relates to presence of excess water (Mehta and Monteiro 2006). The ability to simultaneously account for these factors makes the UPV very useful for assessing the effects of possible segregation and for detecting changes in concrete quality at different locations within a concrete element.

2.4.1.1 Past Research with Ultrasonic Pulse Velocity Testing

Previous studies have made use of UPV tests for several purposes, originally focusing on locating cracks in concrete members, where pulse speeds are greatly slowed by discontinuities (Komlos et al. 1996). UPV testing has also been used to monitor strength and elasticity changes over time, where additional curing results in increasing pulse speeds (Komlos et al. 1996). In some studies (Lin, Lai, and Yen 2003; Solis-Carcano and Moreno 2008), equations were established to predict elasticity and strength based on UPV results. Considering all of the variables affecting UPV results, though, ASTM C 597 (2002), Komlos et al. (1996), Lin et al. (2007), and Naik, Malhotra, and Popovics (2004) advise that predictions are only accurate if accompanied by correlation testing. Thus, the UPV is best suited for comparative investigations of concrete quality (ASTM C 597 2002; Cussigh 1999; Komlos et al. 1996; Naik, Malhotra, and Popovics 2004; Solis-Carcano and Moreno 2008).

The first time UPV testing was used specifically to study the effects of segregation on SCC performance was in France in 1999 (Cussigh 1999). In that research, walls with dimensions approximately 9 ft tall by 8 ft wide by 10 in. thick were cast using SCC of varying degrees of stability. The same walls were also produced using conventional concrete with varying degrees of applied consolidation, thus making it possible to compare varying levels of stability in SCC to levels of consolidation in conventional concrete.

UPVs were determined along the height of the walls and were then used in conjunction with core samples to study segregation. SCC that showed segregation proved to have less uniform velocities over height than stable SCC, but all measured velocities through SCC proved to be as uniform as satisfactorily vibrated conventional concrete. Some of the UPV curves from that project are presented in Figure 2.10. The concept of this testing, in which UPV testing is used to compare levels of uniformity within and between concrete samples, is of interest in the current research project, as certain factors must be considered in order to isolate the effects of segregation on uniformity.

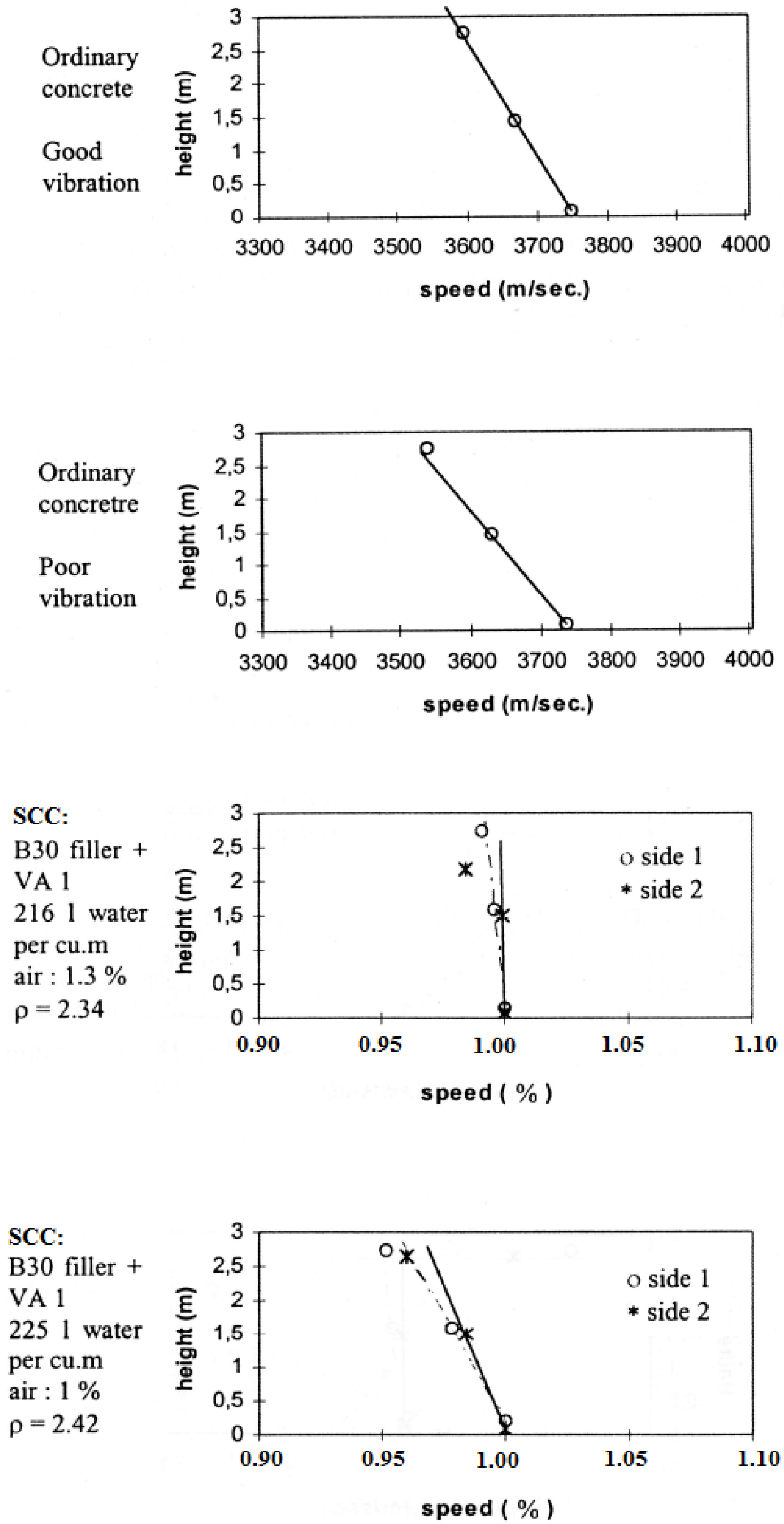

Figure 2.10: Ultrasonic pulse velocities through: *top*, conventional concrete, well vibrated; *second*, conventional concrete, poorly vibrated; *third*, SCC, stable; *bottom*, SCC, poor stability (Cussigh 1999)

2.4.1.2 Configuration of Ultrasonic Pulse Velocity Testing Equipment when Assessing Concrete Uniformity

To effectively use the UPV to study uniformity of SCC, all of the other sources of UPV variability must be avoided. Variability can come from

- Reinforcement, which can either accelerate pulses by transmitting sound more quickly or attenuate pulses by scattering waves as they pass (Mindess, Young, and Darwin 2003; Naik, Malhotra, and Popovics 2004),
- Large aggregate, which can scatter higher frequency waves as they pass through the material (Abo-Qudais 2005; Naik, Malhotra, and Popovics 2004), and
- Cracks, which distort or block the travel of ultrasonic waves (Abo-Qudais 2005; Soshiroda, Voraputhaporn, and Nozaki 2006).

Past research (Abo-Qudais 2005; Gaydecki et al. 1992) and guides for testing (ASTM C 597 2002; Naik, Malhotra, and Popovics 2004) have thoroughly outlined how to avoid these issues. The first line of defense against irregularity is selection of the configuration and frequency of the equipment to be used. The direct transmission method, shown in Figure 2.11, is the universally preferred configuration of all groups referenced in this section because the travel length and form of transmission are easily defined.

For testing concrete, Gaydecki et al. (1992) recommend a frequency of 55–85 kHz and ASTM C 597 (2002) recommends a frequency range of 40–80 kHz, both with a preference for higher frequencies when using shorter path lengths. There is no upper or lower limit to the path length, L, but Naik, Malhotra, and Popovics (2004) recommend L

be between 4 in. and 28 in. for 54 kHz transducers (the frequency used in this research), and Cussigh (1999) used an *L* of 10 inches.

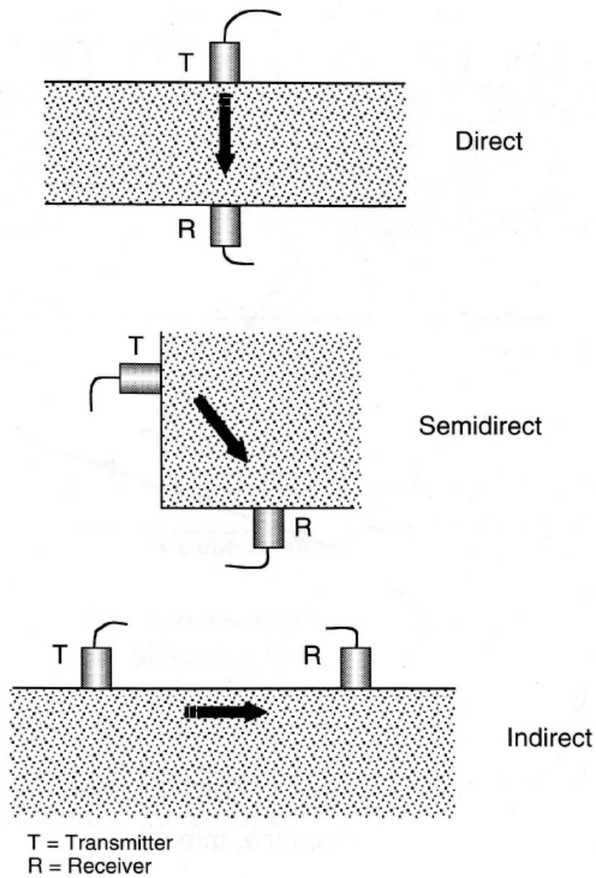

Figure 2.11: Ultrasonic pulse velocity testing transmission methods (Naik, Malhotra, and Popovics 2004)

At a frequency of 54 kHz, aggregate should have nominal dimensions no greater than 2.75 in., which is obviously not a concern for precast, prestressed SCC. For reinforcement parallel to the direction of pulse transmission to be ignored, the bars must generally be laterally spaced at least 0.25*L* away from the test point, with a conservative estimate of 0.35*L* (Naik, Malhotra, and Popovics 2004).

Unavoidable sources of UPV variability include cracking and degree of saturation (ASTM C 597 2002). Good curing conditions, safe handling, and prevention of thermal cracking lessen the risk of cracking and nonuniform saturation. Readings through cracked concrete are drastically different than those taken through uninterrupted travel paths, making it easy to recognize them.

Meanwhile, the influence of degree of saturation can only be normalized by testing samples at a consistent degree of saturation. Soshiroda, Voraputhaporn, and Nozaki (2006) recommend taking readings at the earliest age possible after the concrete achieves final set because, over time, the strength of the mortar phase approaches that of the encapsulated coarse aggregate, resulting in faster UPVs that are less capable of differentiating between coarse aggregate contents. Later-age testing is, therefore, better for studying strength uniformity (Lin et al 2007), but less useful for studying air, water, and aggregate distribution (Soshiroda, Voraputhaporn, and Nozaki 2006).

2.4.2 Pullout Test

As described in Section 2.3.2.2, bond between reinforcement and concrete is a material mechanical property of broad applicability to structural performance. Although many configurations have been used to test it, the principle is the same: apply tension to steel reinforcement cast into concrete specimens while recording the force applied and amount of slip undergone by the reinforcement. If the total bonded surface area is known, the bond stress can be calculated by dividing the pullout force by the surface area. Bond stress can then be related to different levels of slip in order to evaluate bond behavior.

2.4.2.1 Failure Modes and Causes during Pullout Testing

Different bond behaviors occur under different pullout testing configurations. When a long bonded length is used, the reinforcement yields before it debonds from the surrounding concrete. This signifies that the total bond force capacity exceeds the axial force required to yield the reinforcement (ACI 408 2003). In research that has used long bonded lengths, study of bond behavior was limited to a comparison of slip values at lower stresses (Chan, Chen, and Liu 2003; Peterman 2007; Sonebi and Bartos 1999).

When very short bonded lengths are used in pullout testing, the concrete surrounding the reinforcement fails before the steel reaches its yield stress. In these circumstances, there are two modes of concrete failure: cracking failure and shear failure. Refer to Figure 2.12, which illustrates the forces being applied to the surrounding concrete. Cracking failure (also known as splitting failure) occurs when deformations in the reinforcement act as wedges that force the surrounding concrete outward, causing tensile stresses in the concrete and, eventually, splitting tensile failure. This failure mode is associated with a lack of confinement, and results do not indicate the ultimate bond capacity of the concrete mixture (ACI 408 2003; Cattaneo, Muciaccia, and Rosati 2008; Sonebi and Bartos 1999). Although bond has been studied in samples exhibiting this failure mode, the resulting top-bar effects are heavily influenced by the testing arrangement (Peterman 2007).

Shear failure (also known as pullout failure), occurs when sufficient confinement prevents splitting rupture of the concrete. In this failure mode, planes of shear stress caused by the mechanical interlock of ribbing and concrete develop parallel to the reinforcement. Microcracks develop in these planes, eventually coalescing until shear failure occurs (ACI 408 2003). Figure 2.13 provides an example of this failure mode, which shows a gradual buildup of bond stress as cracks form and a gradual decay as friction resists the pullout over extended displacements. Pullout testing that results in shear failure can give a measure of concrete quality and uniformity not affected by inadequate cover or steel quality (Khayat et al. 2003), which makes it useful for studying the potential effects of segregation in SCC.

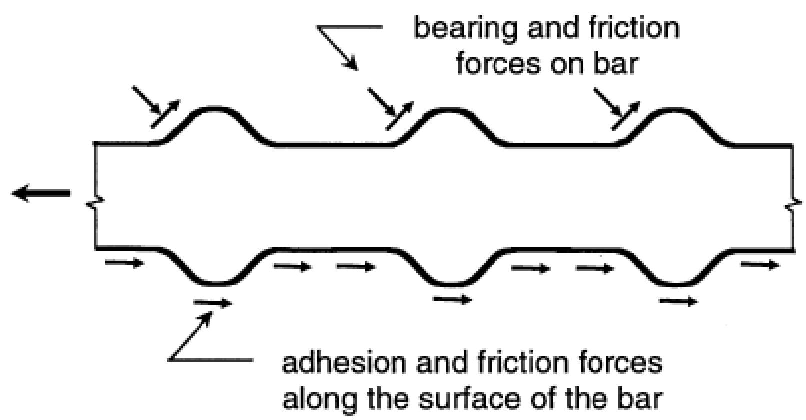

Figure 2.12: Bond forces acting on steel embedded in concrete (ACI 408 2003)

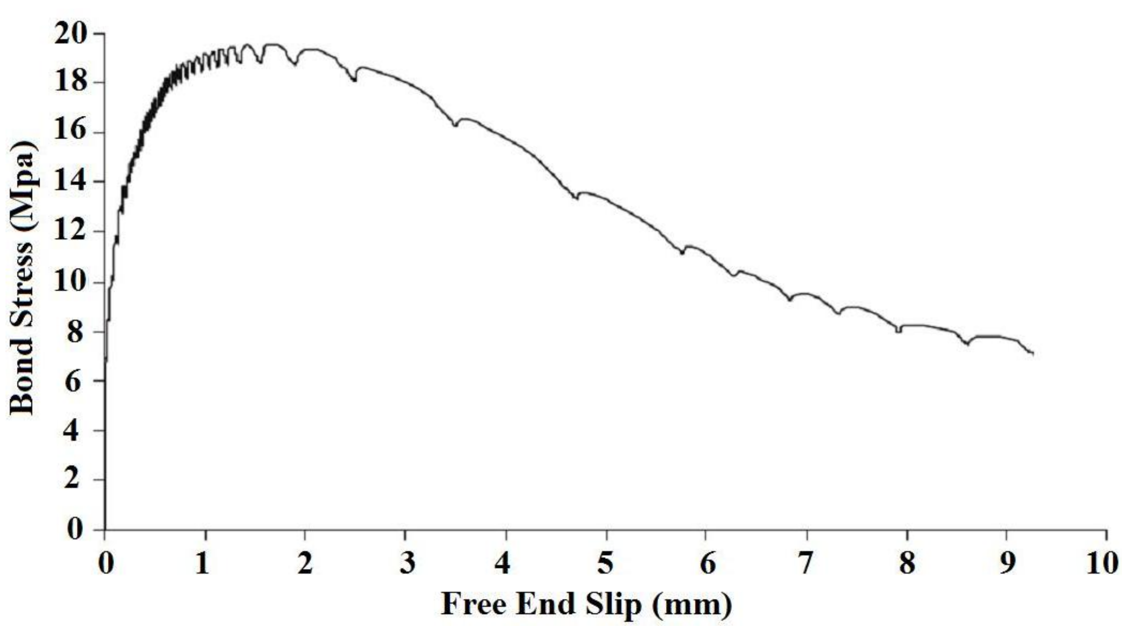

Figure 2.13: Bond stress and slip of shortly bonded rebar during shear failure (Hassan, Hossain, and Lachemi 2010)

2.4.2.2 Configuration of Pullout Testing when Assessing Concrete Uniformity

Researchers have related shearing bond failure to concrete quality using several variations of well confined, shortly bonded pullout specimens. Some researchers (Chan, Chen, and Liu 2003; Hassan, Hossain, and Lachemi 2010) achieved adequate confinement by inclusion of confining reinforcement. To avoid the need for confining steel reinforcement, other researchers (Cattaneo, Muciaccia, and Rosati 2008; Girgis and Tuan 2005) achieved adequate confinement by increasing the lateral cover of concrete surrounding the pullout bars. They (Cattaneo, Muciaccia, and Rosati 2008; Girgis and Tuan 2005) found that the minimum lateral cover that ensures shear failure during pullout testing is eight times the diameter of the steel bars pulled out (8 d_b).

Selection of bond length in past research was not so frequently determined by the yield strength of the steel as much as it was by the uniformity of the pullout results. As steel is pulled from concrete, the resisting force in the surrounding concrete must develop to provide force equilibrium with the steel. When combined with the contraction of steel due to Poisson’s Effect, a gradient develops in the concrete stress along the bonded length. Since calculation of bond strength usually assumes that bond stresses are distributed uniformly, use of short bond lengths is best when studying ultimate bond capacity (Alavi-Fard and Marzouk 2004; Girgis and Tuan 2005; Khayat 1998; Khayat, Manai, and Trudel 1997; Stocker and Sozen 1970). However, due to the heterogeneous nature of concrete, shorter bond lengths result in increased scatter between samples.

In this report, d_b will be used to represent the nominal diameter of the reinforcing steel. In multiple research projects (Alavi-Fard and Marzouk 2004; Girgis and Tuan 2005; Khayat, Manai, and Trudel 1997; Khayat and Mitchell 2009), a bonded length of

2.5 d_b to 3 d_b was found to give a satisfactory balance between achieving a uniform bond stress and having repeatable results. During that research, the bonded region of steel was isolated by debonding the remainder of the bar with commercially available plastic sheathing (Khayat and Mitchell 2009). A typical configuration of this style of pullout test is shown in Figure 2.14.

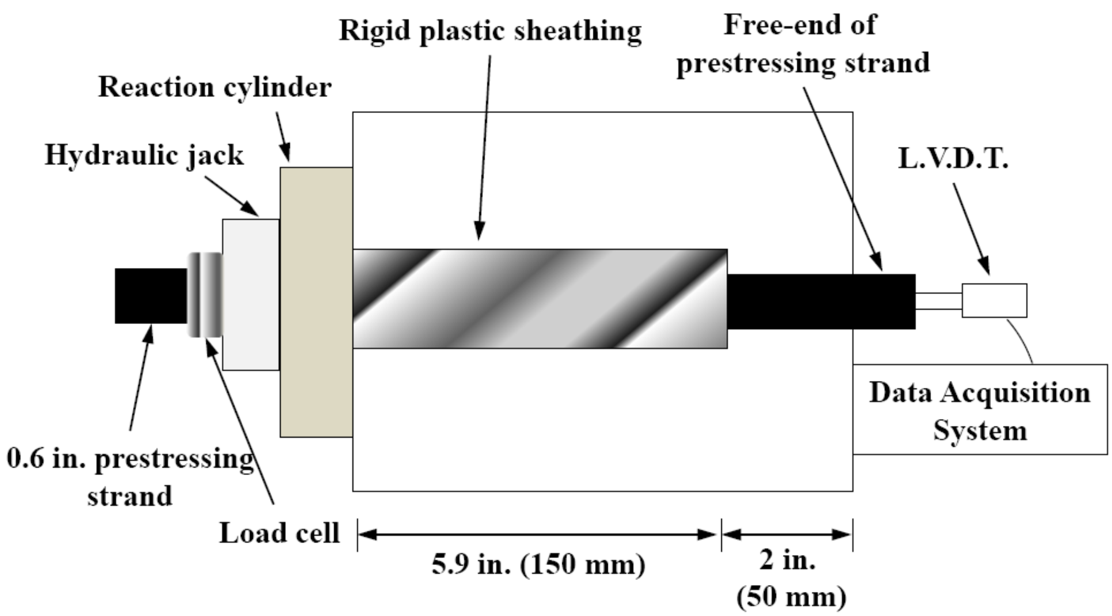

Figure 2.14: Load configuration of shortly bonded pullout test (Khayat and Mitchell 2009)

The stresses in the concrete surrounding the pullout bar must also be considered in determining the test configuration. While the deformed steel reinforcement is tensioned, the concrete on which the tensioning jack rests is compressed. This compression can provide load-dependent, unnatural confining pressure around the steel bars, resulting in mechanically enhanced bond capacity. To avoid this effect, two steps are taken to disperse the compressive forces: seat the hydraulic jack at an adequate lateral distance from the pullout point, and place the bonded region of steel away from the loaded face of the concrete. Khayat (1998) embedded the bonded region 5 in. from the loading surface of the concrete, Khayat and Mitchell (2009) embedded it 6 in. from it, and Sonebi and Bartos (1999) embedded it 3 in. from it.

2.4.2.3 Pullout Testing of Strand

It would seem most appropriate to study the bond capacity of SCC used in precast, prestressed applications by pulling out seven-wire prestressing strand instead of deformed steel reinforcement. In some of the reviewed literature concerning bond to SCC (Girgis and Tuan 2005; Khayat et al. 2003; Khayat and Mitchell 2009; Peterman 2007), and in an older study of bond to conventional concrete for prestressed applications by Stocker and Sozen (1970), strand was used to study bond capacity. Of those, Girgis and Tuan (2005) and Peterman (2007) tested full-scale beams with long bonded lengths and showed that SCC performs as well as conventional concrete in prestressed applications. Khayat et al. (2003), Khayat and Mitchell (2009), and Stocker and Sozen (1970) tested bond to strand using a shortly bonded, shear-failure-inducing configuration.

Stocker and Sozen (1970) confirmed that bond capacity is more significantly affected by bleeding and settlement than by strength, and Khayat et al. (2003) confirmed that stable SCC has better strand bond uniformity over height than conventional concrete. Stocker and Sozen (1970) point out two differences between testing strand and testing deformed reinforcing steel:

- Strand cast into concrete while unstressed does not employ the same bond mechanism as strand prestressed and then released after the concrete is cast. Axial contraction of prestressed strand after it is released increases the lateral pressure in the surrounding concrete, causing confinement that is not easily replicable in shortly bonded pullout specimens. This contraction does not occur while using deformed reinforcing steel.

- While bond of deformed bars depends on axial shear interlock to its fixed deformations, seven-wire strand depends on torsional interlock to its longitudinal spiral of six outer wires. The strand twists as it is pulled out of the concrete, and torsional bond occurs when the outer wires twist out of concrete keys formed during casting. This force interaction is shown in Figure 2.15.

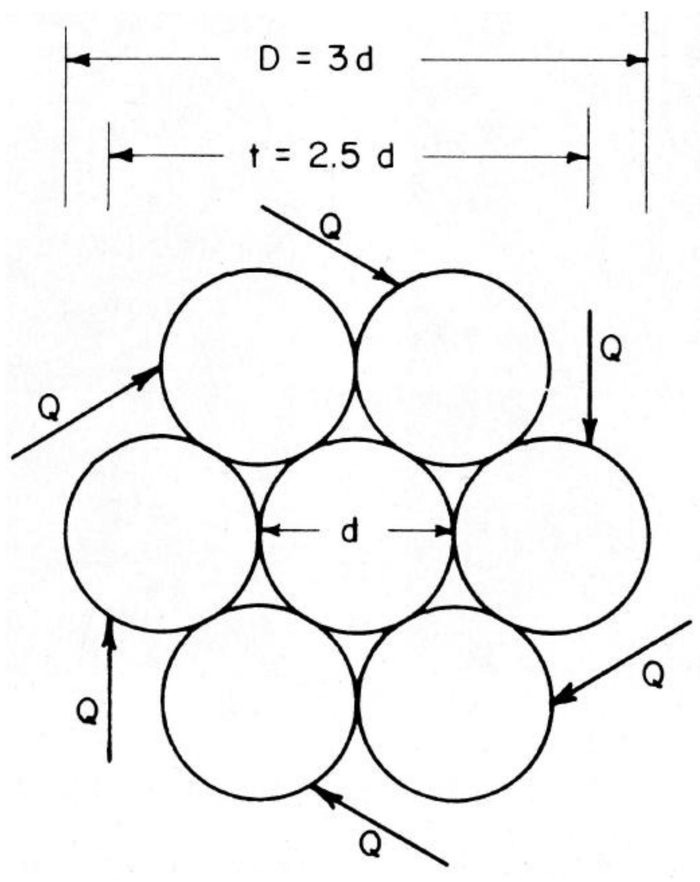

Figure 2.15: Force interaction between strand and concrete (Stocker and Sozen 1970)

2.5 Assessment of Static Stability of Self-Consolidating Concrete by Fresh Stability Test Methods

The tests described in Section 2.4 quantify the effects of segregation on the hardened properties of SCC. They can therefore be useful benchmarks for assessing tests designed to quantify segregation resistance of fresh SCC. The following section is used to identify

- The fresh stability test methods that attempt to estimate the stability of SCC,
- How each of these tests attempts to identify segregation,
- Why each of these tests was incorporated into past research, and
- What other measures were used to verify the efficacy each of these tests.

2.5.1 Rheological Tests

Converse to the other fresh stability tests described in Sections 2.5.2 and 2.5.3, rheological testing of SCC does not directly measure the segregation in a concrete sample. Instead, this class of tests measures the fundamental rheological properties of the sample (viscosity and yield stress) under the assumption that those properties can be related to segregation. Conflicting conclusions have been drawn concerning the relationship of rheology to stability: some have found no statistically significant correlation (Assaad, Khayat, and Daczko 2004; Bartos 2005; Ozyildirim and Lane 2003; Sahmaran, Yaman, and Tokyay 2007), while others have shown a tendency to segregate as plastic viscosity decreases (Koehler et al. 2007; Saak, Jennings, and Shah 2001).

As with the other fresh stability tests described in Section 2.5, consideration must be given to how these conclusions were reached. In some past studies that incorporated the use of rheological testing, other fresh stability tests (including the column segregation test and VSI) were used as a basis for identifying segregation (Assaad, Khayat, and

Daczko 2004; Bartos 2005; Koehler et al. 2007; Ozyildirim and Lane 2003). However, the ability of fresh stability tests to estimate in-place segregation was under investigation during the current Auburn University research, so correlations between fresh stability test methods (such as between rheological tests and the column segregation test or VSI) were not sufficient to prove a test's ability to estimate in-place segregation.

In other past rheological testing for stability, hardened concrete tests, including pullout testing and visual examination of aggregate distributions, were used to identify segregation. In testing of bond quality, Peterman (2007) showed that rheological tests were no better a predictor of bond quality than other fresh stability tests. Koehler et al. (2007) found excessive scatter in comparisons of rheology to aggregate distribution in cores, and Sahmaran, Yaman, and Tokyay (2007) found similar excessive scatter between rheological and UPV testing. Saak, Jennings, and Shah (2001) related rheology to settlement of a weight on the surface of SCC, but only settlement of aggregate was studied, not the bleeding of excess water.

2.5.2 Standardized Test Methods

The first two tests to be standardized by ASTM for measurement of static stability were the ASTM C 1610 Column Segregation Test (2006) and the VSI (ASTM C 1611 2005). The rapid penetration test (ASTM C 1712 2009) was standardized more recently and was validated by comparison to the two previously mentioned tests, while the sieve stability test was developed independently in Europe (EPG 2005). These four tests are reviewed in the following sections, and detailed testing instructions for the sieve stability test are given in Appendix A.1.

2.5.2.1 Visual Stability Index

The visual stability index (VSI) is the most widely used test to assess the stability of SCC (ACI 238 2008; Lange 2007). As the name implies, the VSI involves assigning a rating to the level of segregation seen in a sample of SCC. This sample, the patty left after testing the slump flow according to ASTM C 1611 (2005), is inspected for visible signs of segregation. A rating from 0 to 3 is then assigned based on appearance: 0 showing no signs of segregation; 1 showing some bleed water on the SCC surface; 2 showing a slight, defined mortar halo (< 10 mm) and noticeable bleeding; and, 3 showing clear segregation with aggregate piling in the center and with a well-defined mortar halo (> 10 mm) (ASTM C 1611 2005). PCI (2004) also gives advice on the half-increments of 0.5 and 1.5. In those Guidelines, a 0.5 rating is applicable when very light bleeding is noticeable on otherwise non-segregating SCC, while a 1.5 rating is applicable when some minor mortar separation and aggregate piling are visible. Examples of these VSI values are presented in Figure 2.16 through Figure 2.22.

Figure 2.16: Typical visual stability index rating of 0 (PCI 2004)

Figure 2.17: Typical visual stability index rating of 0.5 (PCI 2004)

Figure 2.18: Typical visual stability index rating of 1 (PCI 2004)

Figure 2.19: Typical visual stability index rating of 1 (PCI 2004)

Figure 2.20: Typical visual stability index rating of 1.5 (PCI 2004)

Figure 2.21: Typical visual stability index rating of 2 (PCI 2004)

Figure 2.22: Typical visual stability index rating of 3 (PCI 2004)

The VSI is qualitative in nature and is subject to each technician's assessment. Therefore, although it is useful for rapid quality assurance during production, the VSI should not be used to determine prequalification acceptance or rejection of a mixture

(ACI 237 2007). Several summary reports (EPG 2005; Ozyildirim and Lane 2003) suggest that the VSI is sufficient for initial segregation inspection, but other researchers (Bonen and Shah 2004; 2005; Lange 2007) suggest that a low VSI (showing good segregation resistance) does not ensure adequate static stability.

Bonen and Shah (2004; 2005) and Lange (2007) state that the VSI is inadequate to study static stability because performance of the slump flow test imparts kinetic energy into the SCC, which can affect the appearance of static segregation. In fact, Tregger, Ferrara, and Shah (2010) suggest that the VSI from the slump-flow patty should only be used to assess dynamic stability. Furthermore, mixtures that do not bleed (one form of segregation) are less sensitive to the VSI (ACI 237 2007). This was confirmed by Khayat and Mitchell (2009) and Peterman (2007), who both found unacceptable mechanical performance in SCCs with stable VSI values.

2.5.2.2 Column Segregation Test

The column segregation test (ASTM C 1610 2006) is often used to assess the static stability of SCC. Illustrated in Figure 2.23, this test involves pouring SCC into a cylindrical PVC mold consisting of three detachable sections and allowing it to rest for 15 minutes. SCC from the top and bottom portions of the column is then washed over a No. 4 sieve, leaving only the coarse aggregate. The coarse aggregate is then brought to the saturated surface dry (SSD) state and weighed. The weights of coarse aggregate in the top section and the bottom section are then used to quantify segregation using a segregation index (I_{seg}). I_{seg} is calculated according to the following equation, in which *CA* is the weight of SSD coarse aggregate in the weighed section:

$$I_{seg} = 2 \times \frac{(CA_{top} - CA_{bot})}{(CA_{top} + CA_{bot})} \times 100$$

According to Koehler and Fowler (2010), the calculated I_{seg} may be less than zero due to test variability. In that case, ASTM C 1610 (2005) states that the value should be recorded as zero. For determination of stability acceptance, Khayat and Mitchell (2009) and Koehler and Fowler (2010) recommend an $I_{seg} \leq 15\%$, while ACI 237 (2007) states that self-consolidating concrete exhibiting an $I_{seg} \leq 10\%$ is generally considered acceptable.

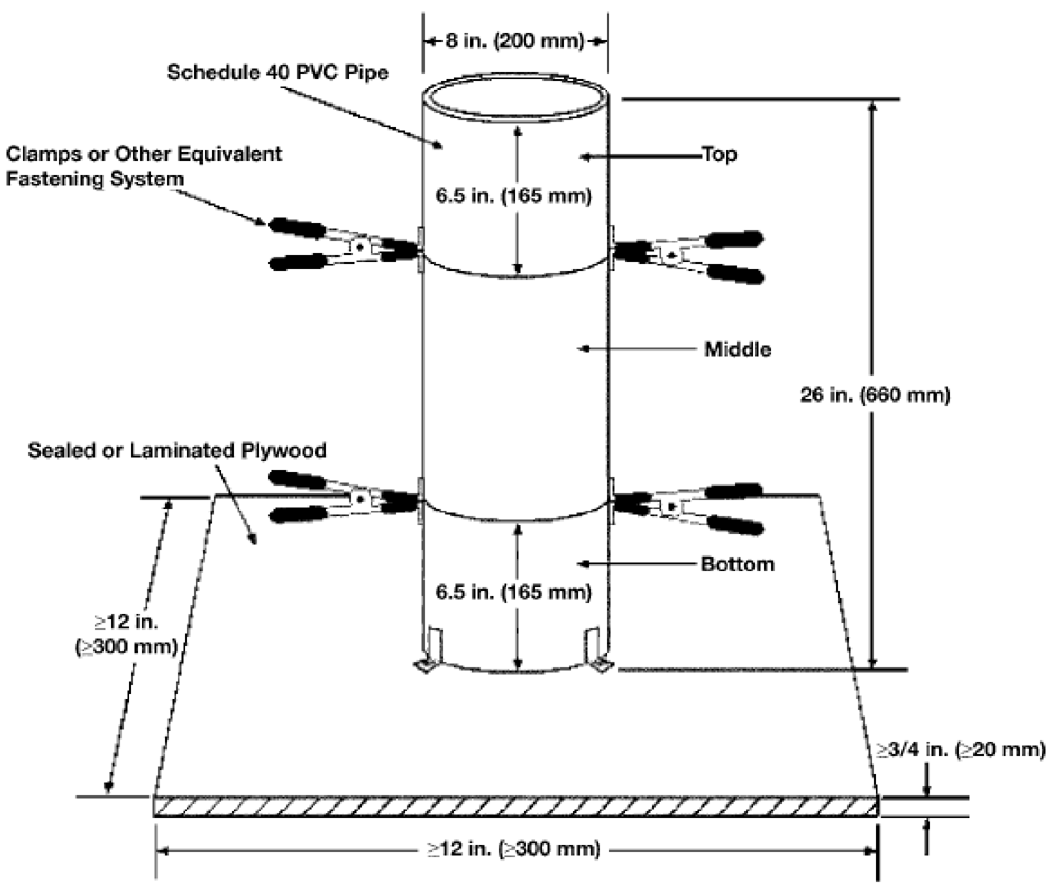

Figure 2.23: Standardized column segregation apparatus (ASTM C 1610 2006)

In a comprehensive survey conducted by Assaad, Khayat, and Daczko (2004), the column segregation test was evaluated alongside the VSI, rheological tests, and compressive strength of various mixtures. They found that the test is sensitive to sedimentation of aggregate, which was confirmed by Mouret, Escadeillas, and Bascoul (2008). As both sources note, the column segregation test is more sensitive when total aggregate content is low (Assaad, Khayat, and Daczko 2004; Mouret, Escadeillas, and Bascoul 2008). As explained in Section 2.2.1, a higher coarse aggregate content is offset by a lower mortar content. The increase in coarse aggregate limits the ability of any individual particles to settle, resulting in reduced column segregation values. Meanwhile, the decrease in binder content makes the mixture more sensitive to bleeding and segregation of binder (Assaad, Khayat, and Daczko 2004; Ng, Wong, and Kwan 2006; Ye, Bonen, and Shah 2005).

Because the column segregation test is affected by the aggregate content in this way, Assaad, Khayat, and Daczko (2004) and Khayat and Mitchell (2009) recommend using the column segregation test in conjunction with the surface settlement test described in Section 2.5.3.1, which is more sensitive to bleeding segregation. Similarly, Mouret, Escadeillas, and Bascoul (2008) recommend using it in conjunction with the sieve stability test described in Section 2.5.2.4, as they, too, found that the tests respond differently to segregation.

Many researchers (Bui et al. 2007; Koehler and Fowler 2010) have found the column test to be too slow and laborious to implement for quality assurance due to the 15-minute testing period and difficulty of separating and wet-sieving the test sample.

However, Assaad, Khayat, and Daczko (2004), Khayat and Mitchell (2009), and Mouret, Escadeillas, and Bascoul (2008) recommend using it for quality assurance testing of SCC stability.

2.5.2.3 Rapid Penetration Test

The rapid penetration test (ASTM C 1712 2009) was originally developed to be a quicker, technician-friendly alternative to the column segregation test (Bui et al. 2007). To that effect, the test is run on SCC already placed in the inverted slump cone for VSI and slump flow testing. After allowing the sample to settle for 80 seconds, a weighted hollow penetration cylinder, shown in Figure 2.24, is placed on the top surface and allowed to settle under its own weight. After 30 seconds, the penetration depth (Pd) of the cylinder is read to the nearest millimeter, which can be related directly to the mortar layer depth at the top of the sample and indirectly correlated to segregation resistance. According to ASTM C 1712 (2009), Pd relates to stability by the following:

- Samples with Pd < 10 mm are resistant to segregation,
- Samples with 10 mm ≤ Pd < 25 mm are moderately resistant to segregation, and
- Samples with Pd > 25 mm are not resistant to segregation.

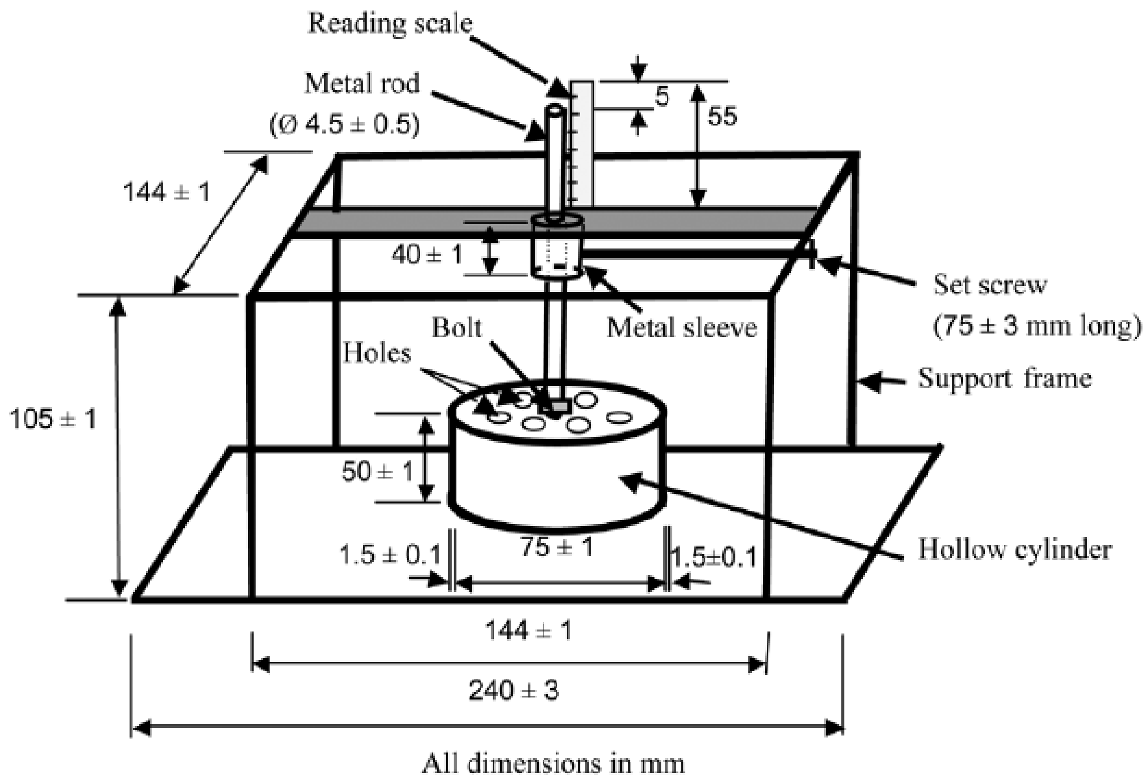

Figure 2.24: Standardized rapid penetration test apparatus (ASTM C 1712 2009)

ASTM C 1712 (2009) was developed by establishing a relationship between its results and those of the column segregation test (Bui et al. 2002; Bui et al. 2007). Additionally, the mortar layer depth at the top of hardened cylinders was determined by vertically cutting the cylinders, and the mortar layer depth was then compared to the column segregation index. Bui et al. (2007) found that mortar depth relates to segregation index and penetration depth relates to mortar layer depth, thereby allowing use of the penetration test in place of the column test. According to ASTM C 1712 (2009) and Bui et al. (2007), the test is useful for both prequalification and quality assurance, as it is faster than the column segregation test and is not subjective like the VSI.

ASTM C 1712 (2009) recommends establishing a new correlation between the penetration and column segregation tests whenever dealing with new mixture proportions, but Koehler and Fowler (2010) have found the rapid penetration test to be poorly related to both the column segregation test and sieve stability test (described in Section 2.5.2.4). The Self-Compacting Concrete European Project Group (EPG 2005) found the rapid penetration test to have greater scatter than the sieve stability test, and they recommend it as a secondary alternative to the sieve stability test.

2.5.2.4 Sieve Stability Test

The current form of the sieve stability test (a.k.a. sieve segregation resistance test, sieve test, or GTM screen stability test) was standardized by the SCC European Project Group (EPG 2005) following a three-year study by the EPG representative organizations. The test, shown in Figure 2.25 and detailed in Appendix A.1, requires a 10-L sample of SCC and approximately 18 minutes of testing time. After sitting for 15 minutes, the top portion of the 10-L sample is dumped from a specified height (usually with the assistance of a pouring apparatus) onto a 5 mm sieve and pan. It then rests on the sieve for 2 minutes to allow separation of mortar and aggregate. After those 2 minutes, the sieve and retained SCC are removed from above the pan, and the segregation fraction (S) is calculated by dividing the weight of SCC passing onto the pan by the total weight of SCC tested according to the following equation:

$$S = \frac{[(pan + SCC\ sieved\ fraction) - (pan)]}{[(sieve + pan + SCC\ total) - (sieve + pan)]} \times 100$$

Figure 2.25: Sieve stability test apparatus

The PCI guidelines (2004), which allow a No. 4 (0.25 in.) sieve to be used in place of a 5 mm sieve, recommend a segregation fraction 5% ≤ S ≤ 15%, as SCC with a segregation fraction less than 5% may begin to lack the flowability necessary to prevent bugholes and provide a good surface finish. The SCC European Project Group (2005) classifies sieve stability using the following classes:

- S ≤ 20 % for Class 1, which is applicable for slabs and applications with limited flow distances and clear spacing greater than 3 in.,
- S ≤ 15 % for Class 2, which is applicable for vertical applications with limited flow distances and clear spacing greater than 3 in., and

- $S \leq 10$ % in demanding applications with greater flow distances and clear spacing less than 3 in., such as for precast, prestressed girders.

Because SCC is dropped from a height of 20 in. onto the sieve, El-Chabib and Nehdi (2006) and Koehler and Fowler (2010) question what form of segregation the sieve stability test identifies. Gravity causes an increase in kinetic energy as the SCC falls, resulting in forced segregation of mortar from aggregate. Also, mixtures with a high mortar fraction and low coarse aggregate fraction may be more susceptible to testing poorly, as more mortar is present to pass through the sieve (El-Chabib and Nehdi 2006; Schwartzentruber and Broutin 2005).

Ng, Wong, and Kwan (2006) contradict this observation. They found that mixtures with a high coarse aggregate fraction may be more susceptible to testing poorly. For the same reason that the column segregation test becomes less sensitive as coarse aggregate content increases (see Section 2.5.2.2), the sieve test becomes more sensitive if it is able to identify bleeding and separation of mortar from aggregate. Mouret, Escadeillas, and Bascoul (2008) also found that the sieve test identifies segregation that the column test does not and vice versa, but others (Koehler et al. 2007; EPG 2005) have found the two tests to be highly correlated.

During a comprehensive study of SCC behavior (EPG 2005), the sieve test was the best indicator of segregation when compared with the column segregation test and the rapid penetration test. Also, because of its simple nature, EPG (2005) recommends it as the primary on-site quality assurance measure of stability for SCC projects in the

European Union. Although the form of segregation it identifies is unclear, the sieve test seems to relate well with in-situ segregation (Koehler and Fowler 2010; EPG 2005).

2.5.3 Experimental Tests

Outside of the four standardized fresh stability tests described above, many other fresh stability tests have been proposed for standardization or have been used during research on SCC behavior. Of these, some are very expensive, time-consuming, and precise, while others attempt to more rapidly, but less precisely, quantify stability. The most promising of these previously unstandardized test methods are described in Sections 2.5.3.1 through 2.5.3.3.

2.5.3.1 Surface Settlement Test

The surface settlement test (a.k.a. surface settlement segregation test) was recommended by Khayat and Mitchell (2009) as the primary stability test for SCC in precast, prestressed bridge element production. The test has not been standardized by ASTM or by other European equivalents, but it has been used in SCC research for several years (Khayat 1998; Khayat, Manai, and Trudel 1997; Khayat et al. 2003). The test is illustrated in its current form in Figure 2.26.

The principle of the test is simple: measure the settlement of a thin acrylic plate as it settles into a column of fresh SCC. The settlement is recorded as a percentage of the height of the column of SCC, and rate of settlement is calculated as a percentage of column height per hour. Either by settlement rate or maximum settlement, the test aims to study the presence of bleed water at the top surface of the column and the settlement of the uppermost coarse aggregate particles.

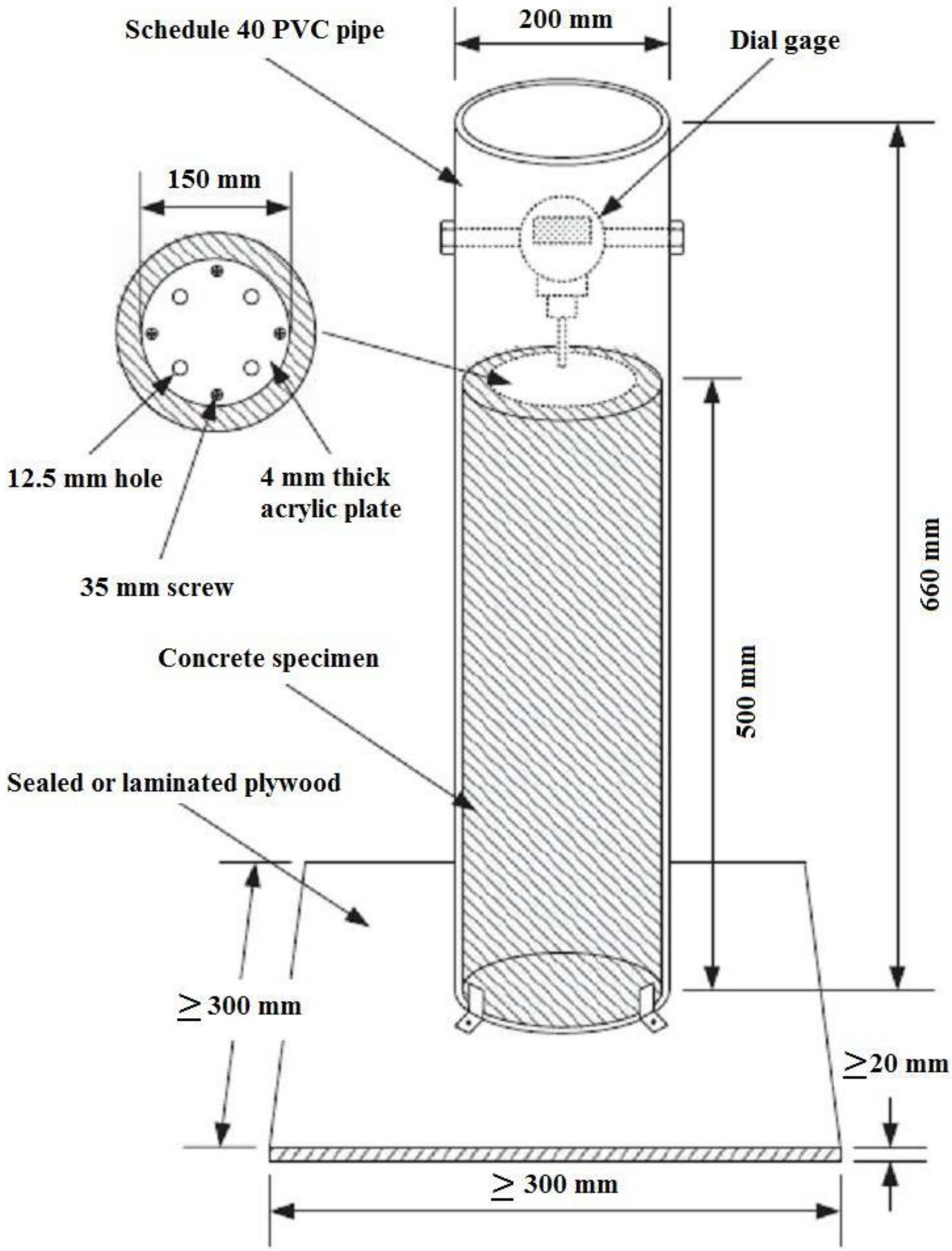

Figure 2.26: Surface settlement test apparatus (Khayat and Mitchell 2009)

The test was originally created to compliment in-situ uniformity testing of concrete walls (Khayat, Manai, and Trudel 1997). Confirmed by pullout testing and visual examination of hardened cores, Khayat (1998; 1999) and Khayat, Manai, and Trudel (1997) showed that the maximum settlement measured before the SCC sets indicates the level of static stability. Since this can take hours to determine, though, further testing was conducted that suggested the use of a rate of settlement calculated over a five-minute interval between 10 and 15 minutes, 25 and 30 minutes, or 55 and 60 minutes after test initiation (Hwang, Khayat, and Bonneau 2006). The relationships they found are shown in Figure 2.27. Because of these relationships, Khayat and Mitchell (2009) recommend assessment by rate in order to speed testing.

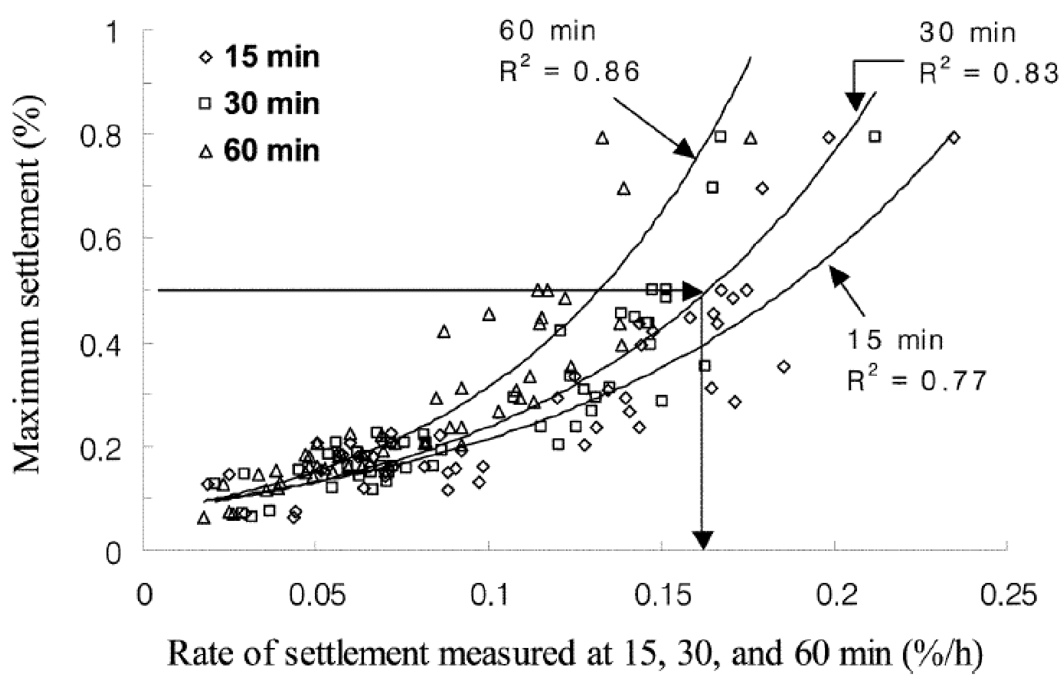

Figure 2.27: Relationships between rate of settlement and maximum settlement measured during the surface settlement test (Hwang, Khayat, and Bonneau 2006)

Assaad, Khayat, and Daczko (2004) and Sonebi and Bartos (2002) have shown that the surface settlement test gives a good measurement of the development of bleeding, which they confirmed by comparison to other fresh stability tests and hardened tests. Like the column segregation test and sieve test, though, surface settlement can be affected by the binder content and coarse aggregate content (Khayat 1999; Khayat, Ghezal, and Hadriche 2000; Sonebi and Bartos 2002). As already explained, increasing coarse aggregate content makes aggregate settlement more difficult, but at the expense of higher bleeding risk. Sonebi and Bartos (2002) also found that the test is sensitive to fine aggregate content, grading, and surface roughness, as these properties affect the bleeding potential of the mixture. Assaad, Khayat, and Daczko (2004) and Khayat and Mitchell (2009) therefore recommend that the settlement test compliment the column segregation test, as the two tests can be used to identify different forms of segregation.

2.5.3.2 Multiple-Probe Penetration Test

The multiple-probe penetration test (a.k.a. multiple-probe test) was originally based on the rapid penetration test (El-Chabib and Nehdi 2006), and a schematic of the test is shown in Figure 2.28. The main difference between the multiple-probe test and the rapid penetration test is that the multiple-probe test incorporates four solid penetration probes instead of one thin-walled penetration cup. El-Chabib and Nehdi (2006) suggests that averaging the displacement of four probes atop the sample can reduce the variability of results. Random packing of coarse aggregate may allow very few coarse aggregate particles to resist the penetration of a circular cup, but four probes should more closely represent the average mortar layer present on the sample (El-Chabib and Nehdi 2006).

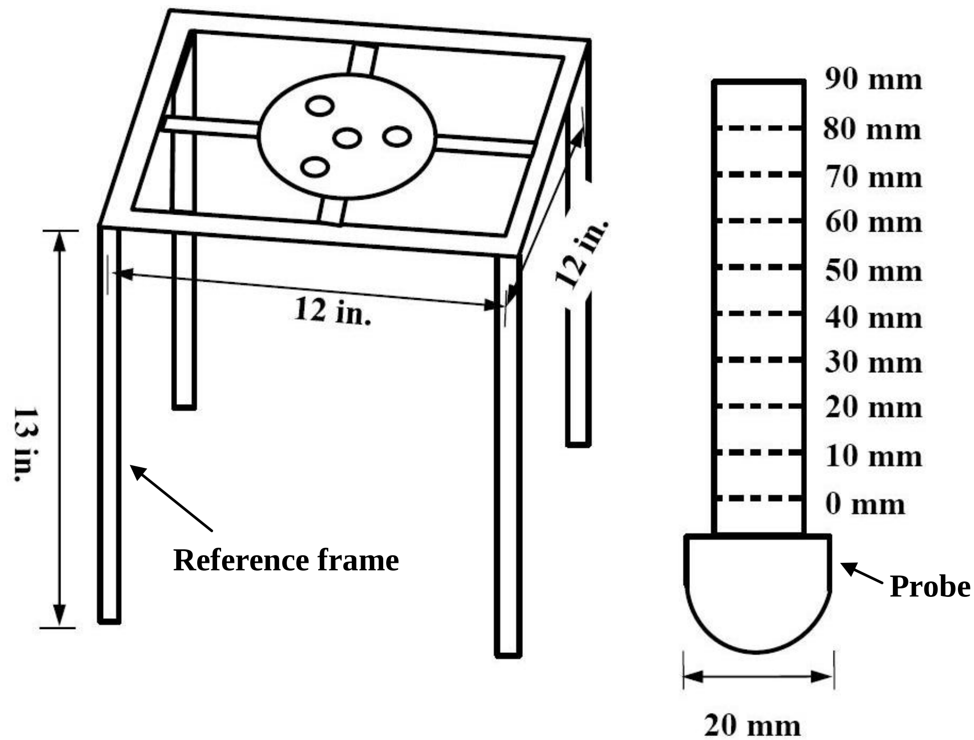

Figure 2.28: Multiple-probe penetration test apparatus
(Adapted from El-Chabib and Nehdi 2006)

The only other variation from the rapid penetration test is that the multiple-probe test requires a sample exclusively for its use, as opposed to the former being run on a sample that can then be used to assess the VSI and slump flow. Although the rapid penetration test can be run within the time allotted for testing the VSI and slump flow, the effect of two minutes of dormancy on the slump flow and VSI has not been studied. The use of a separate sample for the multiple-probe test was proposed in order to remove the influence of the two minutes of dormancy on the slump flow and VSI sample. Using a separate sample also speeds the performance of the three tests by allowing the slump flow and VSI to be tested while the multiple-probe test is still ongoing.

During its development, the multiple-probe test was run in conjunction with the sieve stability test and a variant of the column segregation test. The researchers were able to relate its performance to these two tests in 123 SCC mixtures of varying aggregate contents and strengths, and they used the results to develop a model to predict static segregation based on mixture proportions. Because the multiple-probe test was engineered primarily for that research, it has not been verified by other researchers.

2.5.3.3 Wire-Probe Penetration Test

Another variation of the rapid penetration test, the wire-probe penetration test (wire test) was designed to be a simpler, more repeatable replacement to the rapid penetration test (Lange 2007; Shen, Struble, and Lange 2007). The test equipment, shown in Figure 2.29, is constructed of a single piece of metal wire, twisted into a ring and vertical rod, with markings at every millimeter along the vertical rod. The wire is placed atop SCC in the inverted slump flow cone and allowed to settle for one minute, and the settlement of the metal ring is measured along the vertical rod left protruding from the sample.

Similar to the other two penetration tests, the wire test was intended to measure the mortar layer at the top of a sample (Shen, Struble, and Lange 2007). The developers confirmed the test's ability to do so by visually examining vertically cut hardened concrete cylinders. They also compared its results those of the column segregation test, which showed an exponential increase in segregation as the wire test's settlement increased. The test's use has been limited, though, because of its recent development and its similarity to the more thoroughly studied ASTM C 1712 rapid penetration test. Errors may also occur because of the absence of a lateral guide, as nothing forces the metal ring to sink directly downward into the sample (Bui et al. 2007).

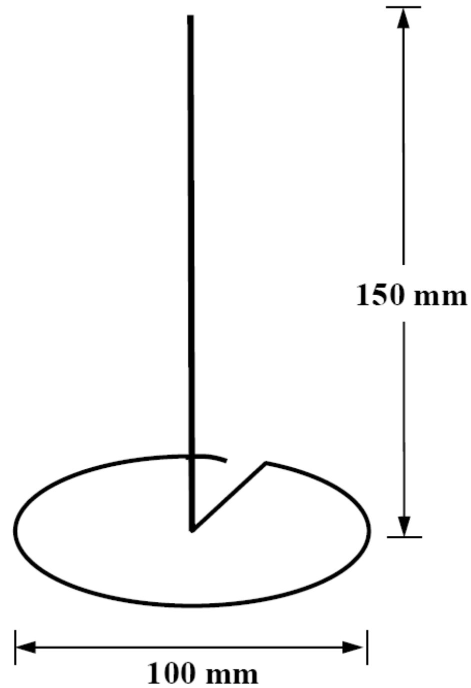

Figure 2.29: Wire penetration probe apparatus
(Based on Shen, Struble, and Lang 2007)

2.6 Mixture Acceptance Criteria

The end goal of any test that studies segregation of SCC is to determine whether a mixture exhibits an acceptable level of stability. The test outputs at which each fresh stability test will estimate that problems with segregation may occur, as well as the origins and applicability of these outputs, are discussed in the following sections. Also, means of determining an adequate level of stability in hardened concrete are discussed in relation to fresh stability.

2.6.1 Identification of Segregation by Fresh Stability Test Methods

All of the fresh stability tests described in Section 2.5 have associated criteria that establish a level of segregation above which SCC should not be accepted. Some of these criteria were based on comparison to hardened properties affected by segregation, while others were based on other fresh stability test methods and past research. Table 2.1 lists the outputs at which each test method estimates that problems associated with segregation will occur, and the origins and applicability of these criteria are discussed in Sections 2.6.1.1 and 2.6.1.2.

Table 2.1: Acceptance limits for various stability test methods

Fresh stability test	Range of Acceptability		Recommended By
Visual Stability Index (ASTM C 1611)	VSI ≤ 1		Khayat and Mitchell (2009)
	VSI ≤ 1.5		PCI (2004)
Column Segregation (ASTM C 1610)	S ≤ 15 %		Khayat and Mitchell (2009) Koehler and Fowler (2010)
	S ≤ 10 %		ACI 237 (2007)
Rapid Penetration (ASTM C 1712)	Depth ≤ 10 mm = Seg. Resistant ≤ 25 mm = Moderately Resistant		Bui et al. (2007) ASTM C 1712 (2009)
Sieve Stability	S ≤ 20 % (Class 1) S ≤ 15 % (Class 2) S ≤ 10 % when demanding*		EPG (2005)
	5 % ≤ S ≤ 15 %		PCI (2004)
Surface Settlement	MSA ≤ ½ in.	Set. rate ≤ 0.27 %/hr Settlement max ≤ 0.5 %	Khayat and Mitchell (2009)
	MSA > ½ in.	Rate ≤ 0.12 %/hr Max ≤ 0.3 %	
Multiple-Probe Penetration	Average Depth ≤ 10 mm		El-Chabib and Nehdi (2006)
Wire-Probe Penetration	Depth ≤ 7 mm		Shen, Struble, and Lange (2007)

*Note: when flow paths exceed 5 meters or spacing is less than 80 mm.

2.6.1.1 Prequalification

To select SCC mixture proportions prior to full-scale use, many of the tests discussed in Sections 2.5 can be used to prequalify SCC mixtures. Because it occurs under conditions where more time is available to assess the mixture's properties, ease of testing is less important than accuracy of results during prequalification testing. Various test methods that could be used for prequalification include the VSI, column segregation test, rapid penetration test, sieve stability test, and surface settlement test.

The fresh stability tests that are usable for prequalification testing tend to require more time (15 minutes in most cases) and use more expensive measurement tools. Acceptance criteria for the VSI were originally established as qualitative estimates (Daczko 2003), and acceptance based on the VSI is non-mandatory during slump flow testing (ASTM C 1611 2005). Although Khayat and Mitchell (2009) still recommend the VSI, they and others (Koehler and Fowler 2010; Peterman 2007) found the VSI to poorly predict hardened performance of SCC.

Acceptable column segregation results have previously been based on visual assessment, but the most recent recommendation was based on comparison to the surface settlement test (Khayat and Mitchell 2009). The acceptance criterion for the surface settlement test was also established by Khayat and Mitchell (2009), and it was based on correlations to in-place strength uniformity from cores and pullout bond uniformity. The relationship between maximum surface settlement and top-bar effect (shown as "modification factor") is shown in Figure 2.30. Because pullout bond uniformity was used to establish the acceptance criteria for all of the fresh stability tests in this research, it will be discussed further in Section 2.6.2.

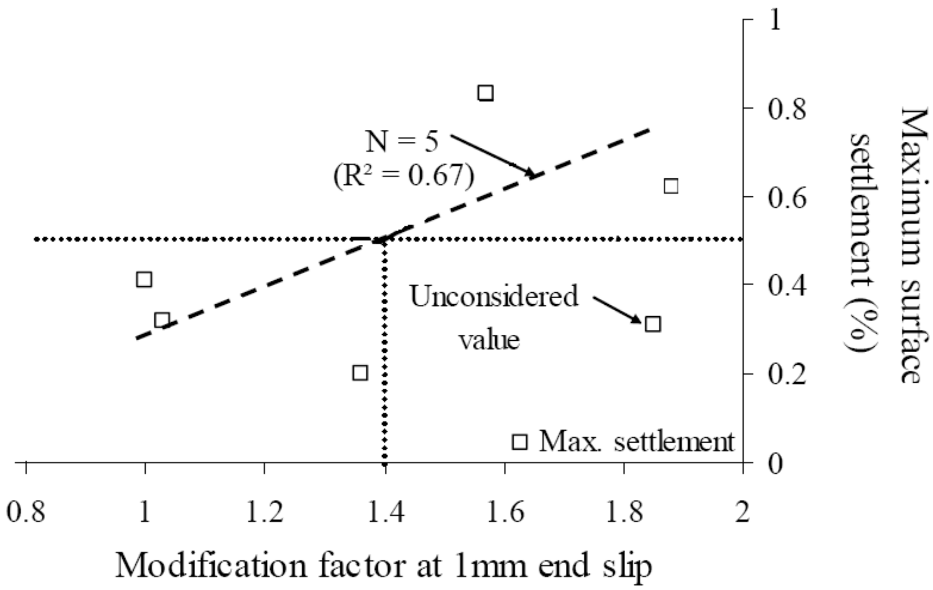

Figure 2.30: Relationship between top-bar effect and maximum surface settlement determined from surface settlement test (Khayat and Mitchell 2009)

As stated earlier, Bui et al. (2007) recommend that the column segregation test be replaced by the rapid penetration test based on a correlation between column segregation results and penetration test results that is shown in Figure 2.31. The recommended penetration depth limit of 10 mm is based on a segregation index limit of 10%, although penetration depths up to 25 mm may be acceptable if a segregation index limit of 20% is employed (Bui et al. 2007).

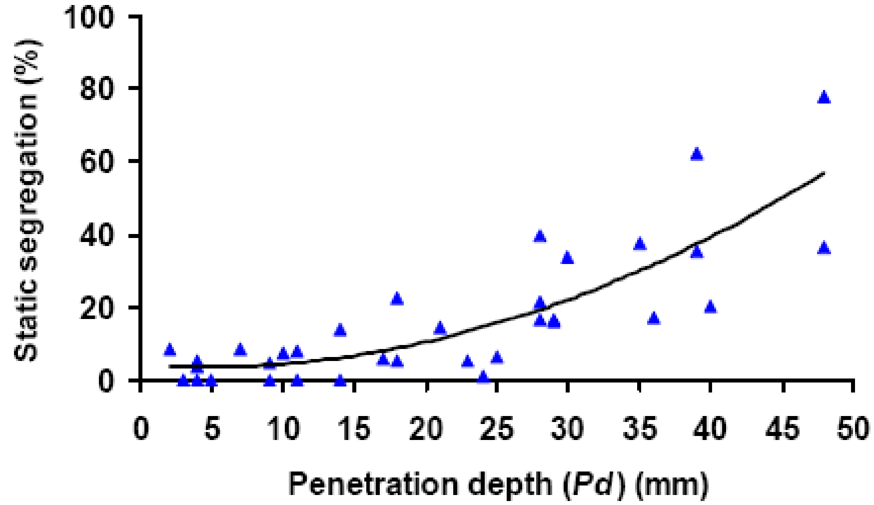

Figure 2.31: Relationship between penetration and column segregation (Bui et al. 2007)

Acceptance criteria for the sieve test were determined by visual observation and coring of hardened concrete during comprehensive testing (EPG 2005). No published findings have recommended revising those acceptance criteria, but European researchers (Kwan and Ng 2009; Ng, Wong, and Kwan 2006; Sahmaran, Yaman, and Tokyay 2007) have frequently used the sieve stability test to verify adequate stability. These researchers allowed sieved fraction (S) values of up to 20%, but EPG recommends only allowing sieved fractions under 10% for SCC used in demanding placements of greater than 15-ft lateral flow through spaces less than 3.5 in. wide.

Also, Koehler and Fowler (2010) found that the 15% S recommended by EPG (2005) corresponds approximately to a 15% I_{seg} from the column segregation test, which was also the value independently recommended by Khayat and Mitchell (2009) for the column segregation test. The relationship between the two tests is presented in Figure 2.32. In this figure, it can be seen that the column segregation and sieve stability tests have a nearly linear correlation throughout their respective ranges of possible outcomes.

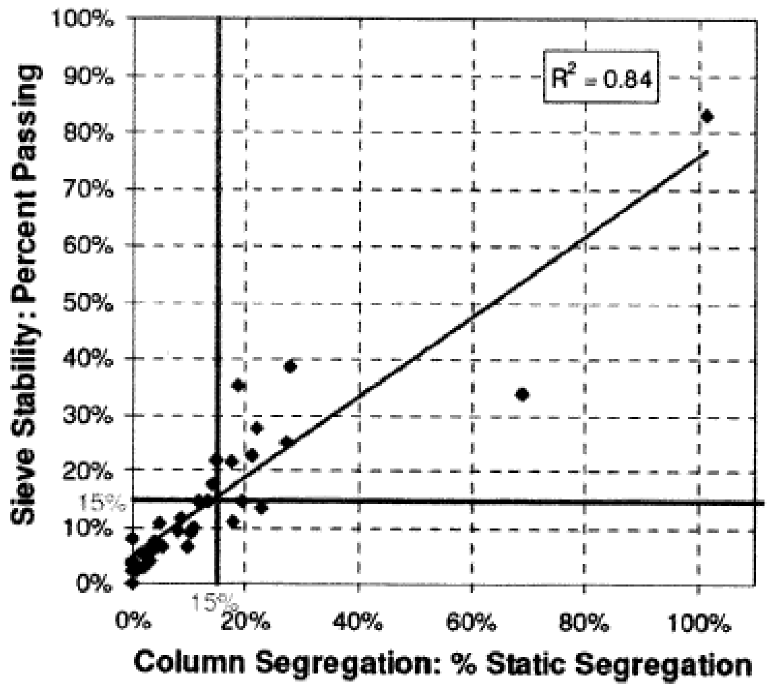

Figure 2.32: Relationship between column segregation and sieve stability tests (Koehler and Fowler 2010)

2.6.1.2 Quality Assurance

Fresh stability tests intended for rapidly determining batch acceptance at construction sites have obvious needs: be rugged enough to survive in a construction environment, simple enough to be performed by technicians on-site, and fast enough to provide immediate feedback and avoid delaying construction. The tests recommended for on-site quality assurance (QA) include the VSI, column segregation test, rapid penetration test, sieve stability test, multiple-probe penetration test, and wire penetration test.

Almost all of the fresh stability tests suggested for rapid QA application require little time (2–3 minutes) and use fairly simple measurement tools. The VSI is currently the only one of these tests commonly used for on-site mixture acceptance, but its deficiencies have already been discussed. PCI (2004) found the sieve test to be unsuitable for on-site use due to its prolonged test duration, while EPG (2005) recommends the sieve test as the primary on-site QA test for SCC stability. The same discrepancy arises for the column test: Khayat and Mitchell (2009) found the column test to be unacceptable for on-site use, while Koehler and Fowler (2010) recommend it as the primary on-site QA test for stability.

As mentioned in Section 2.5.3, El-Chabib and Nehdi (2006) developed their acceptance criteria for the multiple-probe test by comparison to results from the column segregation test. The multiple-probe acceptance criterion corresponded to a segregation index of 10% from the column segregation test. An I_{seg} of 10% had not yet been formally recommended for the column segregation test, but El-Chabib and Nehdi (2006) chose it in consideration of then-current column segregation and sieve test results.

Shen, Struble, and Lange (2007) based their acceptance criterion for the wire test on the column segregation test and visual examination of hardened SCC. They found that penetration depths less than 7 mm corresponded to column segregation results of less than 15% and were correlated well with in-situ mortar depths. As with the multiple-probe test, though, no research has since refined or confirmed the validity of the wire test.

2.6.2 Identification of Segregation by Hardened Concrete Test Methods

Hardened concrete test methods can be used to measure the hardened concrete properties apparently affected by segregation, including strength, uniformity, and bond to reinforcement. Such methods include

- Coring cylinders from large-scale concrete elements to test strength and assess coarse aggregate distribution,
- Measuring ultrasonic pulse velocities through large-scale concrete elements to assess uniformity of aggregate, air, and moisture distributions, and
- Testing bond to steel reinforcement by pulling out steel reinforcement embedded into concrete elements

These tests are rarely used to prove the stability of individual SCC mixtures, as these test methods can be very time-consuming compared to fresh stability testing. Even when possible to prequalify a particular mixture, hardened test methods are of minimal value for on-site batch acceptance, as their results would only become known after the concrete was already placed and hardened. As mentioned in Sections 2.3.2.1 and 2.3.2.2, hardened tests have frequently been used to prove the uniformity of high-quality SCC.

In studies of core compressive strength variation (Khayat, Manai, and Trudel 1997; Zhu, Gibbs, and Bartos 2001), stability was proven through statistical analysis of core strength. If core strength varied along the height of a member at a statistical 90% confidence interval, it implied that segregation was unacceptably high. For the reasons described in Section 2.3.2.1, though, observations had to be tempered because of the variety of factors that may affect the core's apparent strength.

An acceptable level of concrete quality has been established using UPV results, but only for one known aggregate source (Solis-Carcano and Moreno 2008). To establish what UPV results would be acceptable in cast members, Solis-Carcano and Moreno (2008) recorded velocities in cylinders prepared from 100 mixtures of varying compositions, and then they matched those velocities to the strength measured in each mixture. In subsequent tests of cast members, the pulse velocities measured in cast members were used to determine acceptable strength uniformity.

As explained in Section 2.4.1.1, the UPV values determined to be acceptable for that research cannot be applied universally because of the multitude of variables affecting UPVs, and because UPVs measure underlying hardened properties of SCC that can have varying effects on mechanical performance. Pullout testing, on the other hand, directly assesses the mechanical performance of hardened concrete.

Section 2.3.2.2.1 described how the top-bar effect determined by pullout testing can be related to segregation of fresh concrete. Although not unique to SCC (the top-bar effect can occur in all concretes), AASHTO (2007) and ACI 318 (2008) recognize the top-bar effect and account for it with a single factor, commonly known as the 'top-bar factor.' The top-bar factor is used in each code's equation for development length and applies to top-cast bars with greater than 12 in. of concrete cast below them. In these top-cast bars, the development length is multiplied by the top-bar factor in order to ensure the same bond capacity as in bottom-cast bars. The factor is defined as equaling

- 1.4 in AASHTO Bridge Design Specifications (2007) Section 5.11.2.1.2, and
- 1.3 in ACI 318 (2008) Section 12.2.4.

The top-bar factor was experimentally determined and refined by testing conventional concrete, although ACI 408 (2003) notes that both the 12 in. depth limit and the single-increment top-bar factor seem arbitrary considering the contributing research. Regardless, recent research has shown that stable SCC exhibits the same bond behavior (in both bond capacity and top-bar effect) as conventional concrete (Hassan, Hossain, and Lachemi 2010; Khayat, Attiogbe and See 2007).

The top-bar factor was not created to limit the heterogeneity of SCC, but it does allow for a certain level of in-situ variability. If the top-bar effect present in an SCC mixture is less than the code-accepted top-bar factor, then whatever heterogeneity is present must be acceptable for issues related to bond strength. Using this assumption, researchers have compared top-bar effects to the code-accepted top-bar factor to test the viability of SCC as a replacement for conventional concrete (Almeida Filho, M. El Debs, and A. El Debs 2008; Esfahani, Lachemi, and Kianoush 2008), or to test the viability of fresh stability tests that measure the fresh stability of SCC (Khayat and Mitchell 2009).

Chapter 3

Experimental Plan

3.1 Introduction

The objective of this research is to assess test methods that are used to quantify the stability of fresh SCC. The fresh stability tests are run early during the concrete's dormant period; however, segregation could occur at any time until the concrete sets. Therefore, to fully assess the fresh stability tests, concrete was simultaneously tested with the various fresh stability test methods and placed in full-scale wall elements. The concrete walls were allowed to harden, and they were then tested for uniformity to evaluate correlations between the fresh stability test results and the in-place hardened concrete uniformity. Several subtasks were required in order to achieve the project objectives:

- Select the fresh stability test methods to assess and procure necessary equipment,
- Select hardened concrete tests to quantify the effects of segregation on uniformity,
- Select mixture proportions and admixtures to make SCC suitable for precast, prestressed applications,
- Establish a mixing and preparation procedure to accommodate fresh stability testing and casting of concrete elements for hardened testing,
- Conduct the selected fresh stability tests, and
- Conduct hardened concrete testing to assess the effects of segregation.

To accomplish these tasks, consideration was given to the past research described in Chapter 2, as well as to the resources (time, materials, facilities, and manufacturing capability) available to the Auburn University research team. Chapter 3 describes in detail the experimental plan developed and includes testing equipment pictures, test protocols, and the mixture proportions employed.

3.2 Summary of Work

Of the fresh stability test methods described in Chapter 2, six fresh stability tests were selected for evaluation during full-scale wall casting:

- Visual stability index (ASTM C 1611 2005),
- Column segregation test (ASTM C 1610 2006),
- Rapid penetration test (ASTM C 1712 2009),
- Sieve stability test (EPG 2005),
- Surface settlement test (Khayat and Mitchell 2009), and
- Multiple-probe penetration test (El-Chabib and Nehdi 2006).

To assess in-situ uniformity, 3-yd^3 concrete mixtures were delivered by ready-mix concrete trucks to the Auburn University laboratory, and they were then placed in walls of four heights: 94 in., 72 in., 54 in., and 36 inches. As described in Sections 2.3.1.3.2 and 2.3.2.2.1, section height can potentially affect the degree of segregation. The four specimen heights selected are approximately incremental in height difference and correspond to the heights of typical precast girders, which made it possible to study the potential correlation between section height and segregation.

The walls were tested using UPV testing and pullout testing to determine the in-situ effects of segregation. As summarized in Section 2.4.1, UPV testing is a nondestructive test method for evaluation of the relative uniformity of large concrete specimens, and, as summarized in Section 2.4.2, the pullout testing is a direct, destructive method for evaluation of the bond strength of concrete. Segregation can affect both UPV uniformity and bond quality, and both test methods have been used to study the uniformity of SCC, as described in Sections 2.3.2.2.1, 2.4.1.1, and 2.6.2. During this research project, the test methods were used as complimentary, but unique, assessments of in-situ uniformity. Therefore, each in-situ uniformity result could be used to independently assess the ability of the fresh stability test methods to identify segregation.

The researchers desired to assess the fresh stability tests over the full range of segregation severity, so a total of nine SCC mixtures and two conventional concrete mixtures were placed that would provide varied fresh stability test results and varying degrees of in-situ uniformity. SCC mixtures were selected that would achieve high levels of filling ability (as would be necessary with precast, prestressed construction) while exhibiting varying levels of stability. Conventional concrete mixtures were selected that would achieve the workability necessary for precast, prestressed construction while exhibiting acceptable hardened behavior. An outline of the research progression is given in Figure 3.1.

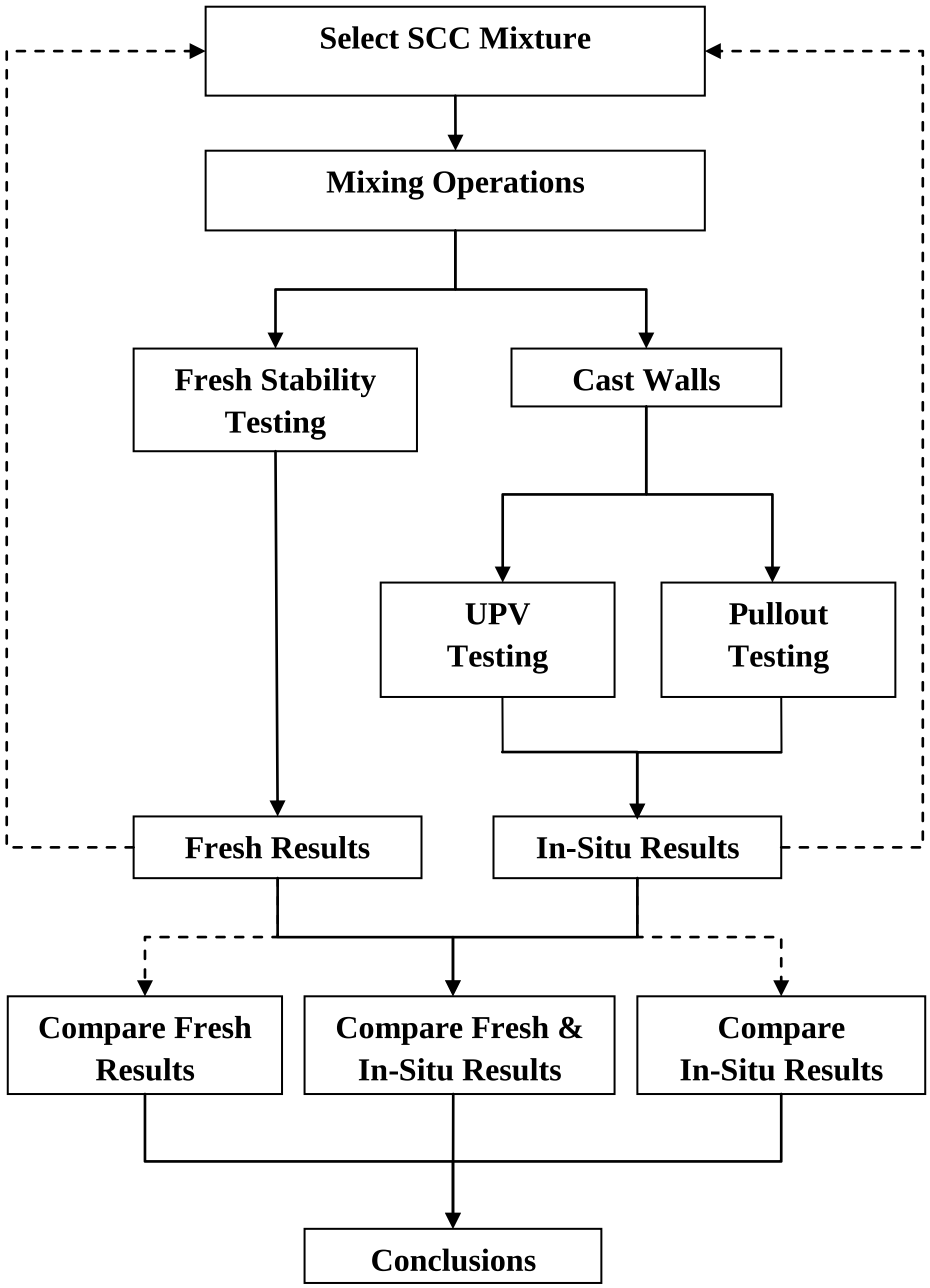

Figure 3.1: Work flow for assessment of fresh stability tests

Preliminary work included selecting primary mixture materials and proportions, procuring the equipment necessary to conduct each fresh stability test, designing the wall elements to be cast, building the formwork for those walls, and scheduling the work to most efficiently accommodate multiple cycles of testing. Once all of these preliminary tasks were accomplished, full-scale testing was conducted on a 7- to 8-day cycle, depending on weather and availability of resources. In the following sections, the procedures followed during full-scale mixing are described, as are the procedures for fresh and hardened testing. Mixture proportions were varied between testing cycles to induce varying degrees of stability; so the materials and proportions used in each mixture are summarized in the last section of this chapter.

3.3 Mixture Preparation

To accommodate the fresh stability testing and wall casting for this research, approximately 2.25 yds^3 of concrete were needed for each concrete batch. To account for waste and ensure sampling uniformity, 3 yds^3 were produced for each testing cycle. As it was impossible to mix such a volume in a single batch at the Auburn University (AU) Structural Engineering Laboratory in the Harbert Engineering Center (“the laboratory”), the majority of batching and mixing took place at the Twin City Concrete plant (“the plant”) in Auburn, Alabama. Certain aspects of mixture preparation thus required the cooperation of Twin City Concrete, while other aspects of concrete production unique to the research project were conducted at the laboratory upon receipt of each batch.

3.3.1 Mixing Procedures at the Ready-Mix Concrete Plant

During each testing cycle, materials were dispensed into a ready-mix concrete truck at the plant, and initial mixing took place as the truck drove to the laboratory, a trip that took approximately 15 minutes. The following activities were conducted with the cooperation of Twin City Concrete staff:

1. *AU staff:* Gather samples of coarse and fine aggregate to determine their moisture content at the laboratory.
2. *AU staff:* Calculate the moisture-corrected batch weights of the concrete constituents.
3. *Plant staff:* Batch coarse aggregate, fine aggregate, cement, fly ash (when used), and all water into a ready-mix concrete truck for mixing and delivery.
4. *AU staff:* Add hydration-stabilizing admixture directly into ready-mix concrete truck before allowing it to leave the ready-mix concrete plant.
5. *Plant staff:* Deliver batch of concrete to the laboratory, using minimal rotation of mixer during transport.

3.3.2 Mixing Procedures at the Laboratory

Upon arrival of the ready-mix concrete truck at the laboratory, several activities were conducted before dispensing the concrete for placement. The following activities were conducted:

1. Add a predetermined amount of water (if necessary to adjust stability from standard mixture) using 5-gallon buckets,
2. Add an initial dose of HRWR admixture (every mixture) and VMA (if necessary to adjust stability from the standard mixture),
3. Mix the concrete in the ready-mix concrete truck for 30 mixer revolutions at half of the truck's maximum rotational speed,

4. Wait 2 minutes to allow the dispersed admixtures to take effect, and
5. Rotate the mixer to bring the concrete up to a visible level in the truck, and either add additional HRWR admixture (if visibly necessary to achieve required filling ability) or VMA (if necessary to further adjust stability), or dispense a small sample for acceptance testing.

Once the mixture reached the apparent level of filling ability desired, the truck's chute was positioned above a waste container, and a 5-gallon bucket of concrete was captured directly from the chute as concrete was dispensed into the waste container. The mixer was not rotated during acceptance testing of the sample, which took approximately four minutes. The chute of the ready-mix concrete truck was washed before any additional concrete was dispensed in order to remove deleterious material.

3.3.2.1 Acceptance Testing

Acceptance of each batch of SCC was based on the fluidity and stability as determined by the slump flow test and VSI, and acceptance of each conventional concrete batch was based on the slump test. The goal for the various SCC mixtures was to create concretes that achieved high levels of filling ability (as would always be necessary with precast, prestressed girder construction) while exhibiting VSI values ranging from 0 to 3. The goal for the two conventional concrete mixtures was to obtain the workability necessary for precast, prestressed applications while exhibiting slumps of up to 9 inches.

No SCC mixture was accepted whose slump flow was less than 25 in., and mixtures exhibiting each possible VSI were desired, as a wide range of stabilities was sought in order to validate the fresh stability tests over that range. Air content was also tested, although it alone did not disqualify a concrete batch. For example, mixture SCC-1D arrived with an air content of 9.5 percent, but slump flow and VSI values were similar to previously prepared concretes of the same proportions, and later testing confirmed that SCC-1D reached a slightly lower, but comparable, strength to those mixtures.

In mixtures that did not achieve a minimum of 25 in. of slump flow, or that were more stable than desired for a particular testing cycle, HRWR admixture was added in 1 to 3 oz/cwt dosages until the SCC exhibited the desired fresh properties. Similar to initial mixing, the adjusted mixture was mixed for 30 revolutions at a slow speed and allowed to rest for 2 minutes before retesting. Partly because admixture effectiveness would diminish over time, and partly because remixing aggravated air content, no batch was accepted that required more than three dosages of admixture (consisting of an initial dosage plus two additions).

3.3.2.2 Sampling for Required Tests

Once a desirable combination of slump flow and VSI were achieved, the batch was dispensed from the ready-mix concrete truck into a 1.5-yd^3 placement bucket, which is shown in Figure 3.2. During SCC placements, the following placement order was followed:

1. Cast the 36-inch-tall wall in a single lift.
2. Fill wheelbarrows with enough concrete to perform all fresh stability tests and start to fill strength cylinders.
3. Refill the bucket from the ready-mix concrete truck.

4. Cast the 94-inch-tall wall in a single lift.
5. Refill the bucket from the ready-mix concrete truck.
6. Cast the 72-inch-tall wall in a single lift.
7. Refill the wheelbarrows to finish casting of all strength cylinders.
8. Refill the bucket from the ready-mix concrete truck.
9. Cast the 54-inch-tall wall in a single lift.

Figure 3.2: Placement bucket used to place concrete in the laboratory

During conventional concrete placements, the above order of placement was adjusted to accommodate consolidation efforts. Following the recommendations set forth by PCI (2004), lifts of approximately 18 in. were placed and then consolidated using a 1-inch-diameter internal vibrator. The same order of wall placement was followed as previously described for the placement of SCC.

Deviation from the above distribution order only took place when necessary to accommodate cylinder production. If necessary, additional wheelbarrow-loads of concrete were dispensed after topping off whichever wall was being filled, but before the placement bucket was refilled. Detailed descriptions of the walls, as well as descriptions of the other hardened tests performed, are given in the following section. The fresh stability tests performed during each testing cycle are described in Section 3.5.

3.4 Hardened Concrete Testing

During each testing cycle, hardened concrete testing was conducted on walls to establish the level of in-situ uniformity of each concrete mixture, and strength cylinders were cast to establish each concrete's strength profile. The following are discussed in this section:

- The specimens cast for hardened testing,
- The construction practices employed during their construction,
- The reasoning behind selection of the specimens and construction practices, and
- The tests run on the hardened specimens.

3.4.1 Wall Casting

Walls cast during each testing cycle were the primary specimens created and tested to quantify the effects of segregation on hardened concrete. As described in Sections 2.3.1.3.2 and 2.3.2.2.1, section height can potentially affect the degree of segregation, so specimens of four heights were cast, each matching the height of a typical precast girder:

- 36 in. to match an AASHTO Type II prestressed bridge girder,
- 54 in. to match an AASHTO Type III or ALDOT BT-54 prestressed bridge girder,
- 72 in. to match an AASHTO Type IV or ALDOT BT-72 prestressed bridge girder, and
- 94 in. to match an AASHTO-PCI-ASBI 2400-2 standard segment.

The wall heights selected changed in approximately even increments, making it possible to observe height-based trends in segregation, including whether segregation increases with height or does not occur below a minimum height. To ensure that any trends with height would be based on segregation and not increased dynamic effects of free-fall placement, a trunk was used to place concrete in the 72 in. and 94 in. walls. This trunk limited the free-fall drop height in those walls to less than 5 ft, in accordance with the guidelines for free-fall placement of conventional concrete set forth in AASHTO Bridge Construction Specifications (2010) Section 8.7.3.1.

3.4.1.1 Geometry Requirements of Walls

The width and thickness of the walls, as well as the location of form ties and hoist anchors permanently cast into them, were selected primarily in consideration of the hardened testing configuration desired. The details of those configurations are described in Sections 3.4.2 and 3.4.3. As will be later explained in those sections, a lateral distance of at least 4 in. was kept between each UPV reading location and the nearest pullout bar, form tie, or wall edge, and 8 in. was kept between pullout bars.

Selection of a wall width of 40 in. thus made it possible to test five vertical lines of UPV measurement locations and four vertical lines of pullout bars, alternating each vertical line with a lateral spacing of 4 in. on-center. A thickness of 8 in. was selected for all walls based on past studies and testing configurations identified in Sections 2.4.1.2 and 2.4.2.2 and on the calculation that unreinforced walls of that thickness would be structurally sound under flexural and tensile loads encountered during maneuvering and testing.

Threaded-rod form ties were used to control the outward deflection of forms under the pressure exerted by the fresh concrete, and their locations were determined assuming that the fresh concrete would exert fully hydrostatic pressure on the forms. The 94 in. wall used four pairs of ties, the 72 in. wall used three pairs, the 54 in. wall used two pairs, and the 36 in. wall used one pair. The vertical locations of each pair of ties can be seen in Figure 3.3.

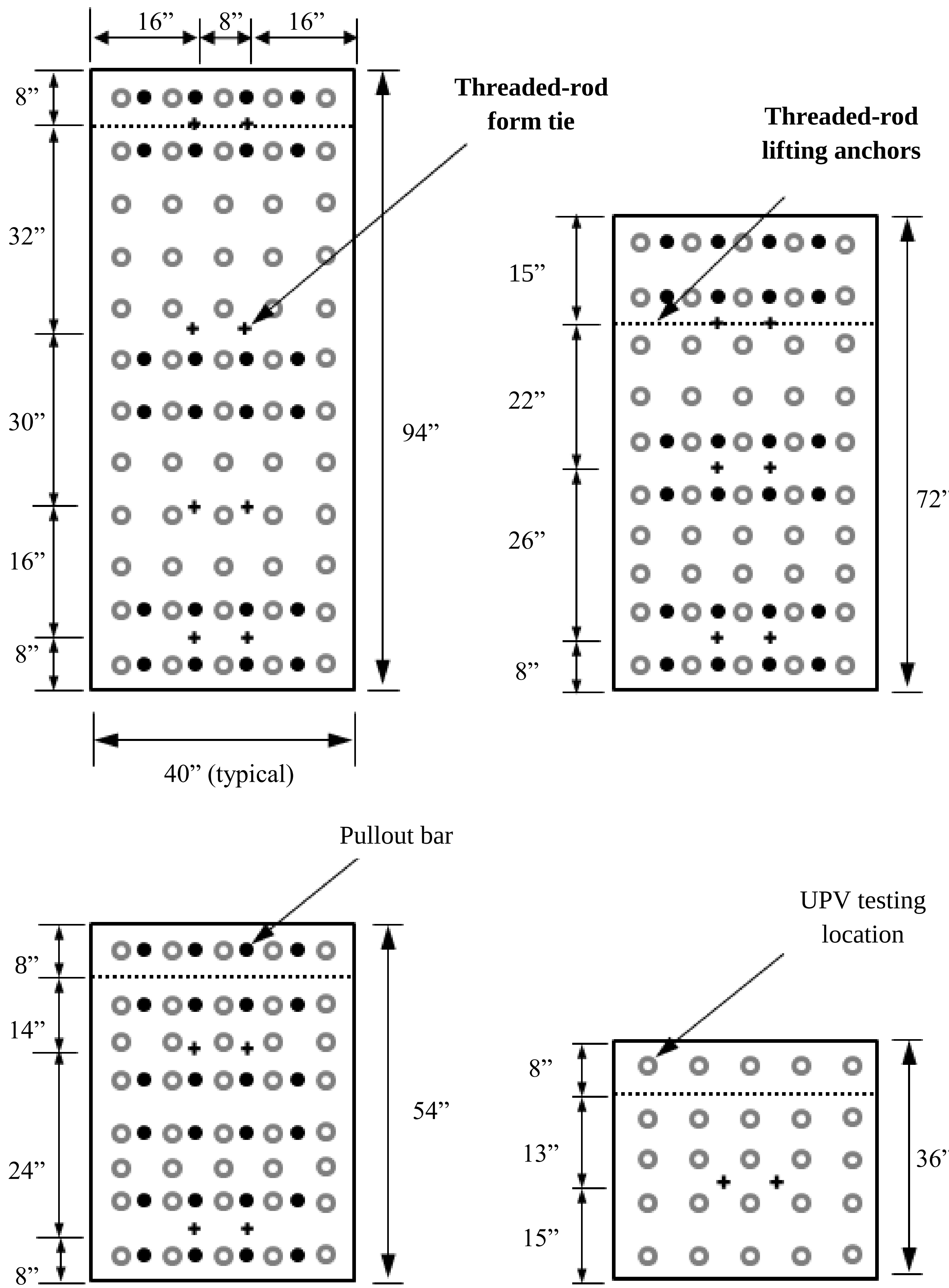

Figure 3.3: Form tie and lifting anchor locations within each wall

As seen in Figure 3.3, the form ties were laterally aligned to coincide with the vertical lines of pullout bars, which ensured that they would be at a distance of at least 4 in. from the nearest UPV measurement location. They were also spaced at least 3 in. from the nearest pullout bar. The minimum clear spacing between parallel reinforcement required by ACI 318 (2008) to allow uninhibited placement was 1 in., which was exceeded in all cases.

Threaded-rod lifting anchors were cast into each wall, and they are also shown in Figure 3.3. They were located at mid-depth through the 8 in. thickness of each wall and were located at heights that provide at least 3 in. vertical spacing to the nearest horizontal line of five UPV measurement locations. Where possible, lifting anchors were cast perpendicular to and directly beneath form ties, which placed them the greatest distance from any pullout bar or UPV measurement location. The anchors only transferred forces to the surrounding concrete near the outer ends of the walls, 8 in. outward from the first pullout bar.

3.4.1.2 Wall Handling Conditions

All joints within each wall, including joints between pieces of formwork and points of entry for form ties and pullout bars, were sealed with Type I silicone. To ease form removal and to promote longevity of the formwork, a release agent, Crete-Lease 880-VOC-Xtra, was sprayed on all inner form surfaces after the form joints and form ties were sealed with silicone but before pullout bars were positioned. The addition of Crete-Lease, which is effective for up to two weeks after application (Cresset, Inc. 2008), typically occurred one day prior to casting. Although circumstances occasionally resulted in a later casting date, casting was never conducted more than one week after the addition of the release agent.

Forms were removed two days after casting. As described in Section 2.4.1.2 , UPV testing is most effective at very early ages. An age of two days was selected as a compromise between early-age testing needs and strength needs to ensure that the walls would be sufficiently strong during form removal and moving. Although the completion of form removal typically took two hours, all form ties and joints were loosened at 48 hours to allow exposure to laboratory humidity and temperature conditions.

As seen in Figure 3.4, two parallel lines were used during this testing: one for form erection and casting and one for wall storage and testing. During each casting cycle, the walls were lifted by the still-attached formwork in the first line, moved to the second line, anchored into place, and then stripped of all formwork. Work crews began stripping the formwork from each wall while the next wall was being moved and anchored, which allowed for UPV testing of the walls to be conducted continuously at as close to an age of 48 hours as possible.

After the forms were removed, wax construction pencils were used to mark a UPV measurement location grid onto each wall, and UPV testing was conducted as soon as possible thereafter. The walls were then left in this position until an age of six days, when UPV testing was conducted a second time. Walls were moved to a third location and laid horizontally during the following week in order to conduct pullout testing at a concrete age of 13 days.

Figure 3.4: Parallel lines of cast walls and wall formwork

To tip the walls from their as-cast vertical orientation to the horizontal orientation needed to conduct pullout testing, metal plates were loosely attached to the lifting anchors that were cast horizontally near the top of each wall. The walls were then lifted by the plates with an overhead crane, moved into place on concrete blocks, and tipped over to lie horizontally on the concrete blocks. While on the blocks, the walls rested on rubber pads that were aligned parallel to their height at a 32 in. horizontal spacing, as shown in Figure 3.5. This support system was used to limit the flexural stresses experienced by the walls while in a horizontal orientation and to ensure adequate clearance for instrumentation during pullout testing.

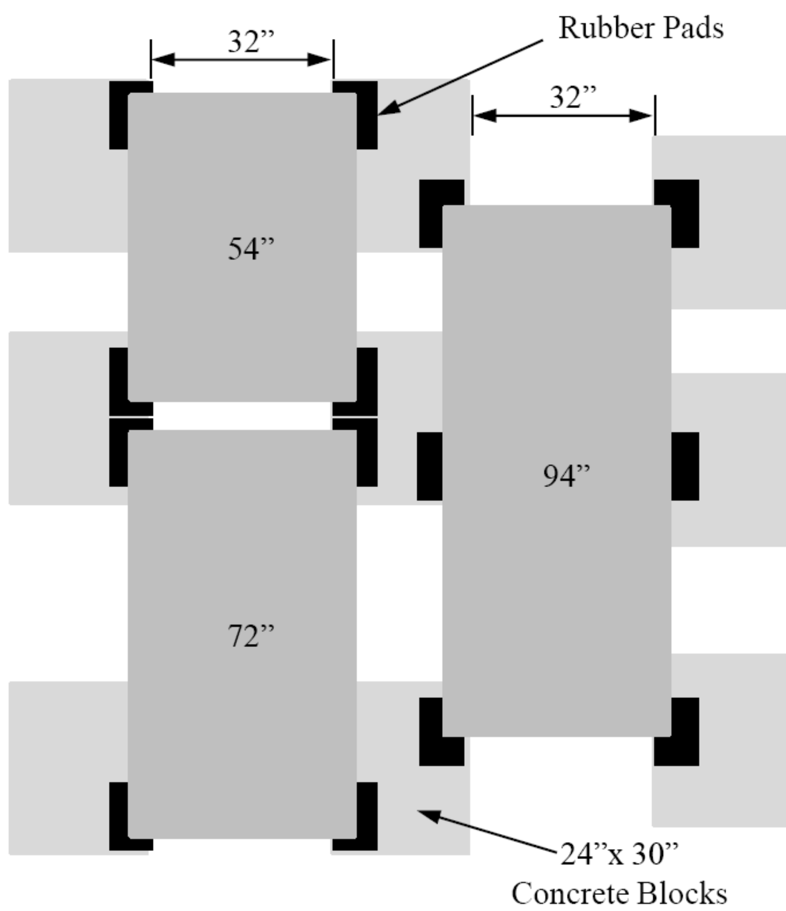

Figure 3.5: Orientation of walls placed horizontally for pullout testing

3.4.2 Ultrasonic Pulse Velocity Testing

Ultrasonic pulse velocity (UPV) testing was conducted on each group of walls two days and six days after casting. The testing equipment used, shown in Figure 3.6, was a Pundit Plus portable ultrasonic instrument from Germann Industries. Following the testing recommendations of Section 2.4.1.2, the Pundit Plus was configured for continuous 54-kHz testing; it displayed ten readings per second at a precision of ± 0.1 microseconds. An alcohol-based ultrasound jelly was used between each metal coupler and wall surface to create a continuous ultrasound path, and the couplers were pressed firmly against the wall surfaces until an unchanging reading was observed. Ultrasound values were then recorded by hand.

Figure 3.6: Ultrasonic pulse velocity testing equipment

As seen in Figure 3.7, the grid spacing was approximately uniform, with slight variations to avoid pullout bars and form ties and to fit at least two horizontal lines of testing between each eight-specimen group of pullout bars. As mentioned in Section 2.4.1.2, UPV testing through concrete at 54 kHz requires a minimum of 2.8 in. of clear spacing to the nearest obstacle oriented parallel to the direction of wave transmission. Typical spacing between UPV measurement points was six to eight inches, and no point was located less than four inches from the nearest edge or obstacle.

The UPV couplers were relocated to the nearest sound cross section whenever necessary to avoid bug holes or outward protrusions that formed where concrete filled cracks and knots in the plywood formwork during casting. No UPV measurement point was relocated greater than one inch away from its original location, and each relocated point was positioned to avoid being affected by obstacles or edges.

UPV measurement locations used for second-day testing were labeled for reuse during sixth-day testing and for wall thickness measurements necessary to calculate pulse velocities. The caliper used to measure wall thicknesses is shown in Figure 3.8A. The caliper was constructed by welding parallel rectangular steel tubing 9 ± 0.01 in. apart. One leg of the caliper was laid flush with one side of the eight-inch wall, and a $1/100^{th}$ in. gradation steel ruler was used to read the distance from the other side of the wall to the inner face of the second leg, as shown in Figure 3.8B. Using this system, the wall thickness at each UPV test location was measured with a precision of ± 0.02 in., which falls well within the precision required by ASTM C 597 (2002).

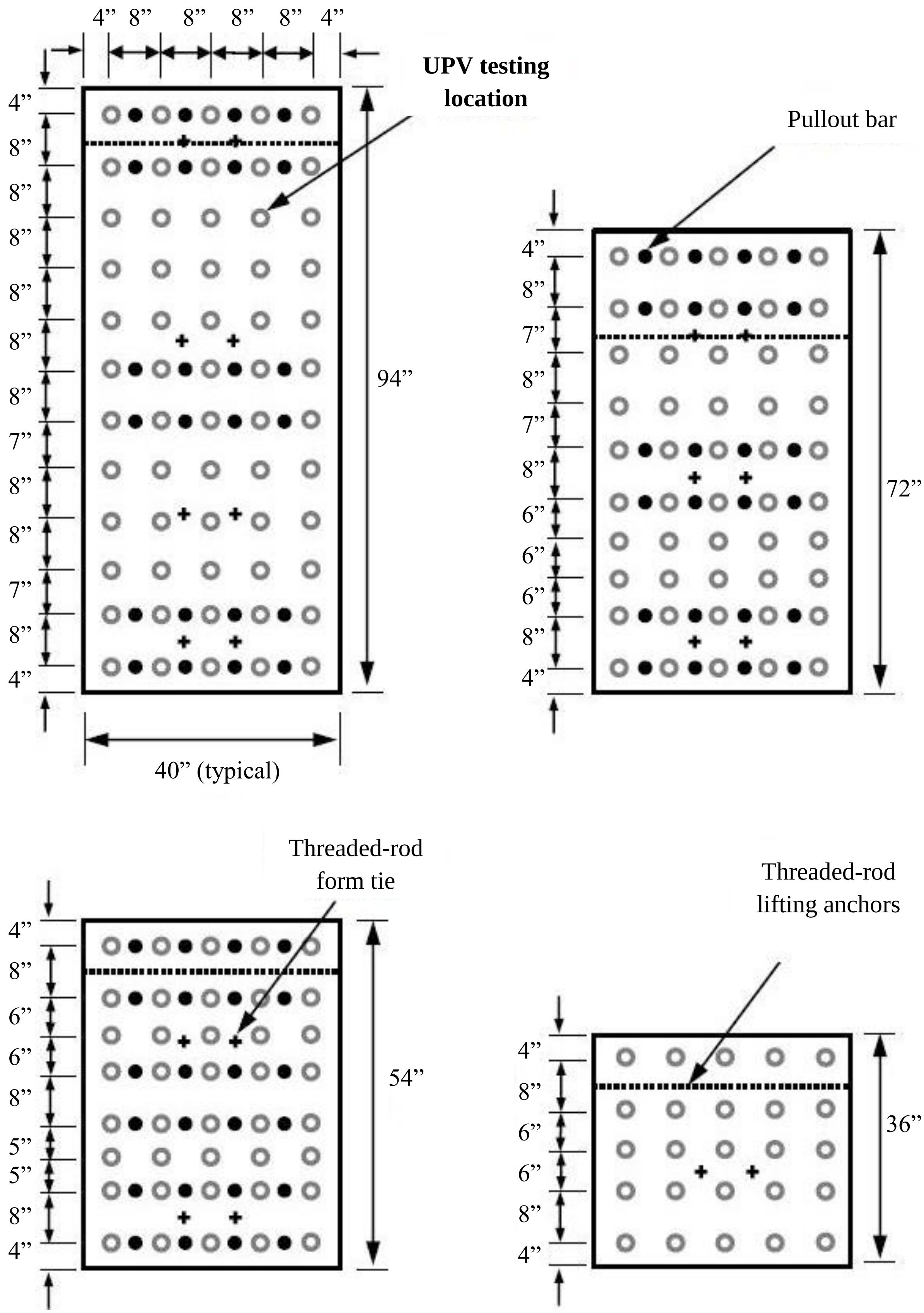

Figure 3.7: UPV testing locations

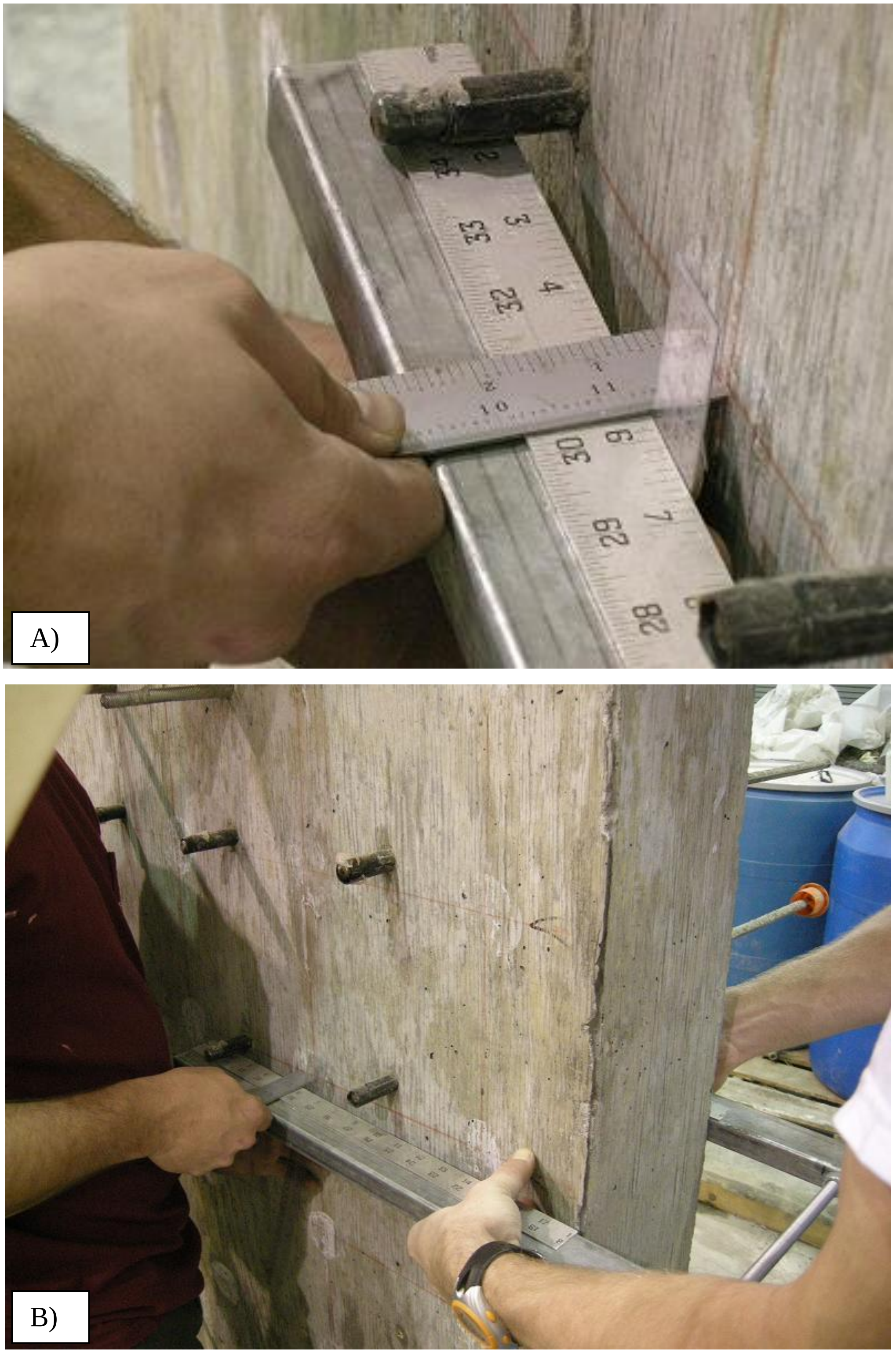

Figure 3.8: A) Measurement of wall thickness using a large caliper and ruler, and B) measurement taken using a 1/100th in. gradation ruler

3.4.3 Pullout Testing

Pullout testing was conducted on the 54 in., 72 in., and 94 in. walls 13 days after casting. Pullout testing was not performed on the 36 in. walls. Pullout bars were not cast into the 36 in. walls because a height of at least 40 in. was necessary to place six adequately spaced rows of pullout specimens to match the taller walls, and the 36 in. height matched a previously described precast segment height. Also, the exclusion was deemed acceptable to reduce the time and labor necessary to prepare, cast, and test the walls during each testing cycle.

As described in Section 3.4.1.2, the 54 in., 72 in., and 94 in. walls were tipped from a vertical orientation to a horizontal orientation before pullout testing. The walls were left in a vertical orientation for as long as possible in order to limit the risk of damage from flexural loads that could occur either while being moved or while supported horizontally prior to testing.

The location of each pullout bar can be seen in Figure 3.9. To ensure adequate cover as described in Section 2.4.2.2, the top and bottom rows of bars were located four inches from the top and bottom of each wall. A distance of eight inches was employed between each vertical line of bars so that:

- An 8-inch-wide reaction frame would be equally spaced between the bar being pulled out and the nearest adjacent bars,
- A 4 in. radius would be kept between the reaction frame and pullout bar in order to dissipate potential confining forces, and
- A 4 in. radius would be kept between the nearest UPV testing location and any pullout bar, as previously explained in Section 3.4.2.

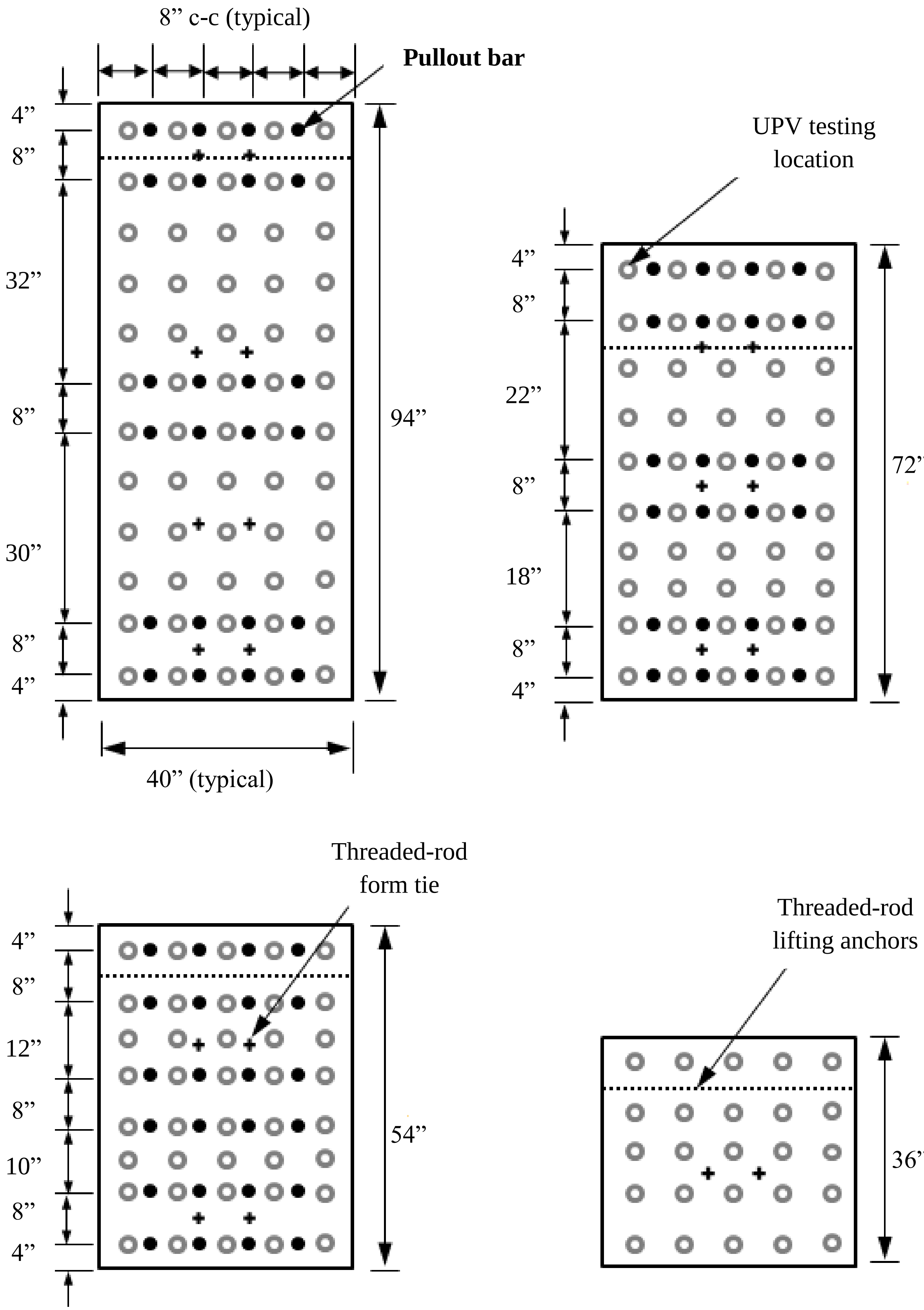

Figure 3.9: Pullout bar locations

3.4.3.1 Configuration of Bars

Pullout testing for this project was conducted using No. 4 reinforcing bars from a single batch provided by Nucor Steel, Inc. of Birmingham, Alabama. The batch exhibited a yield stress of 68 ksi in tensile testing by Nucor, which was confirmed by the AU researchers through the tensile testing of three randomly selected bars from the batch. The AU researchers were also able to study the tensile-stress-versus-strain relationship of the steel during their confirmation testing.

Based on the past research described in Section 2.4.2.2, a bonded length of 2.5 d_b, or 1.25 in., was selected in order to ensure a shearing pullout failure of the concrete, instead of splitting or conical failure. The short bonded length also limited the possibility of steel yielding due to the bond strength of this high-strength concrete.

During the preparation of steel reinforcement to leave only 1.25 in. of bonded length, nonabsorbent paper was first cut into 1.25-inch-wide strips after being marked with a 1/100th in. gradation steel ruler. This is shown in Figure 3.10. After the bar was cleaned, the paper was then taped to the desired location along the length of the pullout specimen, and one inch on either side of the paper was coated with Type I silicone, as shown in Figure 3.11. After allowing the silicone to dry for at least one day, the paper was then peeled away, leaving an exposed length of 2.5 d_b enclosed on both ends by permanent silicone. Commercially available strand-debonding sheathing was then placed on both sides of the exposed section (over the silicone) and securely taped into place using electrical tape. The completed bar with a 1.25 in. long debonded region is shown in Figure 3.12.

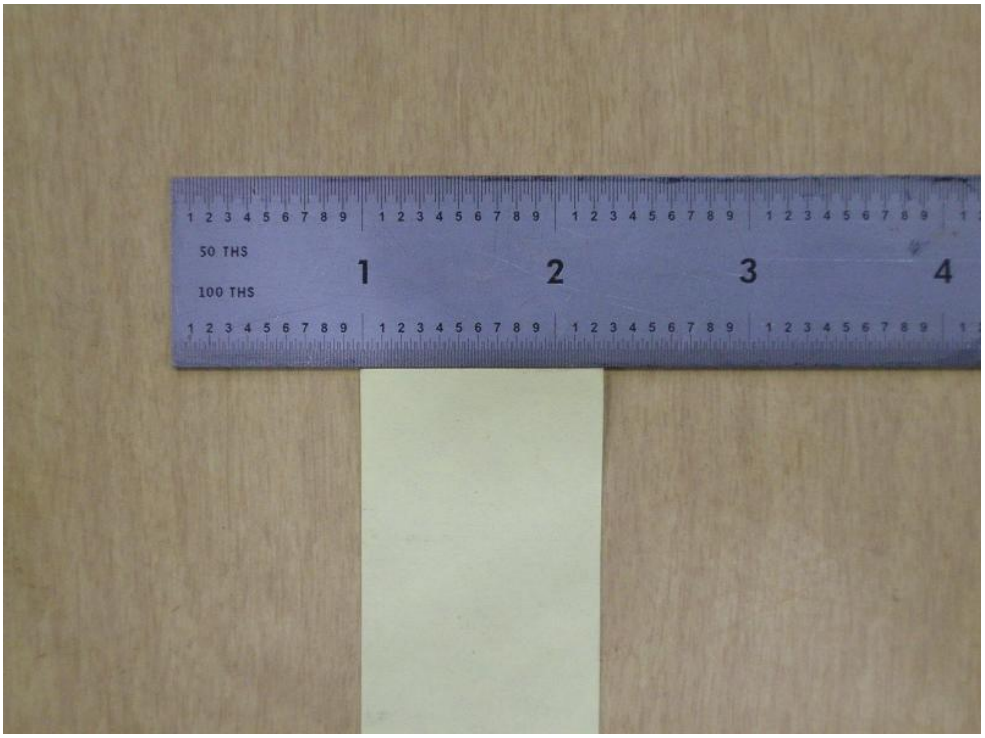

Figure 3.10: 1.25-inch-wide paper used to prepare bonded length of pullout specimen

Figure 3.11: Application of Type I silicone to pullout bars

Figure 3.12: 1.25 in. bonded region of a No. 4 rebar ready for casting into concrete

Once it was encapsulated in concrete, the bonded region of steel began 4 in. away from the loaded face of the concrete wall, similar to the configurations used by Khayat (1998) and Sonebi and Bartos (1999). Unlike those configurations, the end of the bonded region was not flush with the unloaded face of the wall. It was decided that placing the bonded region close to the middle of the wall thickness would remove the risk of uncharacteristic pullout behavior from two sources: different collection of bleed water and aggregate at the face of the wall, and flexural stresses experienced by the wall under its own weight. The surface friction and the preferred orientation of aggregate at the face of the wall could lead to irregularity at this face, and flexure experienced by the wall in a horizontal, simply supported orientation could place the concrete near the top face (nearest the debonded region of steel) in compression while reducing the compression at the bottom face of concrete (near the bonded region of steel).

To both accommodate sealing the other joints and avoid contaminating the pullout bars with form release agent, the pullout bars were placed in the erected formwork after the forms had been sealed and sprayed. Consequently, insertion of the bars was the last activity performed before placement of concrete, leaving at least 24 hours between when the bars were sealed with Type I silicone on the outer face of the formwork and when the concrete was cast. Figure 3.13 shows the inserted bars directly before casting.

Figure 3.13: Pullout bars positioned prior to concrete placement

3.4.3.2 Configuration of Pullout Testing Equipment

Both the 8-inch-tall reaction chair and the center-hole hydraulic cylinder (jack) used in this research project, as well as the aluminum load cell and chuck placed above them, are shown in Figure 3.14. This configuration was based on the configuration used by Khayat and Mitchell (2009), which was shown in Figure 2.14. The load cell had a precision of ± 0.5 lbs and was capable of resisting up to 40,000 pounds of compressive force. The jack, with a capacity of 120,000 pounds, was operated with an air-powered hydraulic pump.

Figure 3.14: Chuck, load cell, hydraulic jack, and 8-inch-tall reaction chair

During testing, bar tensioning was displacement-controlled by controlling the airflow into the hydraulic pump. This was done by opening a variable airflow valve to the minimum amount that would result in continuous movement of the jack. After the peak pullout force was recorded, the rate of displacement was increased in order to maintain continuous operation of the pump. The free-end slip of the pullout bar was recorded using a linear potentiometer that is shown in Figure 3.15. In order to prevent potential damage during loading, the spring-loaded potentiometer was positioned in such a way that it would record the upward displacement of the free end without being physically attached to the bar.

Figure 3.15: Spring-loaded linear potentiometer used to measure free-end slip

The pullout testing apparatus, shown in its entirety in Figure 3.16, made it possible to pull out each bar with minimal additional confining pressure (as discussed in Section 2.4.2.2), without damaging the surrounding concrete, and without causing dynamic loading effects. Loading continued until reaching a free-end slip of 0.25 inches. Loading was not discontinued until the free-end slip of the bar was more than double the slip at maximum pullout force.

Time, load, and slip were instantaneously displayed on a laptop viewable during testing using software in conjunction with an Optim MEGADAC data acquisition system, which made it possible to monitor and record load and free-end slip. The research team was thus immediately made aware of equipment malfunction, bar yielding, or testing completion.

Based on small-scale trial pullout testing, a relationship between bond strength and concrete compressive strength was determined to estimate the necessary minimum yield strength of the rebar (68 ksi) and maximum compressive strength of the concrete (12,000 psi) that would prevent steel yielding during testing. This relationship was corroborated by research results from Khayat et al. (1997) and Stocker and Sozen (1970) and was taken into consideration when selecting concrete mixture proportions, which are described in Section 3.6.1, and when choosing to use deformed bars instead of seven-wire strand, which is discussed in Section 3.4.5.

Figure 3.16: Pullout testing configuration

It should be noted that, during testing, steel yielding occurred in only one instance. After strain hardening began, the pullout specimen achieved a shear pullout failure, and the pullout strength result in that instance was acceptably similar to the strength results from the surrounding specimens. Therefore, it was employed in the uniformity analysis of the tested concrete, as described further in Section 4.4.2.

3.4.4 Compressive Strength Assessment

Twelve standard 6-inch-diameter by 12-inch-high cylinders were cast for each mixture. They were used for compressive strength testing at each of the following ages: two days, to coincide with form removal and the first iteration of UPV testing; six days, to coincide with the second iteration of UPV testing; 13 days, to coincide with pullout testing; and 28 days, to establish a standard compressive strength for each mixture.

SCC cylinders were cast in a single lift by pouring the concrete from a 5-gallon bucket in a steady motion, filling the molds in 6 ± 3 seconds. No rodding or consolidation was used, but the outside of each mold was lightly tapped with a rubber mallet to remove any air pockets caught against the inside of the mold walls.

Molds were removed from the cylinders at the same time as form removal, at two days. The cylinders were then left adjacent to the walls so that they would be exposed to similar laboratory drying and curing conditions.

3.4.5 Other Hardened Tests Considered

3.4.5.1 Use of Deformed Bars Instead of Seven-Wire Strand

SCC to be used for precast, prestressed applications was the primary focus of this project, so seven-wire prestressing strand was the first choice for pullout testing. However, during trial testing in the early stages of this project, strand that was bonded for 2.5 d_b (as described in Section 3.4.3) consistently pulled out in an unwinding failure instead of in a shear pullout failure. As described in Section 2.4.2.3, bond to seven-wire strand depends on torsional forces exerted as the strand attempts to rotate through the concrete. Although Khayat (2003) and Stocker and Sozen (1970) tested strand as described in Section 2.4.2.3, the Auburn University researchers were unable to prevent an unwinding failure of seven-wire strand when a bonded length of 2.5 d_b was used. Evidence of this failure mechanism is shown in Figure 3.17. In that figure, the surrounding concrete still has spiral indentations following the unwinding failure of a seven-wire strand, which shows that shear failure of the surrounding concrete did not occur.

Figure 3.17: Unwinding failure of seven-wire strand during trial testing

As mentioned by Stocker and Sozen (1970), a pullout failure of this type indicates that the concrete surrounding the strand is only bonded to the strand by adhesion and surface friction, not by mechanical interlock. Deformed steel reinforcement, on the other hand, is mechanically locked into the surrounding concrete because of its deformations, as illustrated in Figure 2.12. Because an unwinding, slipping failure cannot occur in this situation, shear failure occurs in the surrounding concrete, which is ideal for studying the quality of that concrete (or lack thereof, if affected by segregation). For that reason, it was decided that, as also done by Khayat (1998), Khayat, Manai, and Trudel (1997), and Sonebi and Bartos (1999), deformed steel reinforcement would be used for pullout testing in this research program.

Concrete failure may have been induced by using longer bonded lengths of strand, which was possible in consideration of the strength of the strand (longer bond lengths would not yield the strand). However, because short bonded lengths were preferred in order to approximate a uniform bond stress (as described in Section 2.4.1.2), the use of deformed bars was deemed acceptable and convenient.

3.4.5.2 Core Testing for Uniformity Analysis

Coring of samples from a large concrete element for uniformity testing, reviewed in Section 2.3.2.1, was considered but abandoned in favor of UPV testing. Coring has the advantage of being able to directly analyze the strength and aggregate distribution within a wall, but its flaws, listed in Section 2.3.2.1, made it a less preferred method when compared to UPV testing.

UPV testing is equally capable of reflecting changes in uniformity, and it offered two distinct advantages: it is nondestructive, so it could be conducted prior to pullout testing without affecting that testing; and it is much faster, so it could be conducted with much greater frequency and ease. The test only offers indirect evidence of segregation, but, as stated by ASTM C597 (2002), Cussigh (1999), Komlos et al. (1996), Naik, Malhotra, and Popovics (2004), and Solis-Carcano and Moreno (2008), it is very effective for relative uniformity analysis.

3.5 Fresh Concrete Testing

A primary objective of this research project was to identify test methods that provide a quantitative assessment of the degree of stability of fresh SCC. From the test methods described in Section 2.5, six were selected for further study in this project:

1. ASTM C 1611 (2005) Visual Stability Index (see Section 2.5.2.1),
2. ASTM C 1610 (2006) Column Segregation Test (see Section 2.5.2.2),
3. ASTM C 1712 (2009) Rapid Penetration Test (see Section 2.5.2.3),
4. Sieve Stability Test (see Section 2.5.2.4, EPG 2005, and Appendix A.1),
5. Surface Settlement Test (see Section 2.5.3.1, Khayat and Mitchell 2009, and Appendix A.2), and
6. Multiple-Probe Penetration Test (see Section 2.5.3.2, El-Chabib and Nehdi 2006, and Appendix A.3).

The VSI was chosen because it is the most frequently specified on-site quality assurance test method. The column segregation test was chosen because it is the only considered test that involves physically determining the aggregate distribution over the height of a sample, and it is an ASTM standardized test method for characterization of the static stability of SCC. The rapid penetration test was chosen because it the fastest test offering a completely objective result and is the most recently ASTM standardized test to assess SCC stability.

The sieve stability test was selected because it is recommended by a European consortium of concrete producers as the primary stability test in Europe (EPG 2005), and the surface settlement test was selected because it is recommended in NCHRP Report

628 (Khayat and Mitchell 2009) as the primary stability test for precast, prestressed SCC. The multiple-probe test was also included because, although similar to the rapid penetration test in speed and simplicity, it may detect nonuniform surface settlement due to its use of four lighter, isolated probes (El-Chabib and Nehdi 2006).

3.5.1 Fresh Stability Tests

All fresh stability tests were conducted in accordance with the recommendations set forth in Appendix A or, where available, their respective ASTM standards. The test procedures given in Appendix A were derived from the most current version of test instructions available to the researcher at the beginning of testing, November 2009, and were not deviated from except as noted in Chapter 4.

3.5.1.1 Slump Flow, Rapid Penetration Test, and Visual Stability Index

During SCC placement, the slump flow test was first performed prior to initiating wall placement, and then it was performed again to coincide with the other fresh stability tests. During its second testing (after beginning the casting of walls), the slump flow was tested in conjunction with the rapid penetration test and the VSI. The rapid penetration test was performed in accordance with ASTM C 1712 (2009), and the VSI was conducted in accordance with ASTM C 1611 (2005). Performing all three of these tests simultaneously met the individual time requirements specified for each, so it was convenient to conduct all three tests on the same sample.

The apparatus used to perform the three tests are shown in Figure 3.18, reading of the penetration depth during the rapid penetration test is shown in Figure 3.19, and a slump flow test in progress following removal of the rapid penetration test apparatus is shown in Figure 3.20. The rapid penetration test apparatus could not be purchased from a commercial concrete laboratory equipment supplier, so the equipment was manufactured by an Auburn University machinist to meet all the requirements of ASTM C 1712 (2009).

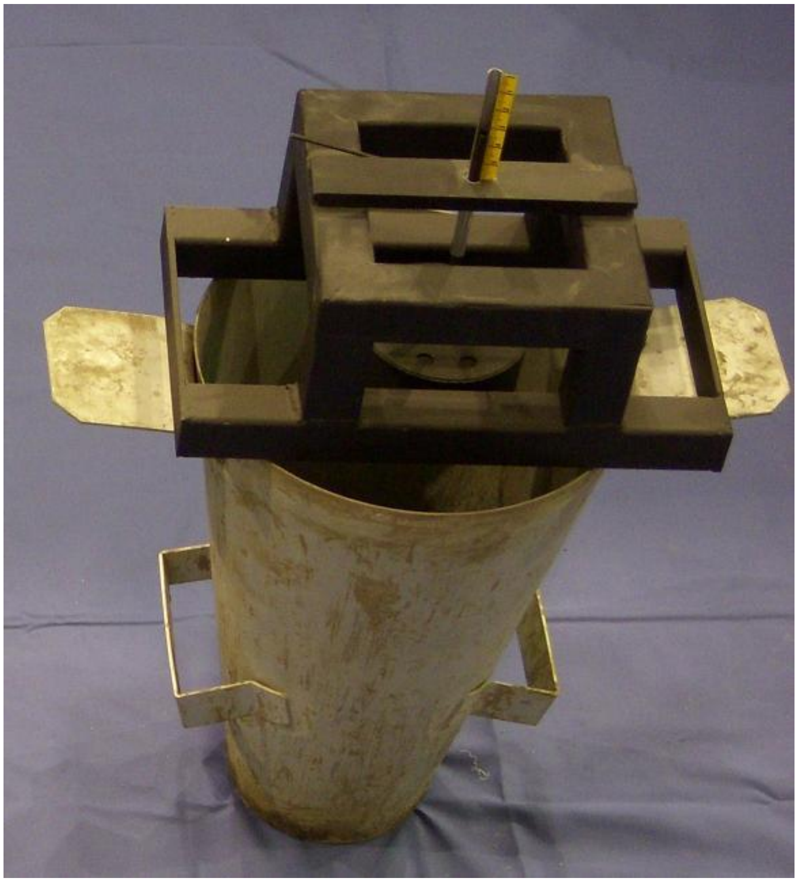

Figure 3.18: Inverted slump cone and rapid penetration apparatus

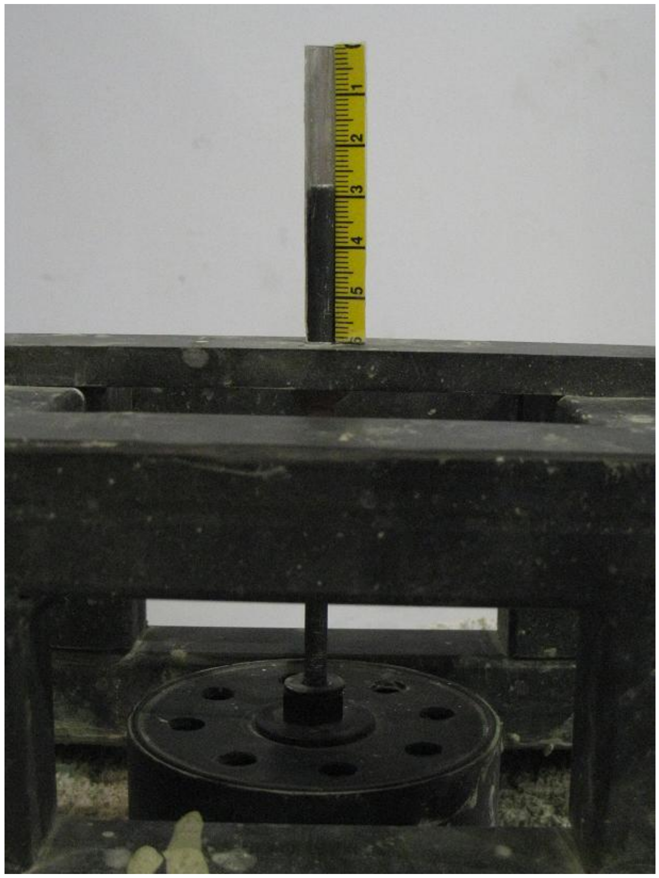

Figure 3.19: Penetration depth of 28 mm using the rapid penetration test apparatus

Figure 3.20: Performance of slump flow test

3.5.1.2 Column Segregation Test

The column segregation test was the only test performed on all SCC and conventional concrete placements. Testing of SCC was in accordance with ASTM C 1610 (2006), and, during conventional concrete placements, testing was completed similarly, except that each column segregation mold was filled in four lifts. For the conventional concrete testing, each lift filled approximately one quarter of the mold and was rodded 50 times as specified in ASTM C 192 (2003).

Column segregation testing was conducted using the apparatus shown in Figure 3.21A. The two column segregation tests were started simultaneously using concrete collected from a single wheelbarrow. Although the white column segregation mold shown has four segments, only the top and bottom portions of concrete were collected for comparison. Collection was facilitated by using a metal pan with a curved lip that fit around each mold, which is shown in Figure 3.21B.

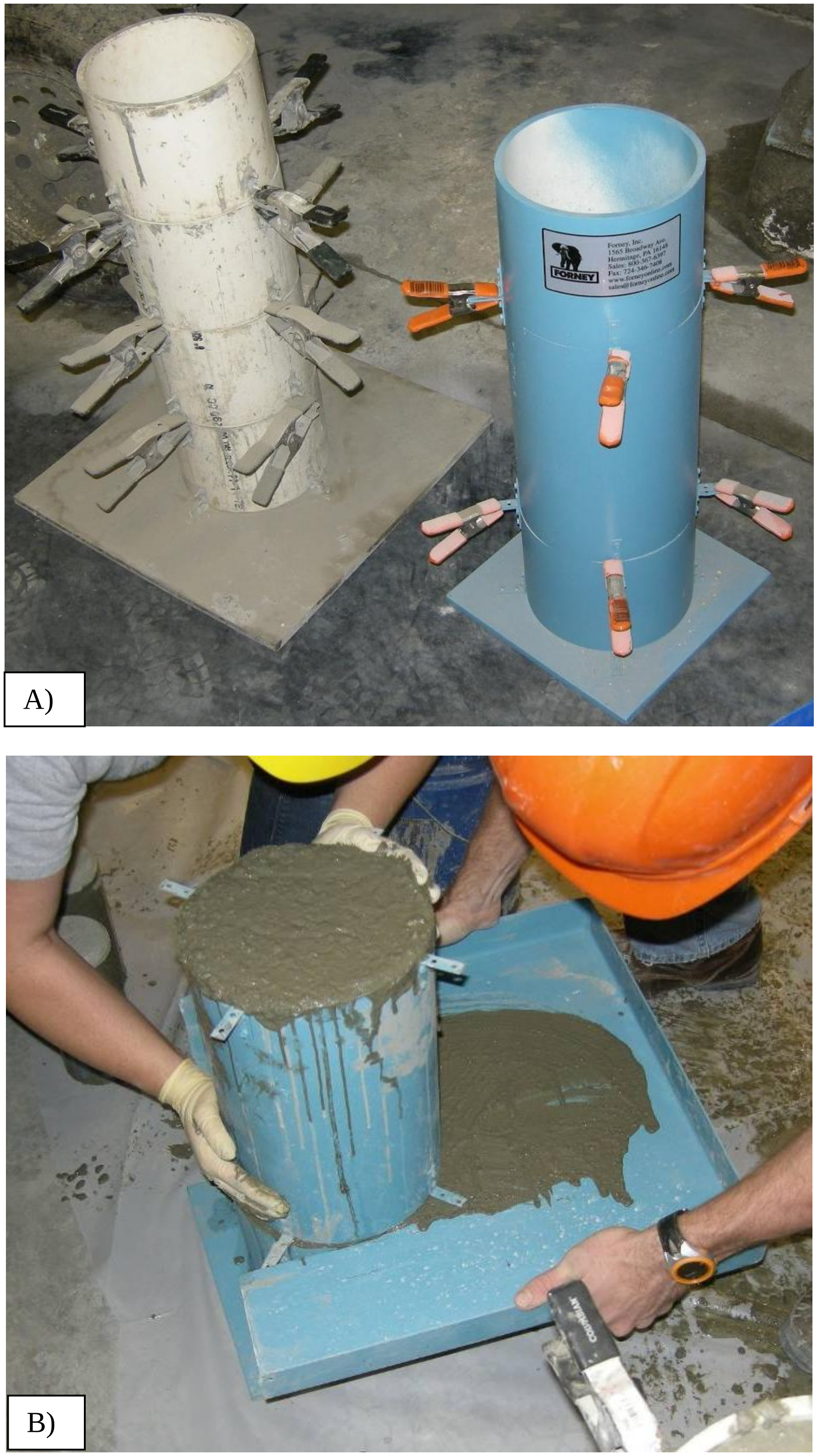

Figure 3.21: A) Two column segregation molds used during simultaneous testing and B) metal plate used to separate column segregation test apparatus segments

3.5.1.3 Sieve Stability Test

The sieve stability test, which measures the percentage of SCC passing through a sieve as it falls from a predetermined height, was conducted according to the procedure outlined in Appendix A.1. As suggested in the European Guidelines for SCC (EPG 2005) to ensure a consistent pouring height, the sieve stability test was operated with the use of a pouring apparatus shown in Figure 3.22.

Figure 3.22: Sieve stability test with pouring apparatus, sieve, and scale

This pouring apparatus was made with plywood, 4x4 lumber, screws, and bolts. The bucket shown in the figure was marked with a dashed line to indicate the level to which concrete should be filled to meet the required sample volume of 10 L (0.35 ft^3). The hinging mechanism for the bucket was attached parallel to the forward lip of the bucket so that, regardless of the angle at which the concrete fell from the bucket onto the sieve, the drop height would remain constant at approximately 20 inches.

A waterproof, rubberized scale with a precision of 0.005 lbs was used for the sieve stability test. The European Project Group (2005) recommended using a 5 mm (0.20 in.) sieve, but the American equivalent, a No. 4 (0.25 in.) sieve was used instead. This was deemed acceptable considering the literature reviewed in Section 2.5.2.4, as well as considering the practicality of using the same sieve required for the column segregation test.

3.5.1.4 Surface Settlement Test

The surface settlement test, which measures the settlement of an acrylic plate into a column of concrete, was conducted according to the procedure outlined in Appendix A.2 and recommended by NCHRP 628 (Khayat and Mitchell 2009). A linear variable differential transformer (LVDT) was recommended by Khayat and Mitchell (2009) to continuously record the settlement of the acrylic plate. However, readings were only necessary every five minutes, and the Auburn University researchers desired to use a measurement instrument offering the least risk of applying either downward pressure or settlement-resisting upward force on the plate. Therefore, a springless digital dial was used, as shown in Figure 3.23A. The entire testing apparatus used for this test is shown in Figure 3.23B.

A)

B)

Figure 3.23: A) Digital dial indicator used to measure settlement of an acrylic plate, and B) four-piece constructed surface settlement test apparatus

The digital dial indicator displayed displacements of up to 2 in. with a precision of 0.0001 in., which met the requirements of Khayat and Mitchell (2009). The dial indicator was supplied by Chicago Dial Instruments and was a Logic Basic model BG2720. The measurement rod of the dial indicator was able to fall freely as the plate settled, and it weighed one gram, which was accounted for in manufacturing an acrylic settlement plate of the required weight.

The testing apparatus shown in Figure 3.23B consisted of four pieces. The main column portion of the mold was split vertically and then sealed with a rubber gasket. The removable base was also sealed with a rubber gasket. This made it possible to possible to disassemble the apparatus after each sample hardened in the mold. The portion of the mold housing the dial indicator was detachable and was attached after filling the mold. This made quick filling and strike off of the concrete at the top of the mold possible without risk of damaging the indicator, and it made disassembly and removal of the hardened sample more convenient.

3.5.1.5 Multiple-Probe Penetration Test

The multiple-probe penetration test, which measures the settlement of four independent probes into a sample of SCC, was conducted according to Appendix A.3. The multiple-probe penetration test apparatus was not available for purchase from any commercial concrete laboratory equipment suppliers, so it was constructed by an Auburn University machinist as shown in Figure 3.24. The probes were lathed from PVC bar stock and had hollow cores that were capped by a metal washer. This construction was used in order to achieve the necessary physical geometry without exceeding the required probe weight of

25 grams (El-Chabib and Nehdi 2006). A vinyl ruler with a one-millimeter gradation was laminated onto the side of each probe so that depth readings could be read at the level of the steel frame as the probes penetrated into the SCC surface.

Figure 3.24: Multiple-probe penetration apparatus in use

3.5.2 Other Fresh Stability Tests Considered

3.5.2.1 Rheological Testing

Rheological testing, which involves testing of fresh SCC or sieved mortar to determine yield stress and viscosity, was considered for use as both a potential indicator of stability and as a benchmark against which to assess the fresh stability tests. However, after reviewing the literature described in Section 2.5.1, the research team decided against using rheological testing for the following reasons:

- Rheological testing would only indirectly assess stability, and the relationship between rheological properties and stability is unclear (Assaad, Khayat, and Daczko 2004; Koehler et al. 2007)
- The least expensive rheological testing equipment available to the research team would have been approximately ten times the cost of the other fresh stability tests, and
- For similar equipment costs, the researchers felt that UPV testing would be more valuable because it could assess as-placed concrete uniformity.

3.5.2.2 Wire-Probe Penetration Test

In the wire-probe penetration test, like the rapid penetration test (ASTM C 1712 2009) and the multiple-probe penetration test (El-Chabib and Nehdi 2006), the settlement of a probe into a sample of SCC is measured. The research team decided not to incorporate the test as it offered little advantage over the former two tests. Reasons for its exclusion were that:

- The test method is not standardized by any agency and is not widely used,
- It measures the same segregation mechanism as the rapid penetration and multiple-probe penetration test methods, and
- It does not incorporate any form of stabilization to ensure that the wire probe would settle directly downward into the sample.

3.5.3 Testing Order

A pair of each of the tests listed in Section 3.5.1 was performed in conjunction with the casting of the four walls described in Section 3.4. As noted in Section 3.3.2.2, concrete sampled for testing was drawn from a 1.5-yd^3-volume concrete placement bucket after it was used to fill the first of the four walls: the 36 in. wall. This was done so that sampling for the bulk of the fresh stability tests came from the middle of the first bucket load and not from the first concrete placed from this bucket.

A total of 10 ft^3 of concrete was needed to perform all fresh stability testing, so wheelbarrows with a volume totaling 16 ft^3 were filled for sampling. The first tests to begin were the tests for air content, unit weight, and temperature, all of which could be conducted with a single sample. Additionally, the first stability tests conducted were always the slump flow, rapid penetration test, and VSI. The tests for air content, unit weight, and temperature were conducted a single time, and the slump flow, rapid penetration test, and VSI tests were run twice, consecutively. The two iterations of these tests were conducted consecutively so that a single operator could conduct them (to eliminate between-user variation) while ensuring that the time spent evaluating the VSI of the first sample would not interfere with evaluation of the second sample. The order of filling and initiation of the other tests, in which two samples were tested simultaneously, was as follows:

1. Sieve stability test,
2. Column segregation test,
3. Surface settlement test, and
4. Multiple-probe penetration test.

This order of preparation and initiation was used during every testing cycle so that, although fresh properties may not have been identical at the beginning of each fresh stability test, consecutive results from each test would be comparable to the results of hardened testing described in Sections 3.4.2 and 3.4.3. Also, to reduce the risk of time-sensitive changes in fresh properties during the initiation of all tests, hydration-stabilizing admixture was added to each batch in the ready-mix concrete truck to delay setting until long after wall casting. Information on the hydration-stabilizing admixture, as well the other mixture constituents, can be found in Section 3.6.

3.6 Mixture Proportions and Raw Materials

The self-consolidating concrete mixtures used for this research were based on mixture proportions used for precast, prestressed applications as developed by Roberts (2005). Two primary SCC mixtures were chosen, SCC-1 and SCC-2, each of which was accompanied by several mixtures that were deliberately adjusted to obtain varying levels of stability. A conventional concrete mixture was also proportioned to mimic the early-age strength characteristics of each primary SCC mixture while exhibiting workability suitable for precast, prestressed applications. A total of 11 concrete mixtures were used.

3.6.1 Mixture Proportions

The mixtures reviewed in Section 2.2 generally contain a high cementitious content, high *s/agg* ratio, low *w/cm* ratio, and low total aggregate content. They also tend to contain large dosages of HRWR admixture, and, less frequently, VMA. As stated in that section, these proportions tend to result in concrete mixtures that are highly flowable and that attain high early-age compressive strengths.

SCC-1 was proportioned to achieve relatively higher strength but less flowability, and SCC-2 was proportioned to achieve moderate strength and higher flowability. From each of these two mixtures, other mixtures of the same cementitious content, aggregate content, and aggregate proportioning were created with varying stabilities. The stability was adjusted by changing the water content, HRWR admixture dosage, or VMA dosage, or by changing a combination of them.

The degree of adjustment was selected between testing cycles, depending on the degree of stability achieved in the mixtures. If a small adjustment in one mixture had little effect on stability test results and hardened test results, a larger adjustment would be used in subsequent mixtures, and if an adjustment resulted in a clearly segregating concrete, a smaller adjustment was used in subsequent mixtures.

Two conventional concrete mixtures were selected as control mixtures to mimic each primary SCC mixture and match conventional mixtures used in precast, prestressed applications. The control mixtures employed a higher *w/cm*, lower *s/agg*, and different coarse aggregate gradation than the SCC mixtures. These changes were selected because conventional concretes for precast, prestressed applications typically employ a larger gradation of stone (No. 57) and lower *s/agg* than recommended for SCC. Still, the following were expected: that one mixture would have a relatively low slump and an early-age compressive strength matching that of SCC-1, while the other would have a higher slump and moderate early-age compressive strength matching that of SCC-2.

As stated in Section 3.5.3, a hydration-stabilizing admixture was used in all mixtures, both conventional and self-consolidating. This dosage was not varied except when cementitious content was varied, and it was the minimum effective dosage recommended by the manufacturer. The proportions used are shown in Table 3.1.

3.6.2 Raw Materials

Materials used for this project were all locally available and within the recommendations set forth in Section 2.2. Lafarge Type I portland cement was used because, as mentioned in Section 2.2.2, Type III portland cement is characterized by rapid setting and early-age strength gains. This could have jeopardized the researcher's ability to initiate all fresh tests while the concrete was still dormant, and the use of Type III portland cement offered no long-term benefits over Type I portland cement in terms of testability.

All SCC-2 mixtures incorporated a 30% replacement of Type I portland cement with Class C fly ash. As mentioned in Section 3.6.1, SCC-2 was proportioned to have a greater flowability and relatively lower early-age compressive strength. Substitution of some Type I portland cement with Class C fly ash made this possible, and it offered the possibility of producing a concrete with a different characteristic reaction to adjustments in stability modifiers (water, HRWRA, and VMA).

The coarse aggregate and fine aggregate used for this research matched those used in earlier studies of SCC conducted at Auburn University described in Section 2.2.1. As mentioned in that section, the coarse aggregate used was a No. 78 gradation crushed limestone supplied by Vulcan Materials of Calera, Alabama. Fine aggregate was a well-graded natural sand taken from the ready-mix concrete plant's general supply.

Table 3.1: Proportions for each concrete mixture

Item	CTRL-1	SCC-1A	SCC-1B	SCC-1C	SCC-1D	CTRL-2	SCC-2A	SCC-2B	SCC-2C	SCC-2D	SCC-2E
Water (pcy)	270	270	310	295	270	290	270	270	270	290	270
Cement (pcy)	640	750	750	750	750	450	475	475	475	475	475
Fly Ash	0	0	0	0	0	190	0	200	200	200	200
w/cm	0.42	0.36	0.41	0.39	0.36	0.45	0.40	0.40	0.40	0.43	0.40
Coarse Agg. (pcy)	1977	1680	1680	1680	1680	1935	1663	1663	1663	1663	1663
Fine Agg. (pcy)	1167	1342	1342	1342	1342	1125	1360	1360	1360	1360	1360
s/agg	0.37	0.44	0.44	0.44	0.44	0.37	0.45	0.45	0.45	0.45	0.45
HRWR Admixture (oz/cwt)	11	6	6	11	9	2	11	12	13	5	9
Type 1 VMA (oz/cwt)	0	2	2	2	0	0	0	0	0	0	0
Type 2 VMA (oz/cwt)	0	0	0	0	0	0	0	0	2	0	2
Hydration Stab. Admix. (oz/cwt)	3	3	3	3	3	3	3	3	3	3	3

Note: Type 1 VMA = Rheomac 362 and Type 2 VMA = Rheomac 450

All chemical admixtures were supplied by BASF Construction Chemicals. The HRWR admixture used was Glenium 7500. Two viscosity-modifying admixtures were used depending on the desired effect: Rheomac 362, a general purpose VMA, was used when moderate viscosity modification was desired, while Rheomac 450, an underwater concreting agent, was used when significant viscosity modification was desired. The hydration-stabilizing admixture used in all concrete mixtures was Delvo Stabilizer. It was added in the minimum effective dosage recommended by BASF (2007), which was expected to retard the concrete's set by approximately one hour.

Chapter 4

Presentation and Analysis of Results

4.1. Introduction

The laboratory testing results of the six fresh stability test methods and the two hardened uniformity test methods are presented in this chapter. The correlations between the results of the six fresh stability tests and between the fresh stability test results and in-situ uniformity results are then evaluated. Since goals of this research included assessing the accuracy and technician-friendliness of the fresh stability test methods, observations from the research team that relate to the testing process are given in Section 4.3.2, and conclusions that can be drawn from the experimental program are given in Section 4.5.

4.2. Concrete Production

4.2.1. Concrete Mixture Properties

Using the proportions shown in Table 3.1, self-consolidating concretes were produced that exhibited varying degrees of filling ability and stability. Two conventional concretes were also produced that exhibited varying levels of workability. Because of the varied proportions, as well as because of fluctuations in batching, mixing, handling, and ambient conditions, the concretes achieved different fresh and hardened properties. Some of these properties are shown in Table 4.1, including slump flow, T-50, air content, unit weight, and compressive strength (f_c) of SCC, and slump, air content, unit weight, and f_c of conventional concrete.

Table 4.1: Fresh and hardened properties of concrete mixtures

Mixture ID	Slump (in.)	Slump Flow (in.)	T-50 (sec.)	Air Content (%)	Unit Wt. (lbs/ft^3)	2-day f_c (psi)	13-day f_c (psi)	28-day f_c (psi)
CTRL-1	5.5	-	-	4.0	149.5	4,680	6,700	7,440
SCC-1A	-	27.5	2.3	2.0	152.8	4,690	7,110	7,390
SCC-1B	-	25.5	6.9	1.7	150.8	5,230	8,030	8,460
SCC-1C	-	27.0	1.5	5.5	144.2	4,340	6,320	6,780
SCC-1D	-	26.0	1.3	9.5	138.5	3,200	4,790	5,190
CTRL-2	7.0	-	-	2.3	148.9	2,460	5,000	5,390
SCC-2A	-	28.0	1.5	6.0	144.6	2,510	5,010	5,530
SCC-2B	-	27.5	2.1	3.6	148.5	1,820	4,160	4,410
SCC-2C	-	26.0	8.0	1.8	148.8	2,620	5,300	5,880
SCC-2D	-	25.5	1.5	2.3	145.2	2,200	4,370	5,060
SCC-2E	-	26.0	4.0	3.5	145.3	2,720	4,890	5,290

4.2.2. Discussion of Concrete Mixture Properties

The batch proportions for mixtures SCC-1A and SCC-1B were intended to be similar, but the resulting concretes exhibited different fresh and hardened behaviors. As stated in Section 3.3.2.1 and Section 3.6.1, admixtures were dosed to achieve a target slump flow and VSI, and when the dosage applied to SCC-1A was applied to SCC-1B, the resulting slump flow and VSI were different but still acceptable. Although the research team was unable to verify it, they assume that this apparent inconsistency was the result of batching fluctuation at the ready-mix plant. Although the proportions of SCC-1A and SCC-1B listed in Table 3.1 may be inaccurate, the inconsistency was deemed acceptable because the proportions used in each mixture were less important than the resulting stability of each.

Similarly, the initial proportions of CTRL-1 and CTRL-2 were nearly the same except that CTRL-2 employed a 30% replacement of Type I cement with Class C fly ash, and 20 pounds of water per yd^3 of concrete were added to CTRL-2 upon its arrival at the laboratory. The water was added because a sample brought to the front of the mixer showed evidence of unhydrated powders, which was unexpected. Subsequently, the initial addition of 2 oz/cwt of Glenium 7500 gave the concrete the desired slump.

The research team is uncertain of how accurately the ready-mix plant followed the proportions supplied by Auburn University. Because the goal of the research was to assess how well fresh stability tests measure in-situ uniformity of a variety of concrete mixtures, fluctuations from the proportions listed in Table 3.1 do not affect the viability of the data collected.

As shown in Table 3.1, no SCC-1 mixtures were proportioned with Rheomac 450, and no SCC-2 mixtures were proportioned with Rheomac 362. This was decided upon by the research team as testing progressed because the goal was to produce concretes acceptable for precast, prestressed applications that exhibited a wide range of stabilities and fresh behaviors, regardless of the chemical admixtures used to achieve them.

4.2.3. Discussion of Concrete Mixing Procedures

Prior to the production of SCC-1A, the researchers conducted a full-scale trial of all fresh testing and wall placements. The trial mixture exhibited an excessively high air content and low f_c, which the researchers believe could have resulted from the use of an excessive rotation speed during the mixing of the concrete within the ready-mix concrete truck. In light of that trial, each subsequent mixture produced during this research program was mixed using a reduced rotation speed, and the only other time a relatively high air content was discovered was in mixture SCC-1D. However, SCC-1D achieved a 28-day compressive strength of approximately 5,200 psi, which was deemed acceptable for inclusion of its results.

Although the amount of concrete ordered from the ready-mix plant for the full-scale trial, 2.5 yd^3, was sufficient for all testing and wall placements, the batch size of 2.5 yd^3 was insufficient to complete the necessary placements of mixture SCC-1A. The deficiency was discovered during placement, so the research team decided to continue placement, and the 54 in. wall was only filled to 50 inches. The consequences of that incomplete placement on the results of hardened testing are discussed in Sections 4.4.1 and 4.4.2. Subsequent concrete orders from the ready-mix plant were each for 3 yd^3, and the batches received were all sufficient to complete the necessary placements.

As a result of the full-scale trial, nine SCC, and two conventional concrete placements, the research team was able to observe several differences in the production of SCC and conventional concrete:

- When placing SCC, all seams in the formwork had to be completely sealed. Any points that were not sealed correctly leaked minor amounts of bleed water and paste.
- Placement of the SCC in the four walls required the assistance of two people for approximately 25 minutes. One person was required to maneuver the bucket, and the other was required to control the release of concrete from the bucket.
- Because SCC flowed quickly from the bucket during placement, care was required in opening and closing the bucket to prevent overfilling and spillage.
- Consolidation of SCC was never needed, but patience was needed to place the SCC in order to prevent entrapment of air bubbles against the formwork, which would result in increased shallow bug holes.
- When placing conventional concrete, labor demand increased in both number of laborers and time spent. The labor was needed to accommodate consolidation efforts in wall placements and increased effort in cylinder production.
- Placement of conventional concrete in the four walls required the assistance of three people for approximately 70 minutes. One person was required to maneuver the bucket, one was required to control the release of concrete from the bucket, and the other was required to consolidate the concrete using an internal vibrator.

- Because conventional concrete placement took more time to place and the concrete was less flowable, care was required in limiting the amount of time the concrete spent resting in the bucket.
- Consolidation of conventional concrete within tall, narrow wall formwork was labor-intensive, even though the walls were essentially unreinforced. The CTRL-2 mixture, which was more workable than CTRL-1, was easier to place.

4.3. Fresh Stability Tests

4.3.1. Stability Test Results

The results of the six fresh stability test methods conducted on each SCC are presented in Table 4.2. The raw test data used to calculate these results can be found in Appendix B. In the table, each result represents the average of the data collected from two tests conducted simultaneously. The following exceptions apply:

- All VSI values and rapid penetration depths are the average of two tests conducted consecutively, as previously discussed in Section 3.5.3,
- During placement of SCC-1A, the acrylic settlement plate in one of the surface settlement tests settled askew to the dial indicator, so the result from that apparatus was not used, and
- During placement of SCC-1A, the sieved fraction result obtained from the sieve stability test was extraordinarily different than the results of the other fresh stability tests. The result of that test was not used, and the irregularity is discussed in Section 4.3.2.1.

Table 4.2: Mixture average fresh stability test results

Mixture ID	VSI	Seg. Index (%)	Rapid Pen. (mm)	Sieve Fraction (%)	Rate of Set. (%/hr)	Max. Set. (%)	Multiple Probe (mm)
CTRL-1	N.A.	3.0	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-1A	2	5.6	6.5	*	0.15	0.60	4.1
SCC-1B	0.75	0.0	5.0	6.5	0.15	0.35	8.9
SCC-1C	1.25	8.4	3.0	8.2	0.11	0.03	15.1
SCC-1D	1.25	17.5	8.5	15.8	0.02	0.01	12.3
CTRL-2	N.A.	5.3	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-2A	1.75	8.0	9.0	13.8	0.05	0.02	20.4
SCC-2B	3	20	7.5	30.5	0.25	0.14	14.0
SCC-2C	1.75	3.0	7.5	9.0	0.12	0.09	20.7
SCC-2D	1.25	11.1	2.5	5.2	0.25	0.13	8.4
SCC-2E	1.75	16.6	3.5	14.3	0.17	0.18	10.4

Note: * = Sieve fraction result not considered. See Section 4.3.2.1 for details.

4.3.2. Discussion of Stability Testing

Section 4.3.2 is divided into two subsections, the first of which includes a discussion of the results presented in Section 4.3.1. Systematic and isolated irregularities in the testing process that might have affected the obtained results are also described in that section and are followed by the research team’s view on the applicability of those results. Section 4.3.2.2 includes a discussion of the technician-friendliness of each test. The qualitative assessment provided in that section is necessary to fulfill the goal of the research project to assess the appropriateness of each test method for field use to assess precast, prestressed SCC.

4.3.2.1. Stability Test Results

In Table 4.2, a visual stability index other than the discrete values discussed in Section 2.5.2.1 (0, 0.5, 1, 1.5, 2, or 3) is listed frequently because the listed value represents the average of two VSI results. Although the two samples were obtained from the same wheelbarrow, the two VSI tests were conducted consecutively, so identical test results were not guaranteed. As stated in Section 3.5.1.1, the research team decided that it was more important to maintain the strict timing of the slump flow, rapid penetration test, and VSI than to conduct two tests simultaneously. Furthermore, since the other fresh stability tests were started after completing the first iteration of these three tests, it was decided that averaging the two values obtained consecutively would be comparable to the results of those other fresh stability test methods.

As mentioned in Section 4.3.2.1, the acrylic settlement plate of one surface settlement test apparatus sank unevenly into the test sample during placement of SCC-1A, which nullified that result. This problem, which is shown in Figure 4.1, most likely occurred due to improper striking and leveling of the sample prior to test initiation. However, it is also possible that the SCC being tested was simply unstable, and the acrylic plate was too thin to resist being engulfed as it settled. The result of the second surface settlement test on SCC-1A, which is shown in Table 4.2, was in the unacceptably high category according to the recommendation of Khayat and Mitchell (2009), which reinforces the possibility that failure of the first apparatus was due to the use of a highly segregating mixture and not testing error.

Figure 4.1: Acrylic settlement plate sinking unevenly during the surface settlement testing of SCC-1A

The two sieve stability test measurements taken during the placement of SCC-1A were extraordinarily higher than the other fresh stability results. It is possible that a nonrepresentative sample of SCC was used to prepare each of the sieve segregation tests or that the test was not conducted in accordance with its guidelines set forth in Appendix A.1. Considering the error encountered in the surface settlement test during the fresh stability testing of SCC-1A, it is also likely that the concrete was very unstable and that, like the surface settlement test, the failure of the test method was due to the use of a highly segregating mixture.

Similar to the problem expected of the wire-probe penetration test (see Section 2.5.3.3), the probes used in the multiple-probe penetration test were not adequately confined to sink vertically into the sample, so measurements were difficult to obtain in some cases. Still, the penetrations measured for all four probes were averaged to determine the value listed in Table 4.2. This difficulty encountered during the multiple-probe penetration test is shown in Figure 4.2.

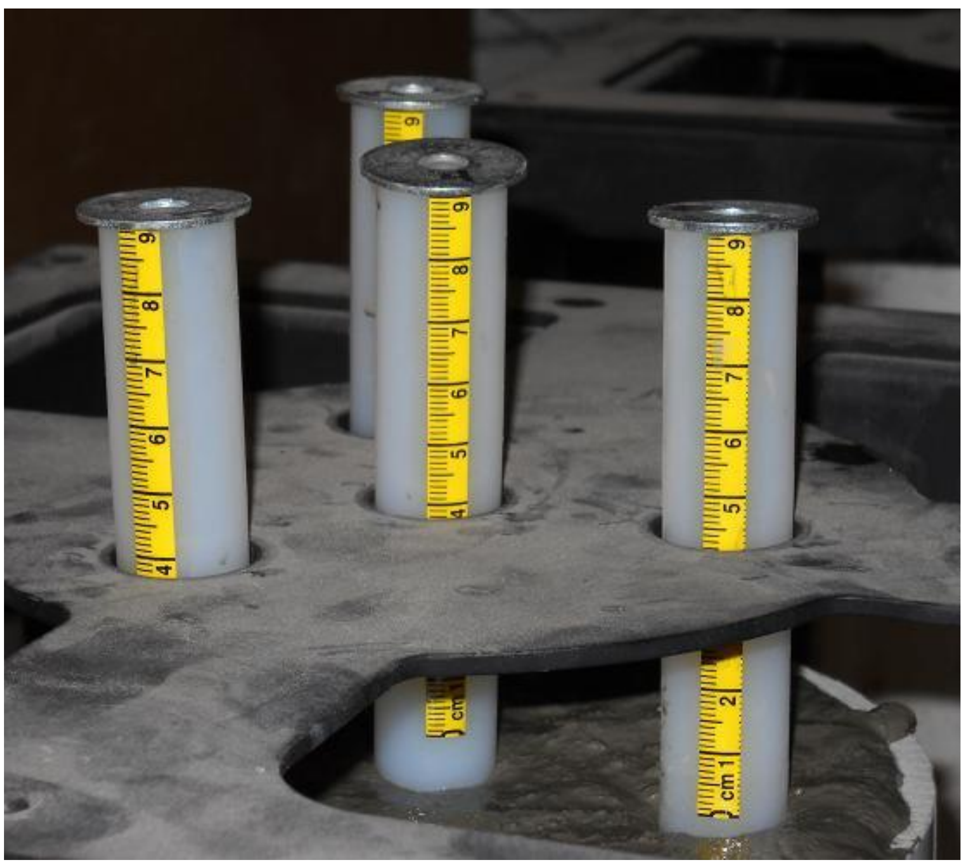

Figure 4.2: Irregular settlement of probes during multiple-probe penetration testing

4.3.2.2. Technician-Friendliness of Fresh Stability Test Methods

Technician-friendliness, which was defined by ease of testing operation and ease of result calculation, was a consideration in assessing each fresh stability test method. The research team decided that ease of testing, from easiest to most difficult, was as follows:

1. Visual Stability Index
2. Rapid Penetration Test
3. Multiple-Probe Penetration Test
4. Sieve Stability Test
5. Surface Settlement Test
6. Column Segregation Test

The VSI requires no equipment beyond that required for slump flow testing, the test can be completed in seconds, and the test action requires only subjective viewing. Thus, the VSI test requires the least amount of physical effort. The rapid penetration test takes the least amount of time of the other five tests, and only two measurements are required (initial and final penetration depth). The multiple-probe penetration test also requires very little time, but it requires eight readings (four initial and four final penetration depths), and the research team found it difficult to simultaneously initiate testing of all probes.

The sieve stability test is easier to conduct than either of the other fresh stability test methods that require an extended testing duration, and the column segregation test is the most difficult fresh stability test to conduct. After the 15-minute dormant period, the column segregation test sample must be divided (which is potentially very challenging) and then wet sieved, and the remaining coarse aggregate must be brought to a saturated surface dry state and weighed. This process can take much more time than required of all other fresh stability test methods except the surface settlement test method, and it requires much more effort to perform than even that test method.

The surface settlement test is simple to initiate, operate, clean, and store, but the dial indicator used must not be contaminated by either water or concrete, and its maximum settlement reading requires several hours to obtain. Thus, neither it nor the column segregation test is suitable for rapid assessment of stability necessary in quality assurance applications.

The other factor determining technician-friendliness, ease of determination of final result, was a consideration because it is important that the result from a fresh stability test be quickly determined by a technician in order to provide quantitative feedback for batch acceptance in the field. In terms of determining a quantitative stability test result, the research team judged that ease of result determination, from easiest to most complicated, was as follows:

1. Rapid Penetration Test
2. Multiple-Probe Penetration Test
3. Sieve Stability Test
4. Surface Settlement Test
5. Column Segregation Test
6. Visual Stability Index

While the VSI is directly assessed as it is conducted, it may also have the most difficult result to determine, as any technician may struggle with the subjective assessment required of the method. The results of the rapid penetration test and multiple-probe penetration tests are relatively easy to compute, with the former requiring only the subtraction of initial penetration depth from final penetration depth and the latter requiring the calculation of an average of four such differences. A calculator, which should be used to calculate the multiple-probe penetration average, is also necessary to obtain the sieved fraction results from the sieve stability test.

Like the two penetration test method results, the sieved fraction result directly represents what is measured. Thus, the technician may be able to obtain a visual indication of the amount of paste segregation and use this assessment to estimate an expected sieved fraction result. The segregation index result determined from the column segregation test, on the other hand, cannot be visually approximated until after completing the very laborious wet sieving of aggregate required to obtain the result.

A distinction must be made when considering the ease of determination of a usable result from the surface settlement test: the first test result (the rate of settlement between 10 and 15 minutes) can be calculated immediately after the settlement measurement is taken at 15 minutes, while the second test result (the maximum settlement) cannot be calculated until much later, after the sample has reached initial setting. Both results require full knowledge of the testing process and apparatus, as both results are expressed as a percentage of the height of the test sample. Also, both results are impossible to visually approximate, as the settlements measured to determine them are imperceptible to the operator.

4.3.3. Correlations between Stability Test Results

Six fresh stability test results were obtained for each concrete, and each concrete's results were compared to each other in order to identify any correlations between the fresh stability test methods. Table 4.3 is a correlation matrix that shows the linear regression coefficients of determination (r^2) between each fresh stability test.

Table 4.3: Linear regression coefficients of determination between fresh stability test results

Test Result	Linear Regression Coefficient of Determination						
	VSI	**Column Seg.**	**Rapid Pen.**	**Sieve Stability**	**Surface Set. (rate)**	**Surface Set. (max)**	**Multiple Probe**
Multiple Probe	0.02	0.00	0.03	0.02	0.00	0.00	-
Surface Set. (max)	0.00	0.00	0.00	0.00	**0.47***	-	
Surface Set. (rate)	0.15	0.03	0.00	0.04	-		
Sieve Stability	**0.77**	**0.54**	0.36	-			
Rapid Pen.	0.12	0.07	-				
Column Seg.	0.26	-					
VSI	-						

Note: * = Nonlinear regression coefficient of determination. See Section 4.3.3 for details.

As seen in the table, very few of the r^2-values between tests exceeded 0.40. The selection of an r^2-value of 0.40 as a threshold for this study was determined after all testing was completed, and it was based on the relative magnitude of the coefficients of determination obtained. An r^2-value larger than 0.40 indicates that more than 40% of the variability in the relationship can be explained by a linear regression model, and it is possible that a higher value may be applicable if more results are obtained.

As seen in Table 4.3, the only fresh stability test correlations having a linear r^2-value greater than 0.40 were the correlations between the sieve stability test and each of the VSI and column segregation test methods. The correlation between the sieve stability test and VSI is plotted in Figure 4.3, and the correlation between the sieve stability test and column segregation test is plotted in Figure 4.4.

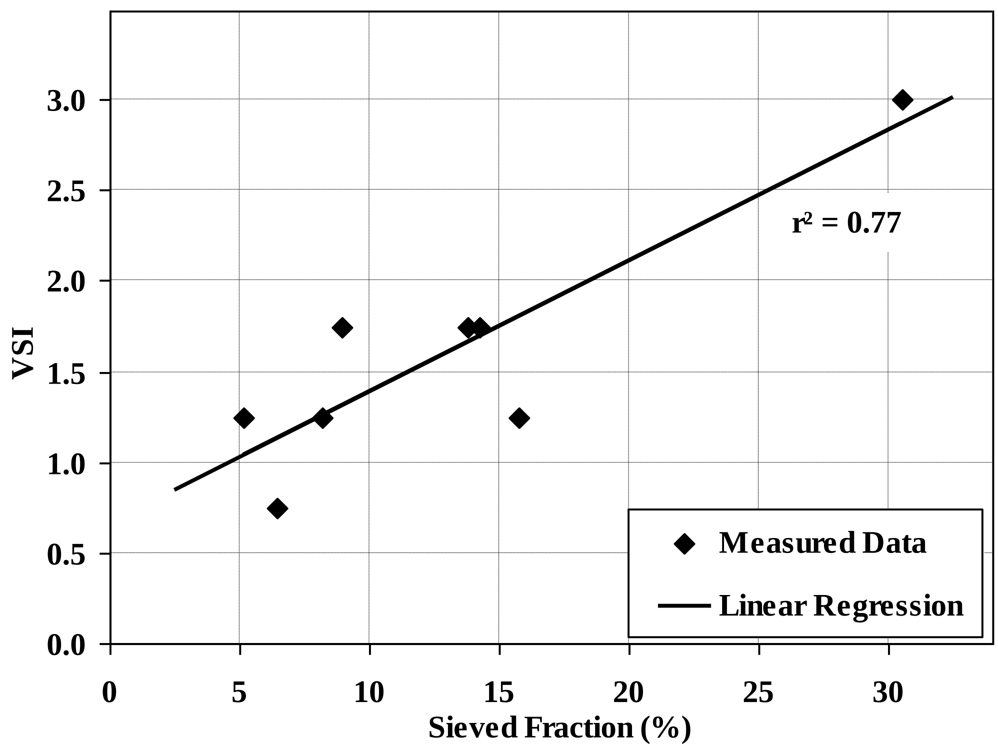

Figure 4.3: Comparison between sieve stability and VSI test results

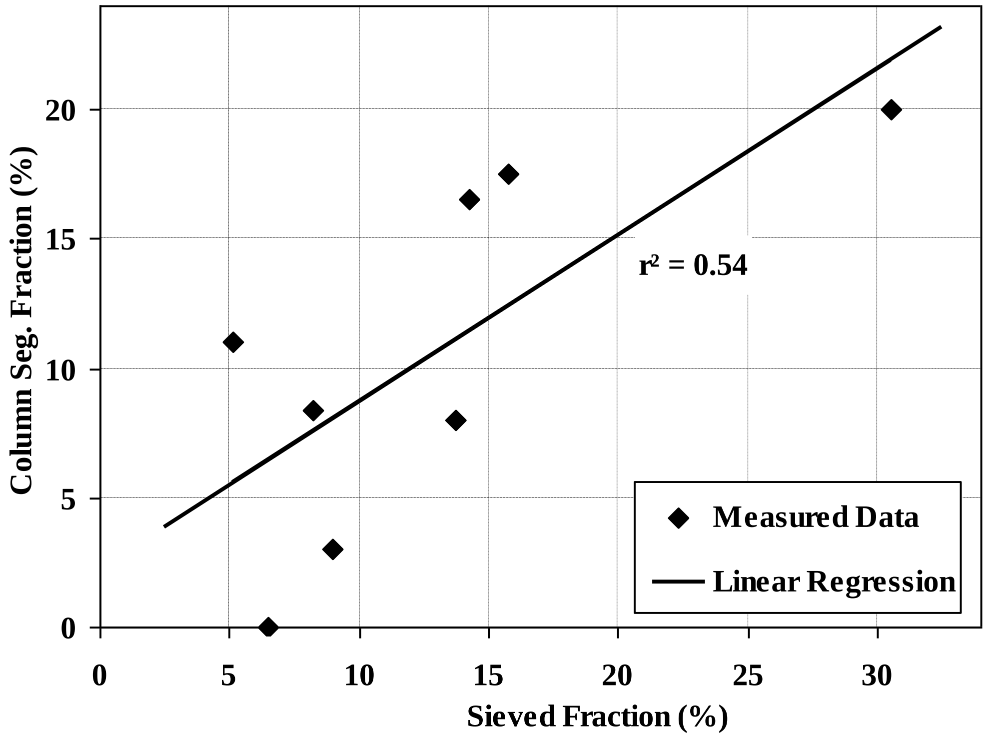

Figure 4.4: Comparison between sieve stability and column segregation test results

Notably, the linear relationship between sieve stability and column segregation test results that is shown in Figure 4.5 is very similar to the relationship found by Kohler and Fowler (2010) that is shown in Figure 2.32.

Coefficients of determination were also calculated for nonlinear models of the relationships between the fresh stability test methods, and these values are listed in Appendix D. When using nonlinear regression models, only one r^2-value was improved by more than 0.10 and increased to exceed 0.40 when changing from a linear to a nonlinear model. That one occurrence was in the relationship between the rate of settlement and maximum settlement from the surface settlement test, in which the r^2-value was improved from 0.10 to 0.47 when switching from a linear to an exponential model. This relationship is shown in Figure 4.5 and is notably similar to the relationship found by Hwang, Khayat, and Bonneau (2006) that was shown in Figure 2.27.

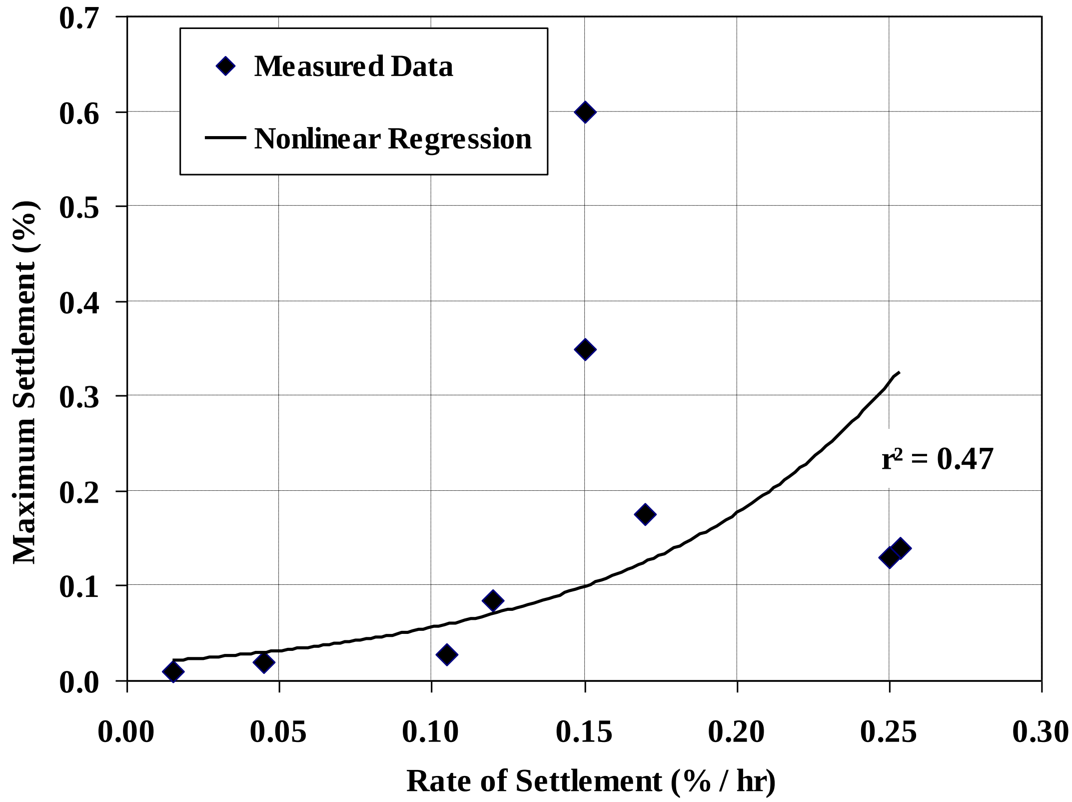

Figure 4.5: Comparison between rate of settlement and maximum settlement results from the surface settlement test

Conclusions that can be drawn from these correlations include:

- When assessed by trained personnel, the VSI gives results that are relatable to more time-consuming but less subjective tests,
- Since the VSI is already used extensively for quality assurance applications, the sieve stability test is a well correlated alternative when determining stability acceptance by the VSI,

- The linear relationship between sieve stability and column segregation result found during this research is similar to the relationship found by Kohler and Fowler (2010),
- The sieve stability test is a viable alternative to the column segregation test, especially considering its increased technician-friendliness,
- The nature of the relationship between rate of settlement and maximum settlement from the surface settlement test is similar to the relationship found by Hwang, Khayat, and Bonneau (2006), and
- The rapid penetration test, multiple-probe penetration test, and surface settlement test do not exhibit a reasonable correlation with the VSI, column segregation test, sieve stability test, or each other.

4.4. In-Situ Uniformity Test Results

This section summarizes the results of UPV and pullout testing conducted on the walls described in Section 3.4.1. The results of UPV testing and observations of the UPV testing program are described in Section 4.4.1, and the results of pullout testing and observations concerning the pullout testing program are located in Section 4.4.2. Finally, the correlation found between the measurements of in-situ uniformity is discussed in Section 4.4.3.

4.4.1. Ultrasonic Pulse Velocity Testing

The pulse velocity was calculated by dividing the wall thickness by the transit time, and the five velocities calculated at each height were averaged to obtain the results that were used to assess in-situ UPV uniformity. The average velocity data collected during this research is presented in Appendix C.

Surface roughness of the walls, voids in the coupling agent, and human error in either testing or recording of measurements occasionally caused outliers in the calculated pulse velocities within a wall. Outliers were identified as any pulse velocity greater than three standard deviations away from the average of the other four velocities at a given height. The use of three standard deviations to determine outliers was necessary due to the limited number of data points (four) used to calculate this standard deviation. Outliers were found in fewer than eleven percent of measurements.

The pulse velocities, separated by concrete mixture type and wall height, are shown in Figure 4.6 through Figure 4.9. The variation of pulse velocity with height was different for each SCC-1 and SCC-2 mixture. This leads to the conclusion that stability, which was varied between mixtures, was the cause of the pulse velocity differences. Also, it can be seen that the conventional control mixtures (CTRL-1 and CTRL-2) exhibited similar levels of uniformity to each comparable SCC but frequently at higher average pulse velocities. The higher averages were likely a result of the increased presence of coarse aggregate.

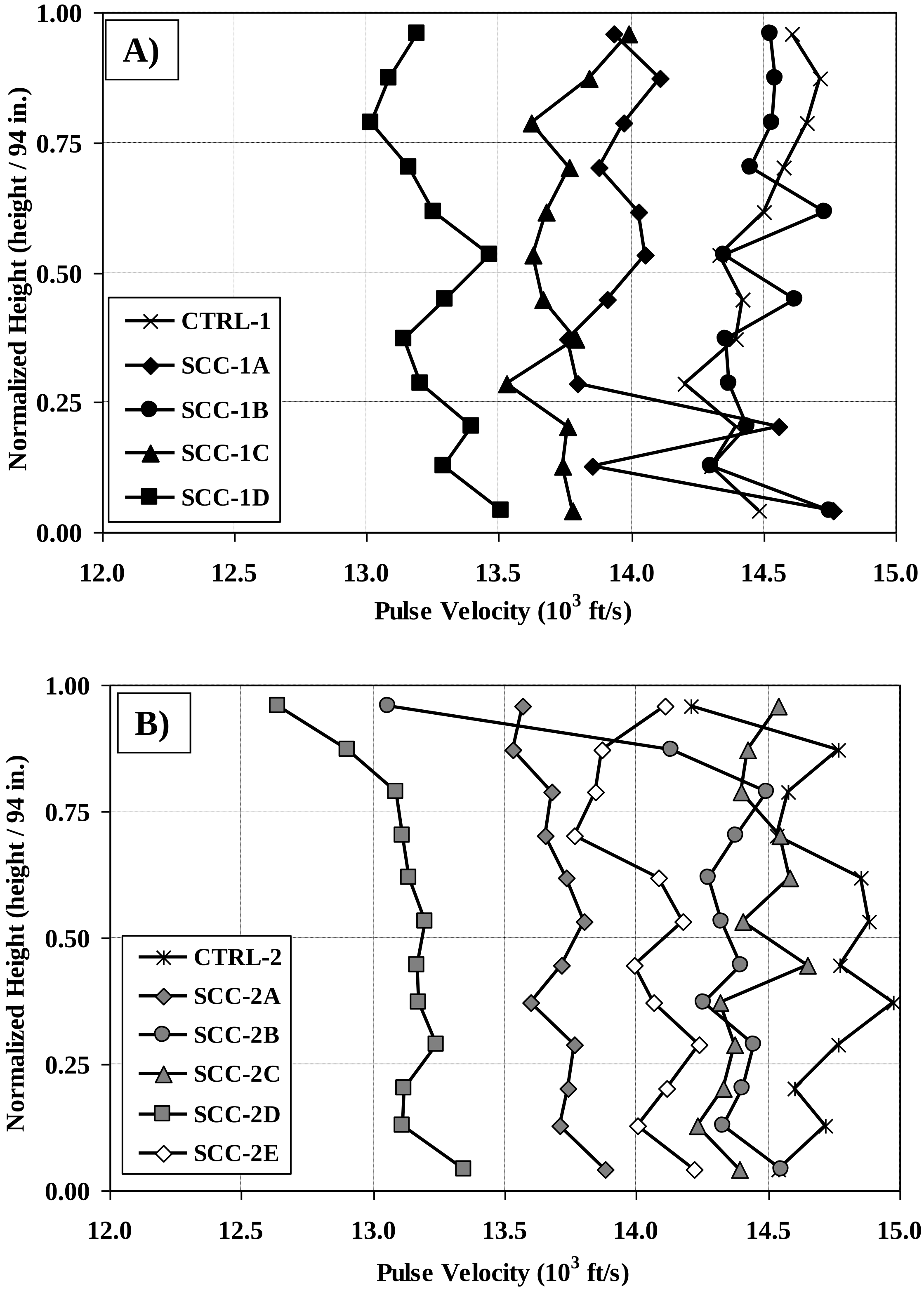

Figure 4.6: Measurement of ultrasonic pulse velocity over normalized height, in 94 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

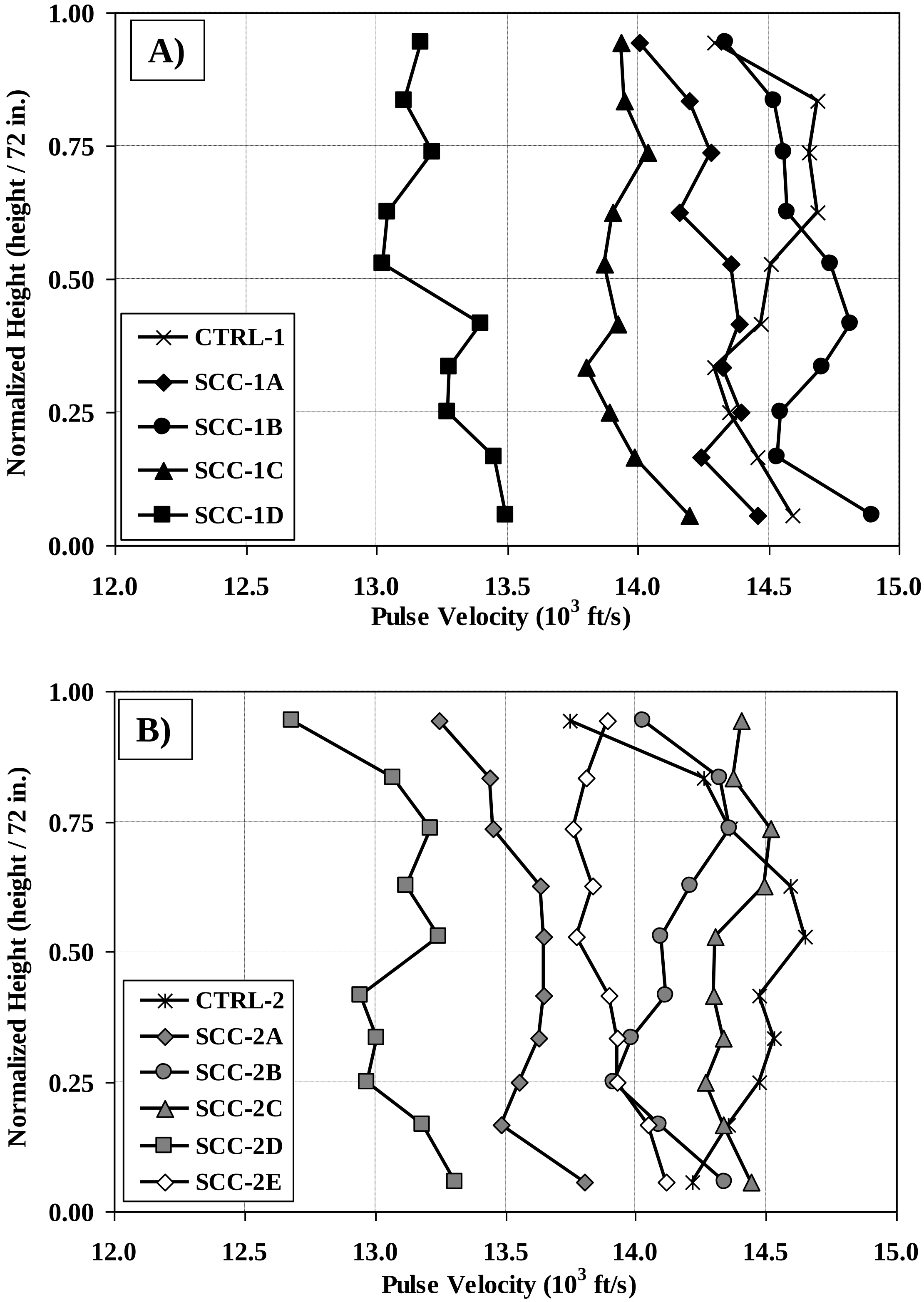

Figure 4.7: Measurement of ultrasonic pulse velocity over normalized height, in 72 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

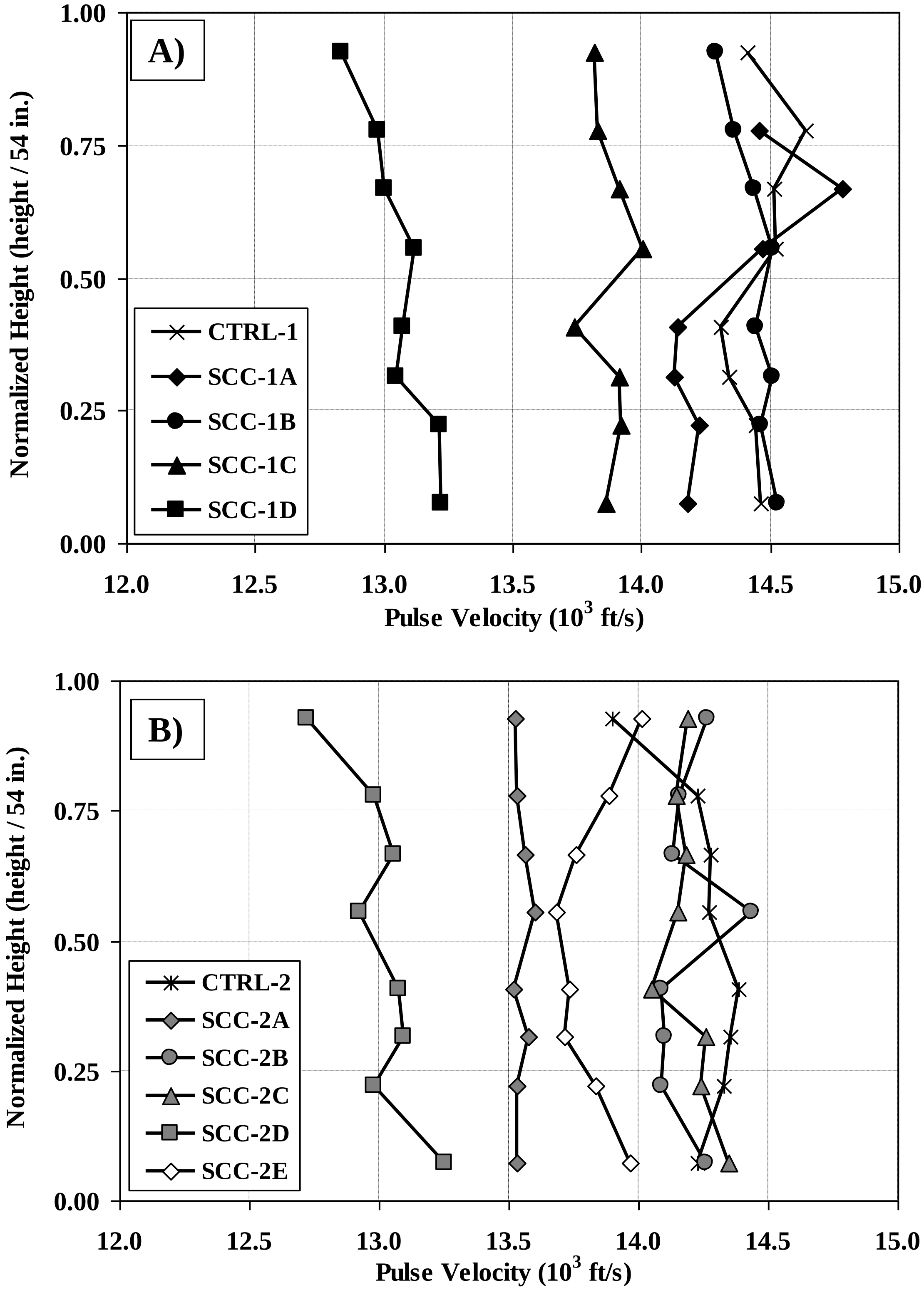

Figure 4.8: Measurement of ultrasonic pulse velocity over normalized height, in 54 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

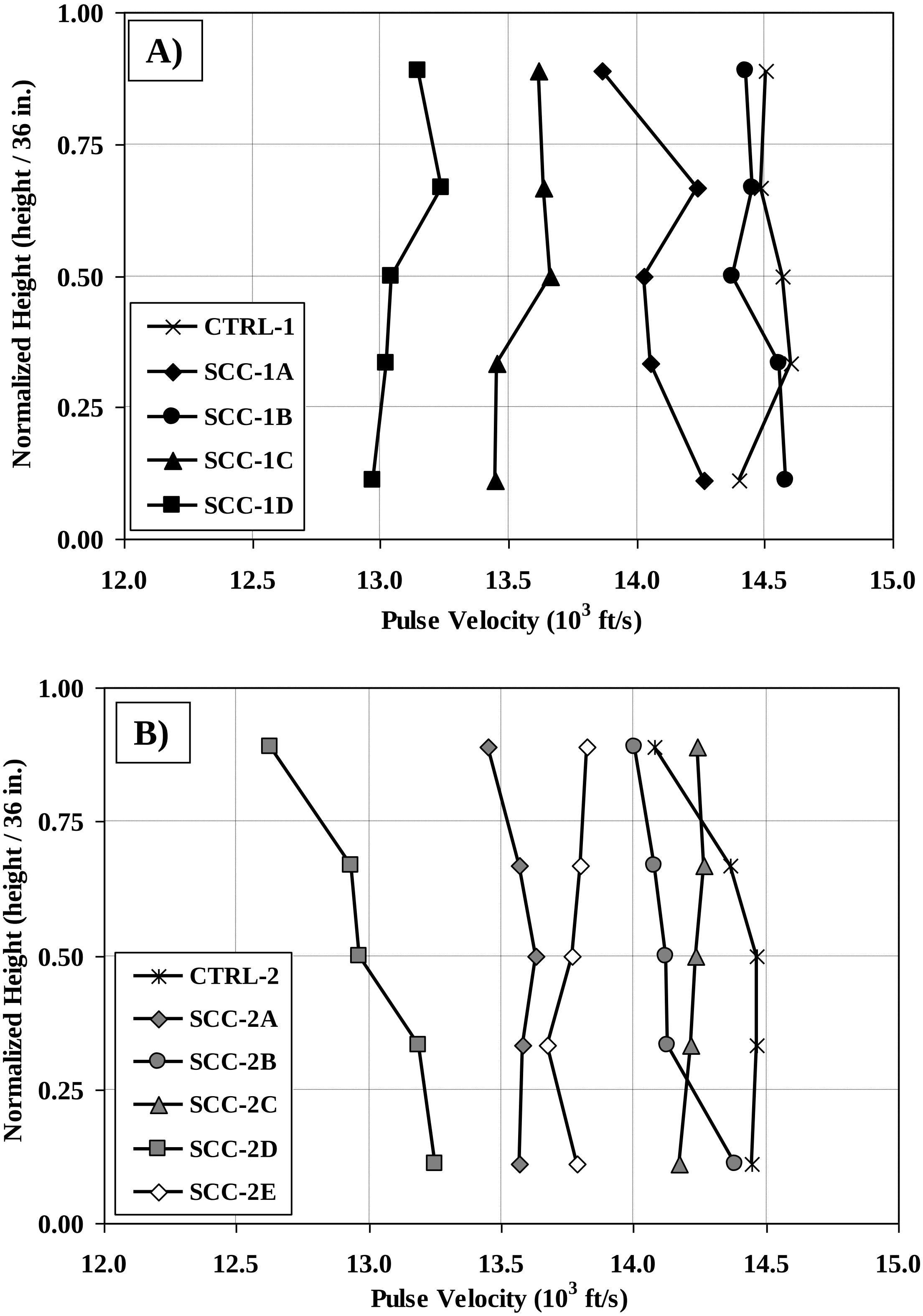

Figure 4.9: Measurement of ultrasonic pulse velocity over normalized height, in 36 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

The researchers expected to find the fastest pulse velocities at the bottom of each wall (due to increased consolidation under self-weight) and the slowest velocities at the top of each wall (due to upward migration of air and bleed water and settlement of coarse aggregate). Although UPV measurements generally decreased with height, the extreme high and low velocities within each wall were not necessarily at the bottom and top of each wall, as seen in Figure 4.6 through Figure 4.9. In total, 17 of 44 walls assessed using the UPV test method were found to exhibit their minimum velocity at the top of the wall and their maximum velocity at the bottom. Only 2 of the 44 walls (the 36 in. walls cast with SCC-2B and SCC-2D) consistently exhibited decreasing ultrasonic pulse velocities with increasing height within the wall.

In Figure 4.8, the top data point is missing from the 54 in. wall cast from mixture SCC-1A. As noted in Section 4.2.3, the 54 in. wall was only filled to 50 in., which meant that the first UPV location tested was at 42 inches. Although testing would have been possible at 46 in., the concrete placed in the uppermost few inches of the wall was gathered from the remaining concrete left in several sampling buckets and may not have been representative of the mixture. Testing at 42 in. matched the testing of all other mixtures, and the results at that level appeared to fit the normal trend in uniformity found in the other concretes and in the other walls cast from the SCC-1A mixture.

Groups of UPV segregation indices determined for each wall and mixture are shown in Figure 4.10. The UPV segregation index was determined by dividing the maximum velocity by the minimum velocity measured within each wall.

$$UPV\ segregation\ index = \frac{UPV_{\max}}{UPV_{\min}} \geq 1.00$$

The use of the maximum and minimum velocities differs from the calculations used by Khayat and Mitchell (2009) and by others mentioned in Section 2.3.2.2.1 to calculate the top-bar effect from pullout testing, but the use of maximum and minimum velocities was deemed most appropriate to assess in-situ uniformity from the UPV data.

Many properties affected by segregation, including distribution of air voids, aggregate, and paste, can affect the measured UPV, and these properties do not necessarily fluctuate linearly. Therefore, although the UPV measurements in a wall may not consistently vary over the wall's height, the maximum and minimum velocities likely indicate the level of non-uniformity within the wall.

The grouping of UPV segregation indices by concrete mixture makes it possible to analyze trends between walls of different heights cast with the same mixture. The researchers expected to find a decrease in uniformity (and higher segregation index) with increasing wall height, but, as can be seen in Figure 4.10, this was not the case. The tallest wall (94 in.) cast from each mixture was often the least uniform, but exceptions included the SCC-1B, SCC-2A, and CTRL-2 mixtures. In those three concretes, the second tallest (72 in.) wall exhibited the least uniformity. In total, UPV uniformity consistently decreased with increasing wall height in four mixtures, while the trend was not consistent within the other seven mixtures.

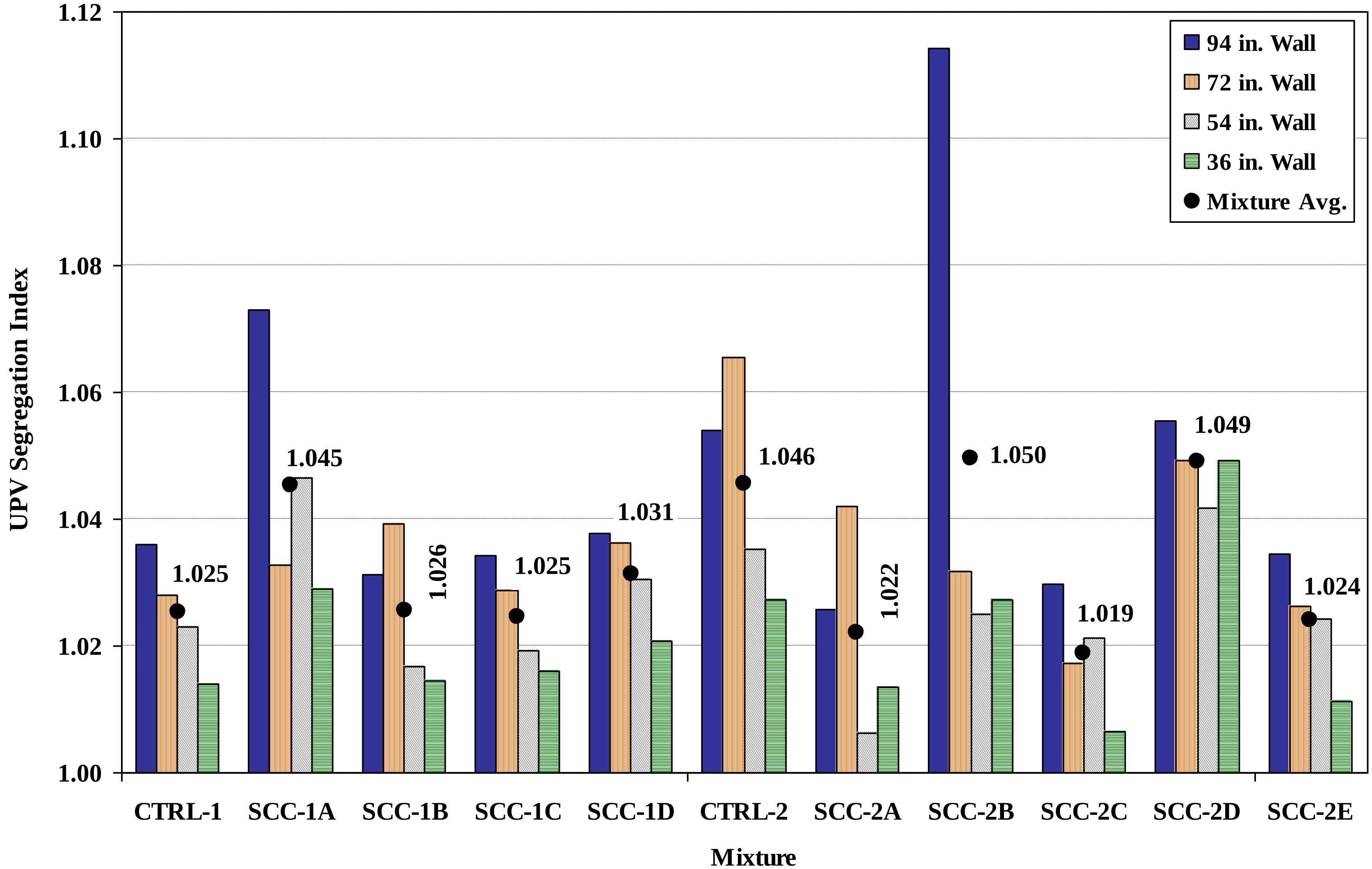

Figure 4.10: UPV segregation indices by wall height and mixture

Since UPV uniformity trends with wall height were different within each concrete, it was necessary to average the UPV segregation indices from all four walls to find a single value that would describe the average in-situ UPV uniformity of each concrete mixture for comparison to fresh stability test results. This was deemed acceptable because walls of all four heights would be subject to the top-bar factor (for having horizontal reinforcement cast with greater than 12 in. of concrete beneath them), and because all four walls were cast using concrete from the same batch.

The average pulse velocity segregation indices measured in the SCC mixtures ranged from 1.019 to 1.050, while the UPV segregation indices were equal to 1.025 and 1.040 in the conventional concretes. These averages are shown in Figure 4.10 above each mixture's data. Based on the range of effects determined during SCC and conventional testing, it can be concluded that differences in UPV measurements are relatively small (five percent different in even the least stable mixtures) but are readily affected by the level of stability of each mixture.

As described in Section 3.4.2, UPV testing was conducted at a concrete age of two and six days. After all testing was completed, the research team decided that the results of second-day testing would be more useful for assessing in-situ uniformity. This decision was based on the literature reviewed in Section 2.4.1.2 which stated that UPV testing should be conducted at the earliest possible age in order to accentuate the effects of differences in paste and aggregate distributions. The decision was also confirmed by the results gathered from sixth-day testing, which did not show any different trends in uniformity than those measured at two days, except that the differences in pulse velocities within each wall were less pronounced at six days. Therefore, sixth-day UPV testing results are shown in Appendix C but were not considered in establishing correlations or reaching conclusions for this research.

4.4.2. Pullout Testing

Pullout testing was conducted as described in Section 3.4.3, and, as expected, the use of a short bonded length of 2.5 d_b resulted in a shear pullout failure mechanism in all but a single pullout specimen. In that one specimen, which was in the bottom-most group of bars in the 94 in. wall cast from SCC-1B, a shear pullout failure occurred after the steel reinforcement yielded and began to strain harden. The occurrence correlated well with the steel yield-strength confirmation testing and small-scale pullout testing discussed in Sections 3.4.3.1 and 3.4.3.2, and the proportions of subsequent concrete mixtures were varied to avoid further occurrences of this failure type.

The results of pullout force within each wall are shown in Figure 4.11 through Figure 4.13, separated by wall height and mixture type. The points shown in those figures were obtained by averaging the pullout strength of eight bars cast within 8 in. of each other at the bottom, top, and approximate middle of each wall. The research team decided to use eight-bar pullout groups to assess uniformity because of the inherent variability of pullout testing and because the eight bars were located within a height of eight inches of each other.

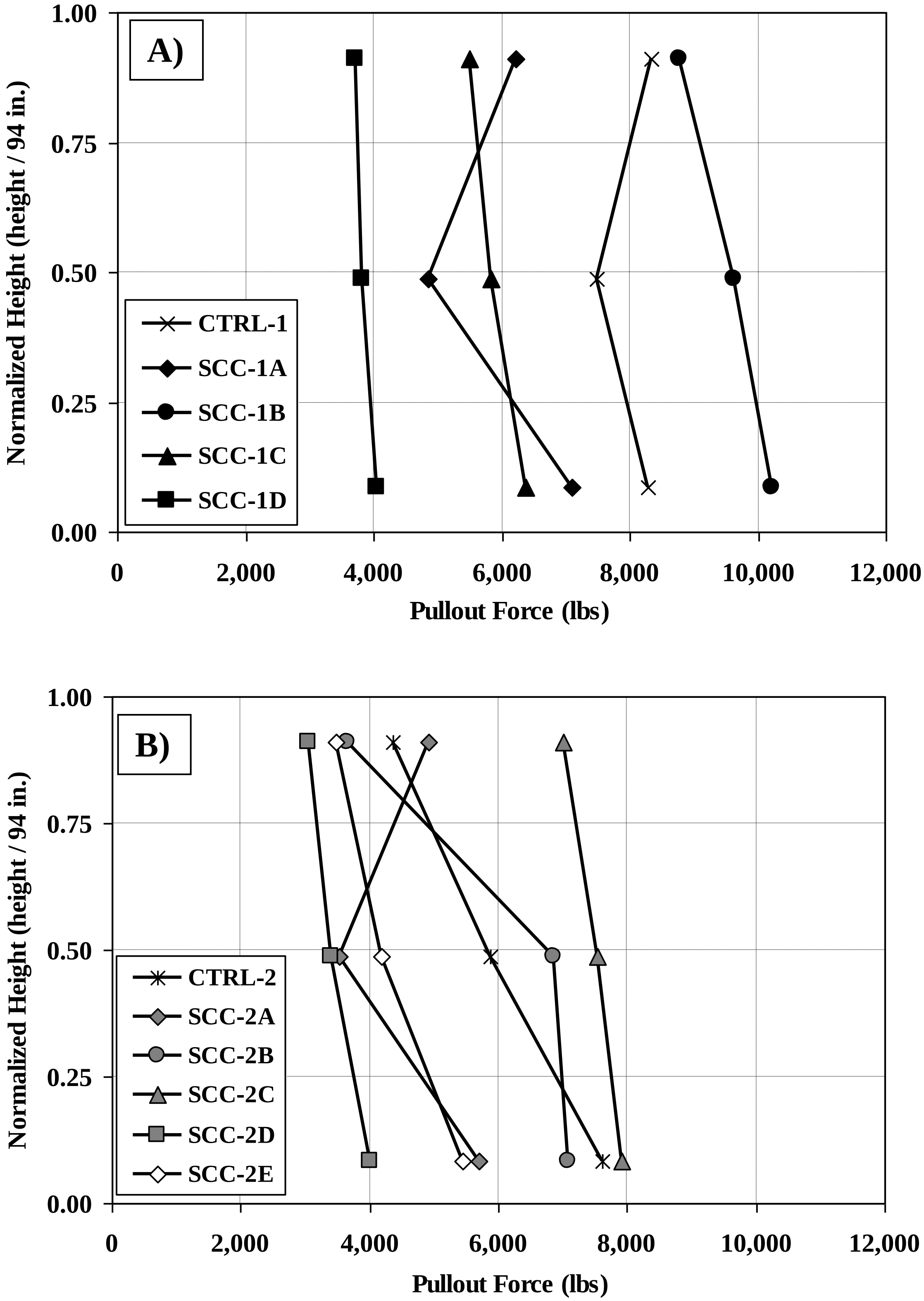

Figure 4.11: Measurement of pullout bond strength over normalized height, in 94 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

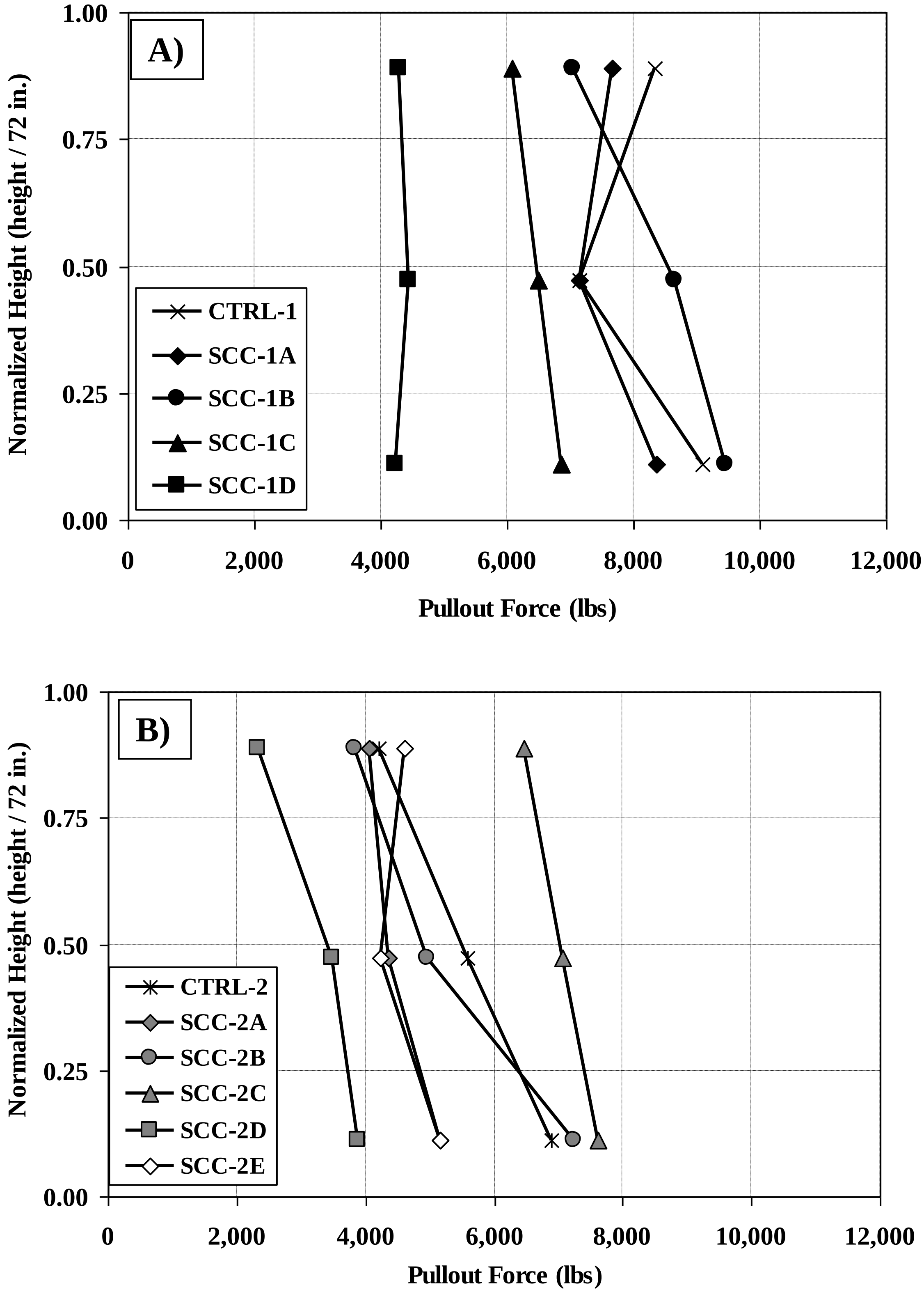

Figure 4.12: Measurement of pullout bond strength over normalized height, in 72 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

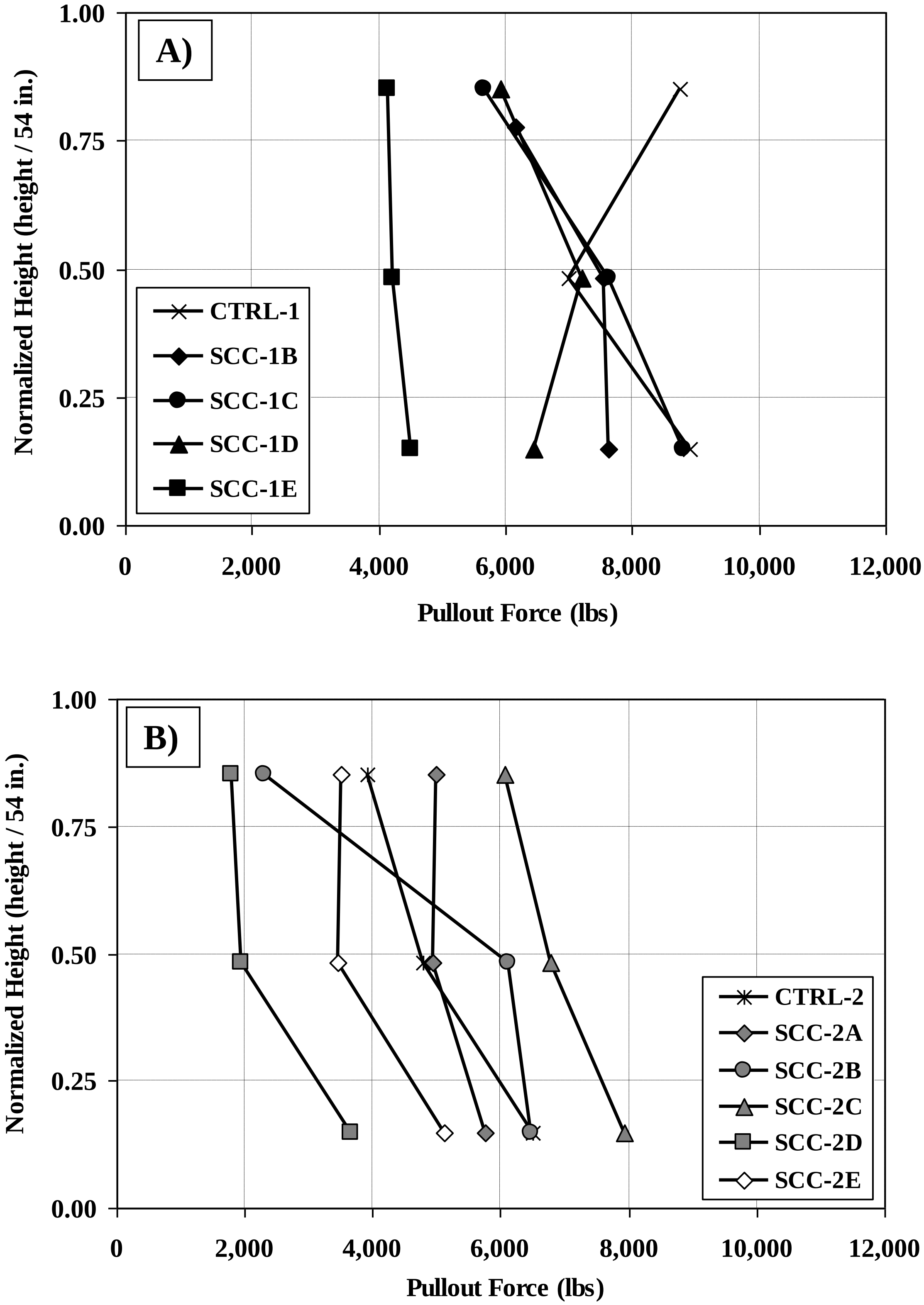

Figure 4.13: Measurement of pullout bond strength over normalized height, in 54 in. walls: A) SCC-1 mixtures and CTRL-1, and B) SCC-2 mixtures and CTRL-2

Similar to the reasons discussed in Section 4.4.1 that explain the existence of UPV outliers, pullout testing outliers were identified and removed from consideration. Outliers were identified as those pullout specimens exhibiting a bond strength more than two standard deviations outside of the average of the other seven specimens in a group. Outliers were found in thirteen percent of measurements, which was similar to the percentage of measurements discarded during UPV calculations. The one pullout specimen that failed after it underwent strain hardening was within this two standard deviation limit, so its pullout strength was averaged with the others from that group.

As seen in Figure 4.11 through Figure 4.13, the lowest eight-bar average pullout strength was not always obtained near the top of a wall, and trends were not consistent within all walls of a particular height. Generally, the SCC-2 mixtures exhibited more consistent trends in bond uniformity, with the top-cast group of bars frequently exhibiting the lowest average bond strength and the bottom-cast group exhibiting the highest average. In total, two-thirds of the walls cast for this program (including both SCC and conventional concretes) showed consistently decreasing bond strength with increasing height within the wall.

In Figure 4.13, the data for mixture SCC-1A starts at a lower height than for the other mixtures in the plot. As noted in Section 4.2.3, that particular wall was only filled to 50 in., which coincided with the level of the top row of pullout specimens. The top row of specimens was untestable, but the next lower row, which was embedded beneath 8 in. of concrete, was deemed acceptable for inclusion of its results. UPV testing at that level (42 in.) showed no discrepancy from UPV testing of the other 54 in. walls, and the cover over the row of specimens at 42 in. well exceeded the minimum necessary to provide adequate confinement. Both of these circumstances supported the possibility that the single row of pullout specimens at 42 in. would exhibit a bond behavior representative of the SCC-1A mixture.

Groups of top-bar effects calculated for each wall and mixture are shown in Figure 4.14. Matching the work of Khayat and Mitchell (2009) and others (Khayat, Manai, and Trudel 1997; Stocker and Sozen 1970), the top-bar effect was calculated by dividing the pullout force in the bottom group of bars (F_{bottom}) by the lesser average of either the mid-height group of bars or the top-cast group of bars (F_{low}).

$$top\ bar\ effect = \frac{F_{bottom}}{F_{low}} \geq 1.00$$

As outlined in Section 2.6.2, the top-bar factor (the factor equal to 1.3 or 1.4 in various design codes) is applicable for steel reinforcement with greater than 12 in. of concrete cast below it, meaning that the factor was not applicable to the group of eight specimens at the bottom of each wall. Since the top-bar factor will be used to determine an acceptable level of uniformity, the pullout strength of the bottom eight bars is always in the numerator in the calculation of the top-bar effect. Both the middle and top group of bars qualified to be considered “top-bars” according to ACI 318 (2008) and the AASHTO Bridge Design Specifications (2007), and the lesser average pullout strength was not always found in the same group. Therefore, the average of the three top-bar effects from each mixture provided the best indicator of a mixture’s uniformity.

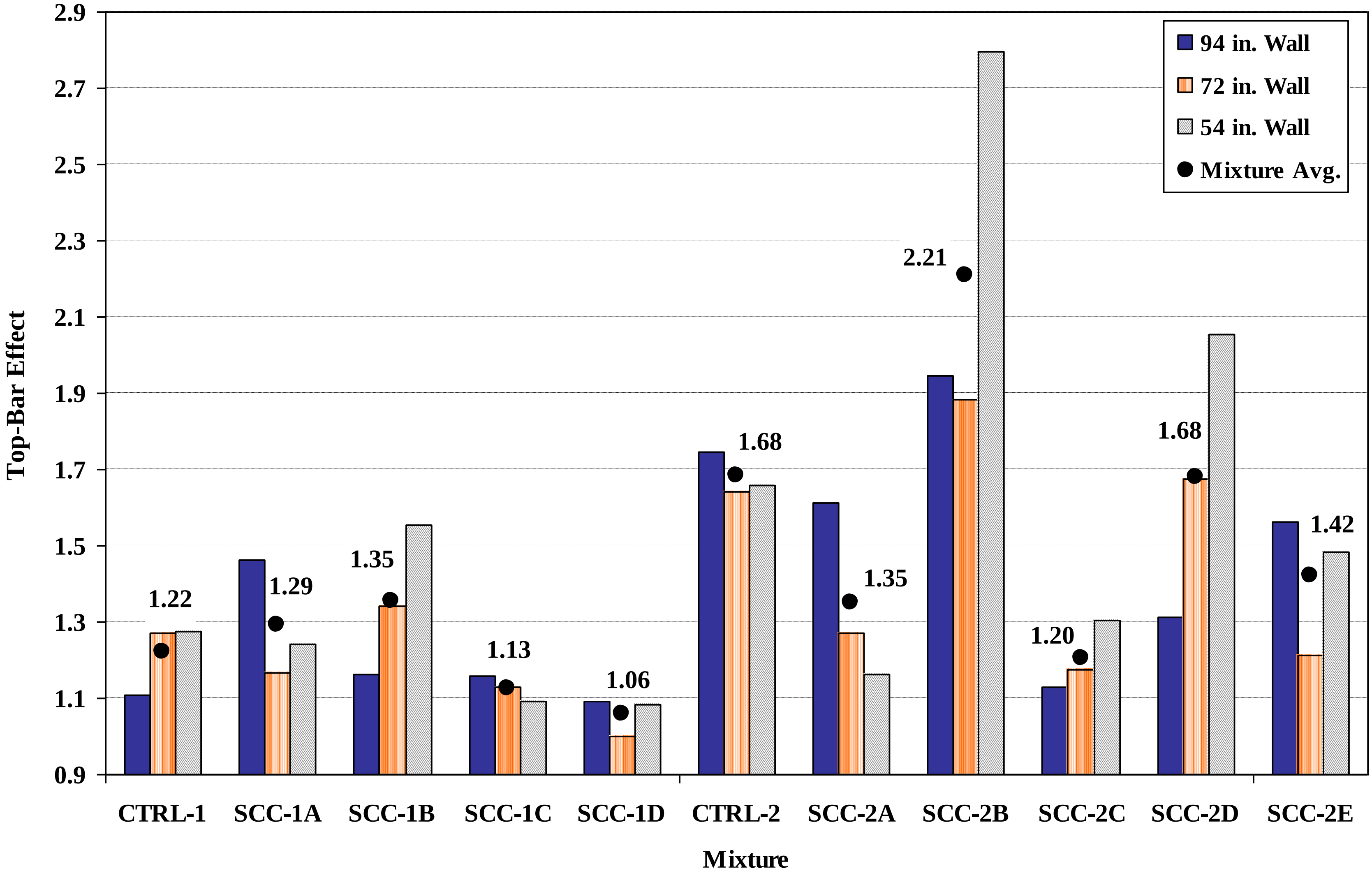

Figure 4.14: Top-bar effects by wall height and mixture

Similar to the observation discussed in Section 4.4.1 concerning the inconsistency of trends in the UPV segregation indices between walls cast from the same mixture, Figure 4.14 shows that the level of within-mixture pullout bond uniformity does not always decrease uniformly with increasing wall height. In total, two concrete mixtures consistently exhibited decreasing uniformity with increasing wall height, four concrete mixtures consistently exhibited decreasing uniformity with decreasing wall height, and five concrete mixtures did not exhibit a consistent trend in uniformity with changing wall height.

As can be seen in Figure 4.14, a top-bar effect of 1.00 was calculated in the 72 in. wall cast from SCC-1D. By comparing this top-bar effect to the plotted pullout strengths measured in that wall shown in Figure 4.12, it can be seen that a top-bar effect of 1.00 does not necessarily indicate a perfectly uniform concrete. Instead, it indicates that the pullout strength of the bottom group of bars (the only group not considered as "top-bars") was the lowest of any group in the wall.

The average top-bar effects measured in the SCC mixtures ranged from 1.06 to 2.21, while the top-bar effects were equal to 1.22 and 1.68 in the conventional concretes. Three of the nine SCC mixtures exhibited average top-bar effects less than either conventional concrete, and one of the nine SCC mixtures exhibited an average top-bar effect greater than the CTRL-2 mixture. Also, the variation of the top-bar effect is greatly magnified in comparison to the variation of the UPV segregation index, with variation of up to 121% versus a variation of up 5% in UPV testing.

4.4.3. Correlation between Ultrasonic Pulse Velocity and Pullout Testing

A correlation between UPV results and pullout testing results was evaluated by comparing each mixture's average UPV segregation index and average top-bar effect. Because no pullout testing was conducted on the 36 in. walls, the average UPV segregation indices employed during this comparison were calculated as the average of the indices from the three taller walls (54 in., 72 in., and 94 in. walls). This correlation is shown in Figure 4.15. As seen in that figure, a reasonable correlation exists between the factors, as an r^2-value equaling 0.54 was determined. Second order nonlinear models were also evaluated, but they did not exhibit r^2-values any greater than the linear relationship shown in Figure 4.15.

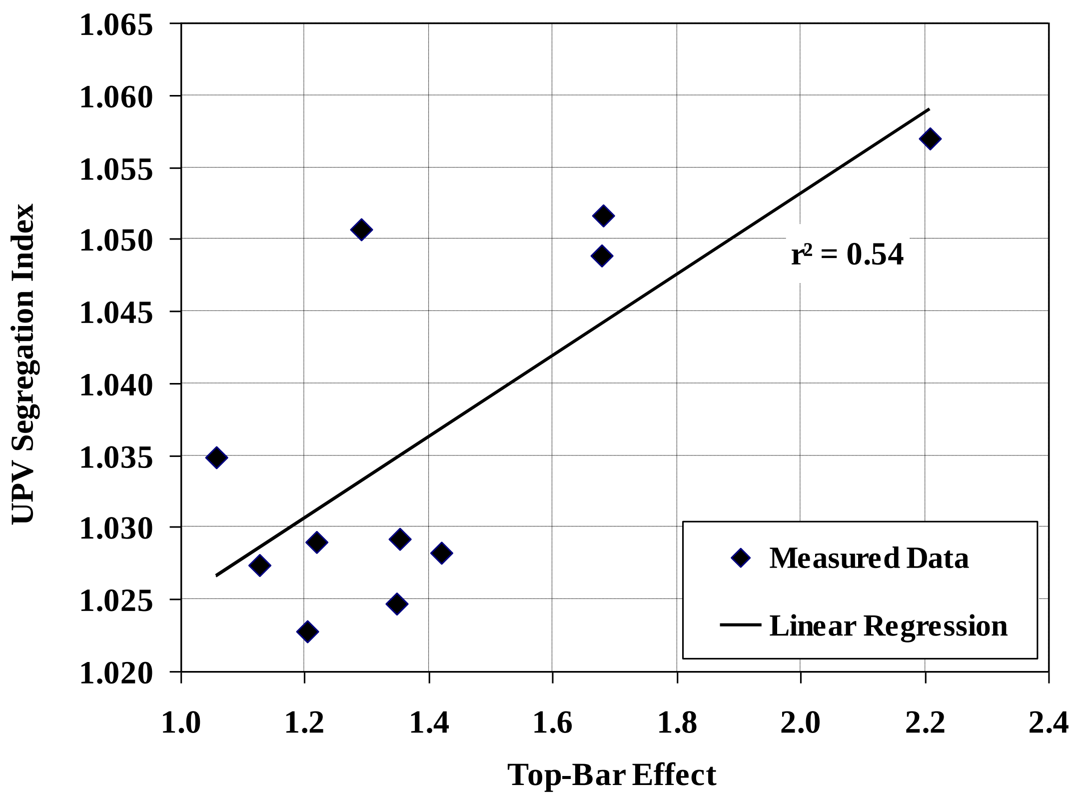

Figure 4.15: Comparison between top-bar effect and UPV segregation index

Further testing would be necessary to confirm the correlation between UPV segregation index and top-bar effect in other concretes, but it is understandable why the two effects are correlated. Differences in pulse velocities and in bond quality are both related to factors that are affected by segregation: air void distribution, aggregate distribution, and accumulation of bleeding, as described in Sections 2.4.1.1 and 2.3.2.2.1. Regardless of the correlation, though, both test methods are given equal consideration in this research as independent measures of in-situ uniformity to determine the ability of fresh stability tests to assess stability.

4.5. Correlation between Fresh Stability Test Results and In-Situ Uniformity

The correlations between results of fresh stability testing described in Section 4.3.1 and the measures of in-situ uniformity described in Sections 4.4.1 and 4.4.2 were important in reaching the project goal of assessing the accuracy of the fresh stability tests. In the same fashion as used to compare fresh stability test results to each other and to compare in-situ uniformity measures to each other, the fresh stability test results were compared to each measure of hardened uniformity, and substantial correlations were identified as those exhibiting an r^2-value greater than 0.40. Table 4.4 is a correlation matrix showing the r^2-value between each fresh stability test result and in-situ uniformity result, and correlations with an r^2-value greater than 0.40 are printed in bold face.

The strongest correlations identified in Table 4.4 are each discussed in the following subsections. Notably, the surface settlement test was the only fresh stability test that correlated well with both the UPV segregation index and top-bar effect. Meanwhile, the rapid penetration, multiple-probe penetration, and column segregation tests showed no correlation to either measure of in-situ uniformity, an occurrence that is discussed in Section 4.5.4. No correlation between fresh stability test result and either measure of in-situ uniformity was significantly improved through the use of a nonlinear regression model. Nonlinear r^2-values are presented in Appendix D.

Table 4.4: Linear regression coefficients of determination between measures of in-situ uniformity and fresh stability test results

Test Result	**Linear Regression Coefficient of Determination**						
	VSI	**Column Seg.**	**Rapid Pen.**	**Sieve Stability**	**Surface Set. (rate)**	**Surface Set. (max)**	**Multiple Probe**
UPV Index	0.19	0.16	0.01	0.17	**0.44**	0.14	0.00
Top-Bar Effect	**0.46**	0.21	0.01	**0.41**	**0.65**	0.00	0.00

4.5.1. Surface Settlement Test versus In-Situ Uniformity

Two sets of results were analyzed from the surface settlement test: the rate of settlement experienced between 10 and 15 minutes, and the maximum settlement experienced. Only the rate of settlement results correlated well with both the UPV segregation index and top-bar effect, and the ultimate settlement results did not correlate well with either. The correlations between rate of settlement and each in-situ uniformity measurement are shown in Figure 4.16 and Figure 4.17, and the data used to assess the correlations between ultimate settlement and each in-situ uniformity measurement can be found in Appendices B and C.

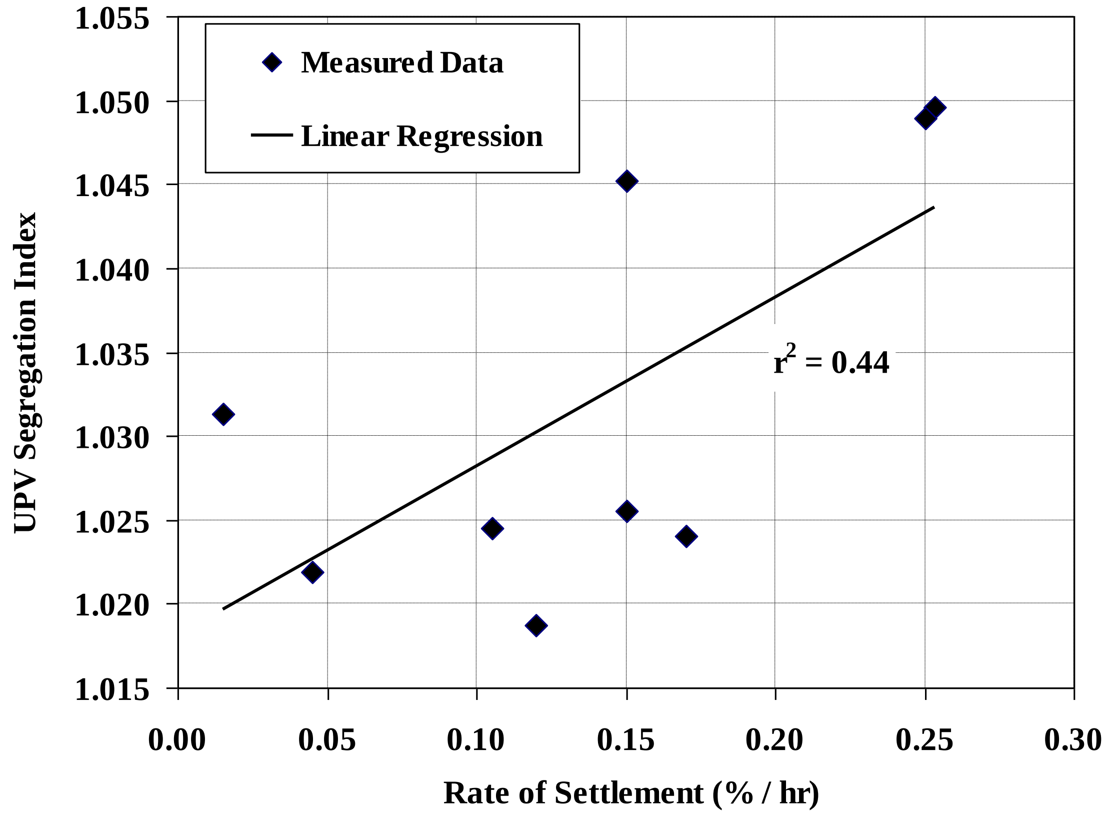

Figure 4.16: Comparison between rate of settlement results and UPV segregation index

The coefficients of determination between rate of settlement and each in-situ uniformity measure were the highest among fresh stability tests ($r^2$of 0.44 with UPV segregation index and r^2 of 0.65 with top-bar effect). Because the maximum settlement results from the test were not well related to either measure, only the rate of settlement should be necessary to assess mixture stability while using the surface settlement test.

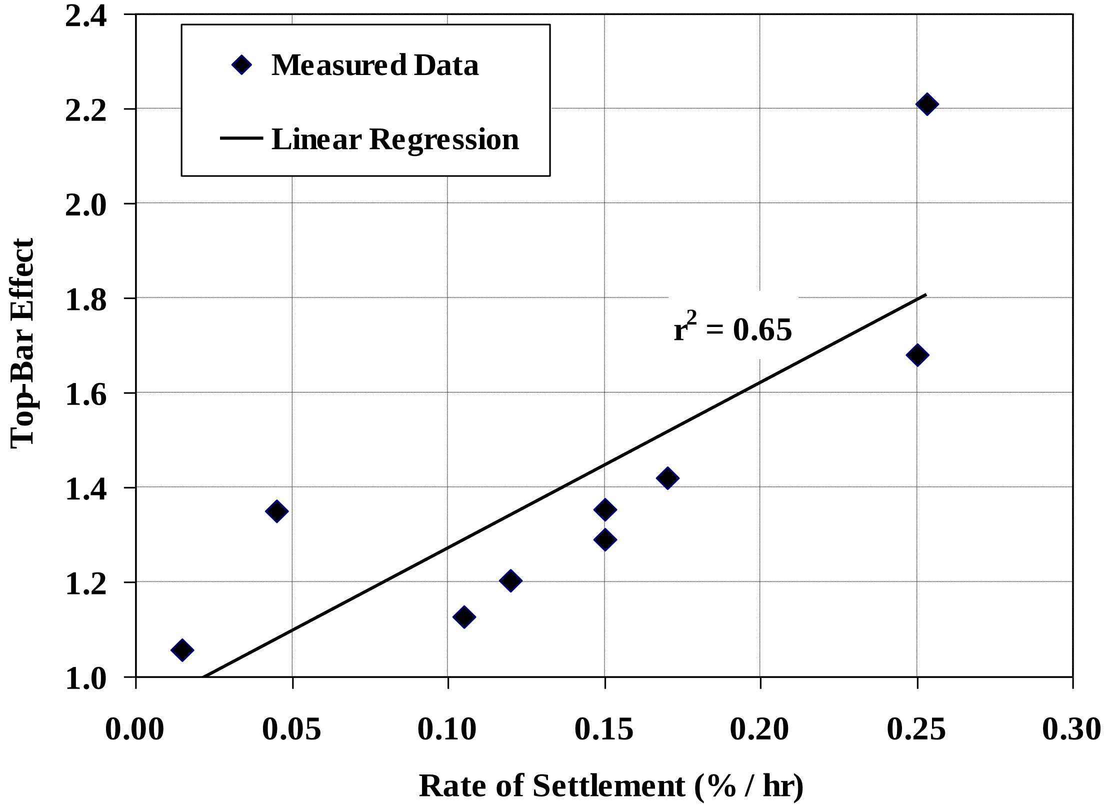

Figure 4.17: Comparison between rate of settlement results and top-bar effect

4.5.2. Sieve Stability Test versus In-situ Uniformity

The results of the sieve stability test correlated well with both the VSI and column segregation test results as described in Section 4.3.3, and the sieve stability results also correlated reasonably well with the top-bar effect. The correlation between the sieved fraction and top-bar effect is shown in Figure 4.18, and it exhibited an r^2-value of 0.41, which is the third highest r^2-value between any fresh stability test and the top-bar effect.

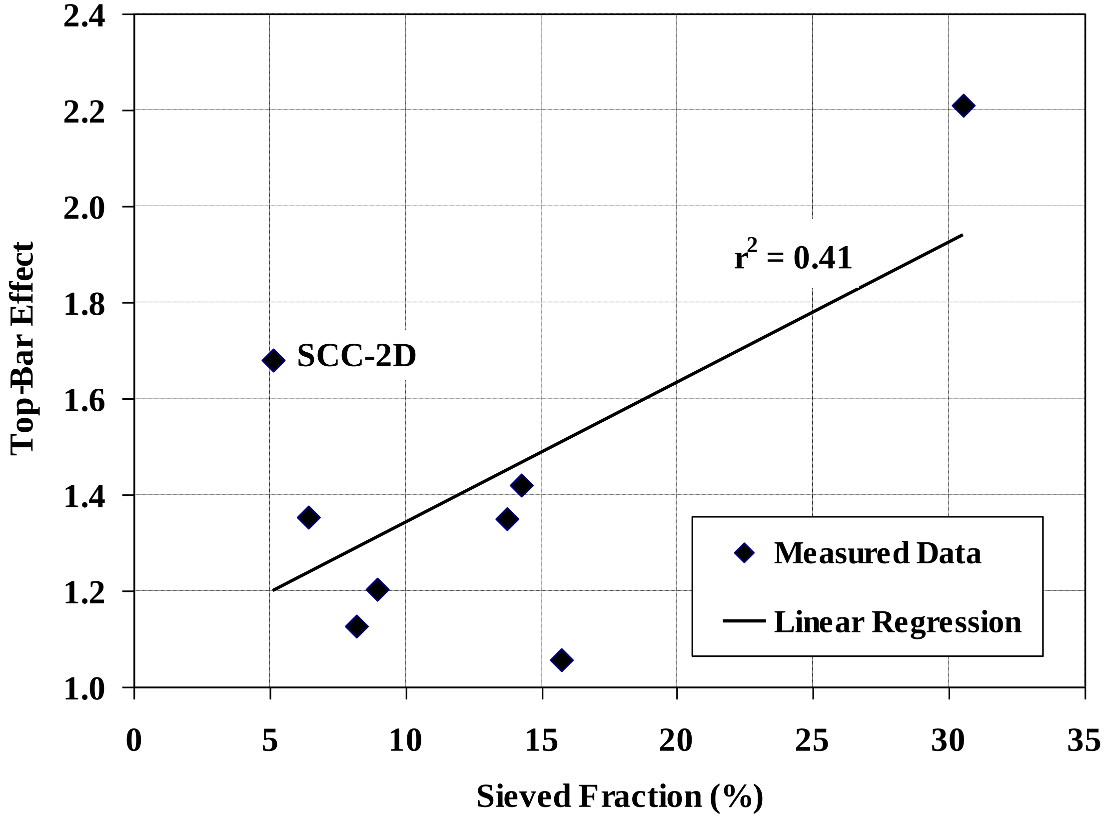

Figure 4.18: Comparison between sieve stability results and top-bar effect

Sieve stability test results and the UPV segregation index were also correlated (exhibiting the third highest coefficient of determination among fresh stability tests), except in results from mixture SCC-2D. This correlation is shown in Figure 4.19. UPV uniformity and top-bar values from SCC-2D fit the correlation between UPV segregation index and top-bar factor that is shown in Figure 4.15, but SCC-2D's segregation indices did not fit the correlation between sieve stability results and top-bar effect or between sieve stability results and UPV segregation index (see data point [5.15, 1.68] on Figure 4.18 and data point [5.15, 1.049] on Figure 4.19). Therefore, exclusion of mixture SCC-2D was not permissible in analyzing the correlation between sieve stability results and UPV results.

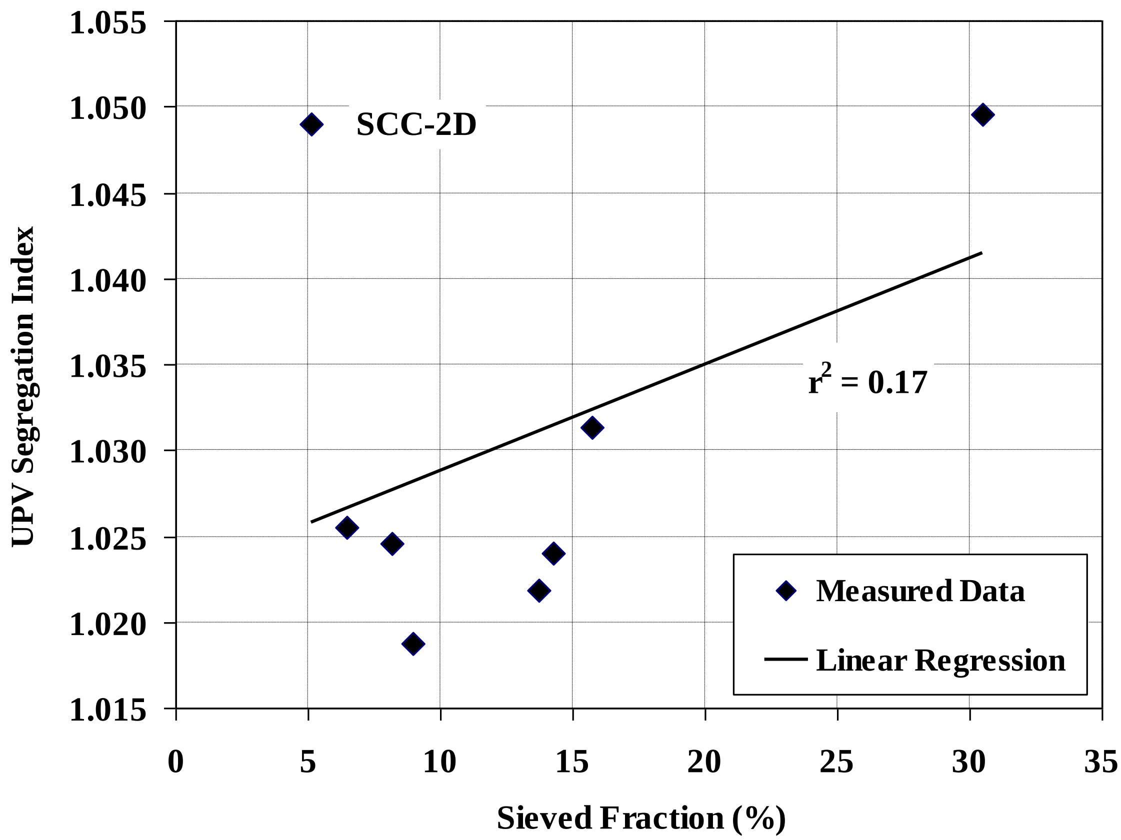

Figure 4.19: Comparison between sieve stability results and UPV segregation index

4.5.3. Visual Stability Index versus Top-Bar Effect

The correlation between VSI results and top-bar effect is shown in Figure 4.20 and exhibited an r^2-value of 0.46, the second highest coefficient of determination between the top-bar effect and any fresh stability test.

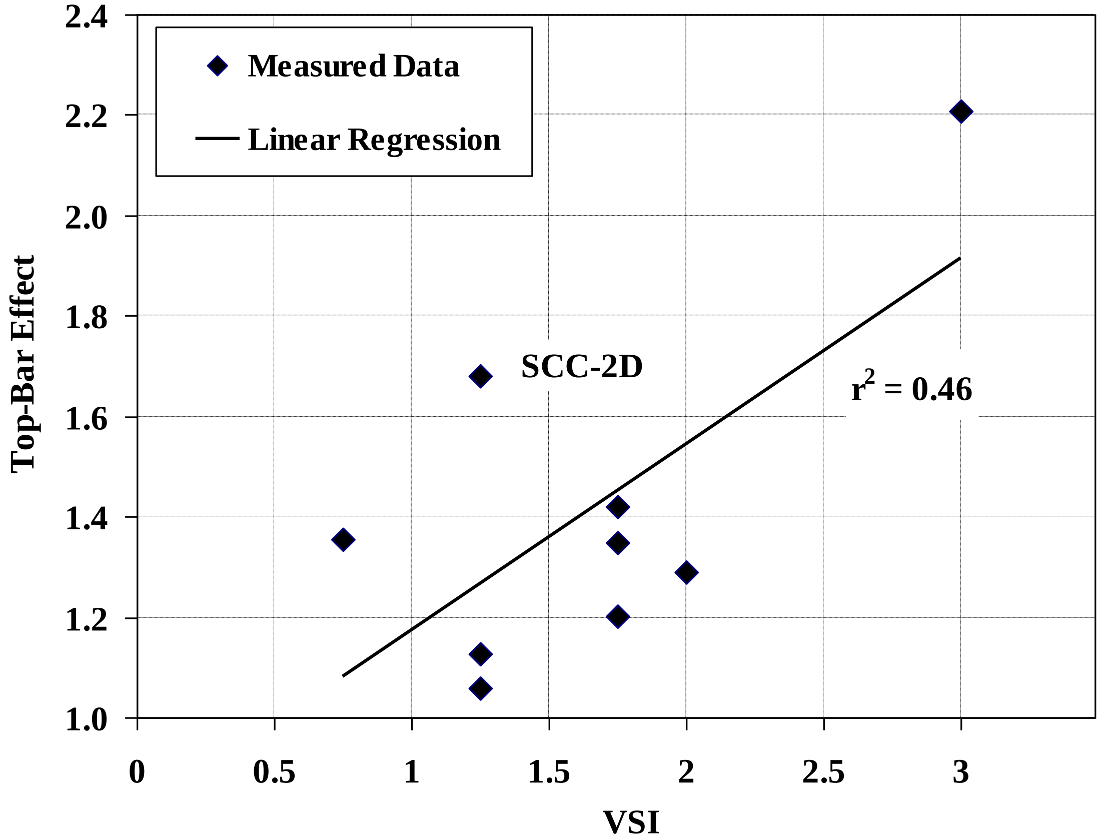

Figure 4.20: Comparison between VSI results and top-bar effect

Similar to the sieve stability test results, the VSI and the UPV segregation index were also correlated (exhibiting the second highest r^2-value among fresh stability tests), except in results from mixture SCC-2D. This correlation is shown in Figure 4.21. Much like with the sieve stability test results, SCC-2D's segregation indices did not fit the correlation between VSI and top-bar effect or between VSI and UPV segregation index (see data point [1.25, 1.68] on Figure 4.20 and data point [1.25, 1.049] on Figure 4.21). As already stated in 4.5.2, the results from SCC-2D could not be excluded from comparisons with in-situ uniformity measures, which greatly reduced the correlation factor between those measures and all fresh stability measures except the rate of settlement from the surface settlement test.

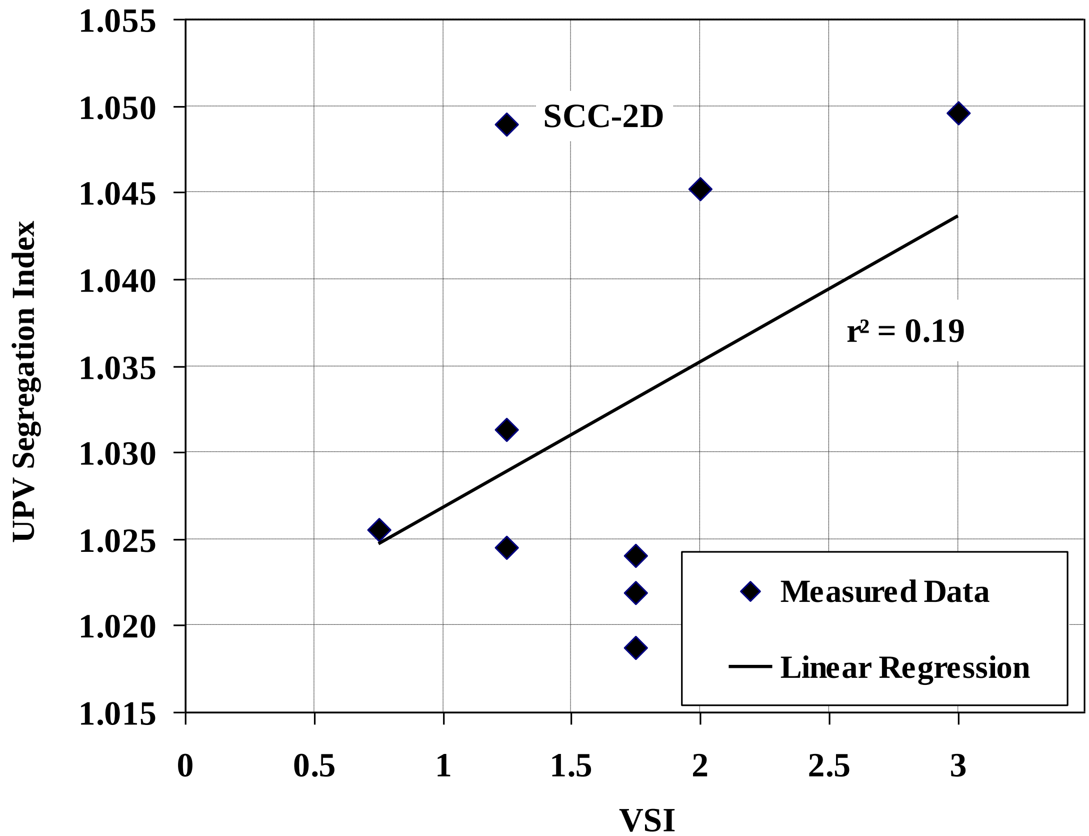

Figure 4.21: Comparison between VSI results and UPV segregation index

4.5.4. Discussion of Tests Exhibiting no Correlation to In-Situ Uniformity

The results from the rapid penetration, multiple-probe penetration, and column segregation test methods did not correlate well with either measure of in-situ uniformity, as can be inferred from their low coefficients of determination shown in Table 4.4. Conclusions concerning the inaccuracy of the rapid penetration test and multiple-probe penetration test must take into consideration the fresh stability tests that were successful. Both the VSI, which is faster than either test, and the surface settlement test, which measures the settlement of a specified weight into a sample of SCC, were more accurate. Therefore, either the specific form of segregation measured by these penetration tests cannot be sufficiently studied in such a short time, or the precision of these tests is insufficiently low.

The column segregation test, which takes more time to conduct than the sieve stability or surface settlement (rate of settlement) test methods, is not as well correlated to in-situ uniformity measures as either. Therefore, it is likely that the form of segregation identified by the column segregation test does not correlate to in-situ performance as well as the other two measures, at least in the mixtures studied in this research project. Furthermore, the column segregation test correlates well with the sieve stability test, and the sieve stability test is easier to conduct. For those reasons, the column segregation test should be replaced with the sieve stability test for determining stability of SCC.

4.6. Recommended Fresh Stability Test Values to Determine Mixture Acceptance

As discussed in Section 2.6.2, a top-bar factor of 1.4 is used in the AASHTO Bridge Design Specification (2007) to account for the top-bar phenomenon. Based on a top-bar factor of 1.4, fresh stability test results could be determined from the above figures in Sections 4.5.1, 4.5.2, and 4.5.3 that could be used to assess whether a mixture exhibits acceptable or unacceptable uniformity. The rounded fresh stability test results beneath which the tested concrete should not exhibit a top-bar effect greater than 1.4 are summarized in Table 4.5.

Table 4.5: Fresh stability test result expected in SCC with a top-bar effect less than 1.4

Fresh Stability Test	**Results expected in SCC with a top-bar factor < 1.4**
Surface Settlement Test	Rate of settlement ≤ 0.15 % / hr
Sieve Stability Test	Sieved fraction ≤ 15%
VSI	VSI < 2

The linear regression model shown in Figure 4.17 for the relationship between the rate of settlement and top-bar effect identifies a top-bar effect of 1.4 at approximately 0.13 % / hr. A rate of settlement limitation of 0.15 % / hr is shown in the above table for two reasons:

- Two mixtures with a measured rate of settlement equal to 0.15 % / hr exhibited top-bar effects less than 1.4, and
- No mixture with a measured rate of settlement of less than or equal to 0.15 % / hr exhibited an unacceptably high top-bar effect.

The linear regression model shown in Figure 4.18 for the relationship between the sieved fraction and top-bar effect identifies a top-bar effect of 1.4 at approximately 12%. However, a sieved fraction limitation of 15% is shown in Table 4.5 because it matches the maximum sieved fraction recommended by the European Project Group (2005) for Class 2 applications and because it is reasonably effective at identifying mixtures that exhibited an unacceptably high top-bar effect.

The linear regression model shown in Figure 4.20 for the relationship between the VSI and top-bar effect identifies a top-bar effect of 1.4 at a VSI value of approximately 1.6. Therefore, a VSI limitation of 1.5 is shown in Table 4.5, as it is the closest assignable VSI value. A VSI of 1.5 is also reasonably effective at identifying mixtures that exhibited unacceptably high top-bar effects.

In conjunction with a review of Table 2.1, several conclusions can be drawn from the calculated values shown in Table 4.5:

- The 0.15 percent-per-hour rate of settlement determined from the surface settlement test that is deemed acceptable based on this research is much lower than the 0.27 rate recommended by Khayat and Mitchell (2009),
- The sieved fraction limit of 15 percent as determined by the sieve stability test matches the maximum sieved fraction recommended by the European Project Group (2005) for Class 2 applications such as the production of the walls used in this research, but exceeds the EPG (2005) limit recommended for demanding applications such as the production of precast, prestressed girders,
- Despite the poor coefficient of determination between it and the UPV segregation index, the 15 percent sieved fraction limit would correctly pass or fail all but one mixture (mixture SCC-2D) based on acceptability of UPV uniformity, and
- Limiting the VSI to less than 2 would correctly assess all but two mixtures (SCC-2D and SCC-2E) based on bond uniformity.

Notable from the latter two conclusions, SCC-2D would have been incorrectly identified as acceptable by both the sieve stability test and the VSI. After reviewing the other fresh stability test results presented in Table 4.2, the rate of settlement from the surface settlement test was the only fresh method found to correctly identify that mixture as unstable. Although the VSI result incorrectly assessed the stability of mixture SCC-2E, the top-bar effect measured in that mixture was 1.42, compared to the acceptable top-bar effect of 1.4, and the two VSI values averaged to obtain a VSI of 1.75 were a 2 and 1.5.

4.7. Summary of Results and Discussion

4.7.1. Fresh Stability Testing

4.7.1.1. Use of Fresh Stability Test Methods

- The VSI, rapid penetration, and multiple-probe penetration test methods were the most technician-friendly to operate, while the column segregation test and surface settlement test were the least technician-friendly.
- Results from the VSI, rapid penetration, multiple-probe penetration, and sieve stability test methods could be visually discerned during testing, which may be advantageous to rapid testing and verification of results.
- As currently specified, the probes used in the multiple-probe penetration test method are not adequately confined to settle directly into the concrete sample, which could affect the accuracy of the measured results.
- The column segregation test is not viable for in-field quality assurance testing due to the prolonged time and additional effort required to determine its result.

- The surface settlement test is not viable for in-field quality assurance testing due to the sensitivity of its testing equipment and because field vibration may impact the measurements obtained.
- The sieve stability test is questionable as an in-field quality assurance test method because it takes approximately 18 minutes before its result can be determined.

4.7.1.2. Relationships between Fresh Stability Test Methods

- Because only nine data points were compared for each test method, a linear regression coefficient of determination $r^2 = 0.40$ was used as a minimum threshold to identify relationships exhibiting a relatively strong correlation.
- Results from the sieve stability test were significantly correlated to both the VSI and column segregation test results (r^2-values of 0.77 and 0.54, respectively), and these were the only two strong linear correlations between fresh stability test methods.
- The relationship between sieve stability and column segregation test results is similar to the relationship found by Kohler and Fowler (2010).
- Although subject to technician judgment, the VSI is clearly relatable to more time-consuming, quantitative fresh stability test methods because it was correlated to the sieve stability test.
- The rate of settlement and maximum settlement determined from the surface settlement test were strongly correlated (r^2-value of 0.47) in this research when using a nonlinear regression model. This matches the findings of Hwang, Khayat, and Bonneau (2006).

- The relationship between the rate of settlement and maximum settlement was the only relationship between fresh stability test results that was significantly improved through the use of a nonlinear regression model.

4.7.2. Measures of In-situ Uniformity

4.7.2.1. Ultrasonic Pulse Velocity Testing

- The uniformity of ultrasonic pulse velocities measured in walls of four heights (36 in., 54 in., 72 in., and 94 in.) was determined using rows with five UPV measurement locations that were approximately equally spaced over the height of each wall.
- Pulse velocities tended to decrease with height within each wall, but the maximum and minimum velocities were not always found at the bottom and top of each wall.
- When walls of varying heights were cast with the same mixture, no consistent trend was found between wall height and degree of UPV uniformity in either conventional or self-consolidating concrete.
- UPV uniformity increased over time, so UPV testing should be conducted as early as possible if seeking to assess uniformity.

4.7.2.2. Pullout Testing

- The bond strength uniformity in walls of three heights (54 in., 72 in., and 94 in.) was determined using groups of eight pullout test specimens placed in the bottom

12 in. of each wall, the top 12 in. of each wall, and approximately half way between them.

- Use of a short bonded length (2.5 d_b) ensured a shear pullout failure of steel reinforcement from concrete instead of rupture of concrete or steel yielding.
- Within each wall, bond strength decreased with increasing pullout specimen height (lowest strength in top-cast bars and highest strength in bottom-cast bars) in two-thirds of the walls tested for this program.
- Within walls of varying heights cast from the same mixture, no trend was found between wall height and bond strength uniformity in conventional or self-consolidating concrete.

4.7.2.3. Relationships between Measures of In-situ Uniformity

- A reasonable correlation (r^2-value of 0.54) was found between each concrete mixture's average ultrasonic pulse velocity segregation index and top-bar effect. In this comparison, the UPV segregation index was calculated as the average of the indices measured in the three walls that were also tested for top-bar effects.
- The correlation between the measures of in-situ uniformity was not improved through the use of a nonlinear regression model.
- The correlation between UPV testing and pullout testing may be attributed to the similarity in what properties affect each test: air void distribution, aggregate distribution, and presence of bleeding.

- Although only relatively small variations were observed in UPV measurements compared to pullout measurements (up to 5% versus up to 121%), either test method can be independently used to assess in-situ uniformity.
- Mixture SCC-2D was determined to be unstable by both the UPV and pullout tests, but, among the fresh stability tests, the mixture was only identified as unstable by the rate of settlement from the surface settlement test method.

4.8. Relationships between Fresh Stability Test Methods and Measures of In-Situ Uniformity

- The rate of settlement determined by the surface settlement test was found to have a reasonable correlation to both UPV uniformity results and pullout strength uniformity results (r^2-values of 0.44 and 0.65, respectively), and it was the only fresh stability test strongly correlated to both measures of in-situ uniformity.
- The sieve stability test exhibited a reasonable correlation to pullout bond uniformity (r^2-value of 0.41).
- The VSI exhibited a reasonable correlation to pullout bond uniformity (r^2-value of 0.46).
- The rapid penetration, multiple-probe penetration, column segregation, and surface settlement (maximum settlement) test methods did not correlate well with either measure of in-situ uniformity.
- No correlations between fresh stability test methods and either measure of in-situ uniformity was improved through the use of nonlinear regression models.

4.9. Recommendations for Fresh Stability Testing

- The rapid penetration test, multiple-probe penetration test, and column segregation test may not be able to accurately assess the stability of fresh SCC, and further research would be necessary before recommending their use for this application.
- Because it correlates well with both measures of in-situ uniformity (UPV testing and pullout testing), the surface settlement test should be the primary test used to determine SCC mixture stability acceptance for prequalification.
- It is only necessary to measure the rate of settlement determined between 10 and 15 minutes while conducting the surface settlement test.
- A rate of settlement less than 0.15 percent per hour measured between 10 and 15 minutes during the surface settlement test should verify that the tested SCC will exhibit a top-bar effect less than 1.4.
- Because it is not suitable for field use due to the sensitivity of the test apparatus, the surface settlement test should not be used for QA batch acceptance.
- Because it correlates well with pullout testing results and both the VSI and column segregation tests and provides a quantitative result, the sieve stability test should be the primary stability test method used for QA batch acceptance.
- A sieved fraction of less than 15 percent measured by the sieve stability test should verify that the tested SCC will exhibit a top-bar effect less than 1.4.
- Because it correlates well with the column segregation test, requires less time to conduct, and is better correlated to in-situ uniformity measurements, the sieve

stability test should be used in place of the column segregation test when testing SCC stability.

- Because it correlates well with the quantitative but more time-consuming sieve stability test, as well as with pullout testing results, the VSI is a viable quality assurance test method in the field.
- A VSI value of less than 2 assessed according to the VSI test method should verify that the tested SCC will exhibit a top-bar effect less than 1.4.

Since it is quicker, but is subjective, the VSI test should be the first test method used to screen a load of SCC for quality assurance during full-scale production. If the load exhibits a VSI value of greater than 1.0, then the result of the sieve stability test should be waited upon to provide a quantitative result to determine the load's acceptance or rejection. While any VSI value less than 2 should ensure that the tested SCC will exhibit a top-bar effect of less than 1.4, enforcing the sieve stability test result in borderline VSI situations will remove the subjectivity of the VSI from determination of batch acceptance or rejection. This approach will require that technicians simultaneously start the VSI and sieve stability test methods; however, if the SCC exhibits a VSI of 1 or less, the sieve stability test can be discontinued.

Chapter 5

Summary, Conclusions, and Recommendations

5.1. Summary

The research described in this thesis was undertaken as part of a larger research project funded by ALDOT to study the behavior of SCC used in the production of precast, prestressed bridge girders. This project phase was undertaken to address the assessment of fresh SCC stability, as this is a concern that may limit the use of SCC in precast, prestressed applications.

Six fresh stability tests were selected for further study:

- ASTM C 1611 Visual Stability Index (described in Section 2.5.2.1),
- ASTM C 1610 Column Segregation Test (described in Section 2.5.2.2),
- ASTM C 1712 Rapid Penetration Test (described in Section 2.5.2.3),
- Sieve Stability Test (described in Section 2.5.2.4),
- Surface Settlement Test (described in Section 2.5.3.1), and
- Multiple-Probe Penetration Test (described in Section 2.5.3.2).

To assess these tests, they were conducted concurrently with the casting of four 40 inch wide, 8 inch thick concrete walls, whose heights were 36, 54, 72, or 94 inches. Walls were cast and fresh stability tests were conducted on a total of eleven mixtures, nine of which were self-consolidating concretes. The nine SCC mixtures were based on two sets of primary mixture proportions, and each mixture was adjusted to exhibit different fresh behavior and stability. The adjustments to stability were controlled by varying either water content, HRWR admixture content, VMA content and type, or a combination of the variables.

The first group of four SCC mixtures (SCC-1) was proportioned with a higher cementitious content than the second group (SCC-2). The SCC-1 group was more robust and required larger stability-controlling adjustments to significantly affect stability. Also, all SCC and conventional concrete mixtures were proportioned with a hydration-stabilizing admixture so that fresh stability testing and placements could be conducted with a minimal loss of workability.

The two conventional concrete mixtures were proportioned similarly to the SCC mixtures but using a higher *w/cm*, lower *s/agg*, and larger aggregate gradation typical of conventional concrete used in precast, prestressed applications. From the six fresh stability tests being assessed, only the column segregation test was conducted on the conventional concrete mixtures. In-situ uniformity tests, however, were conducted on all conventional concretes and all SCCs.

Two test methods were selected to measure in-situ uniformity of the concrete walls: ultrasonic pulse velocity (UPV) testing and pullout bond testing. UPV testing was conducted on all four walls as described in Section 3.4.2. It was used primarily to identify changes in overall uniformity of concrete, including changes in air void distribution and aggregate distribution. Pullout testing was conducted on eight-specimen groups of deformed steel bars cast horizontally through the three tallest walls at the bottom, mid-height, and top of each. This method was used primarily to identify changes in bond uniformity.

UPV segregation indices were determined for each wall and mixture based on the ratio of the fastest average pulse velocity to the slowest. An average UPV segregation index was then determined for each mixture. A top-bar effect was calculated for each wall and mixture based on the ratio of the pullout strength of the bottom group of bars to the lesser strength among the upper two groups of specimens cast into each wall.

Results from the six fresh stability tests were then compared with each other and with the results of each of the in-situ uniformity tests. The observations and conclusions made during the collection and analysis of these results are included in Section 5.2. The recommendations made based on this research project are given in Section 5.3.

5.2. Research Observations and Conclusions

5.2.1. Observations from Fresh Stability Testing of Concrete

- The visual stability index (ASTM C 1611 2005), rapid penetration (ASTM C 1712 2009) and multiple-probe penetration (El-Chabib and Nehdi 2006) test methods are much more technician-friendly than the column segregation (ASTM C 1610 2006) and surface settlement (Khayat and Mitchell 2009) test methods.
- The sieve stability test (EPG 2005) is almost as technician-friendly as the VSI, rapid penetration, and multiple-probe penetration test methods, except that it requires much more time than those three tests.

- Results from the VSI, rapid penetration, multiple-probe penetration, and sieve stability test methods could be visually discerned during testing, which may be advantageous to rapid testing and verification of results.
- The probes used in the multiple-probe penetration test may not settle directly downward into the tested sample. Modifications to this test may be possible that would ensure that only vertical movement is attained.
- The acrylic plate used in the surface settlement test does not always settle directly downward into the sample. This can be corrected through proper sample preparation. Uneven settlement may occur in SCC that is highly segregating.
- The European Project Group (2005) recommended using a 5 mm (0.20 in.) sieve, but the American equivalent, a No. 4 (0.25 in.) sieve, was used instead. This was allowed by the PCI guidelines for SCC (2004), and it was practical to use the same sieve required for the column segregation test.
- The sieve stability test was well correlated to both the VSI (r^2-value of 0.77) and the column segregation test (r^2-value of 0.54). No other reasonable linear correlations were found between fresh stability test methods.
- The rate of settlement determined during the surface settlement test correlated well with the maximum settlement found during the same test (r^2-value of 0.47) when compared with a nonlinear regression model. This agreed with the findings of Hwang, Khayat, and Bonneau (2006).

5.2.2. Observations from In-situ Uniformity Testing

- The UPV segregation index (ratio of fastest to slowest pulse velocity) ranged from 1.019 to 1.050 in nine SCCs of varying stability and equaled 1.025 and 1.046 in two conventional concretes.
- Pulse velocities decreased with increasing height in both conventional concrete and SCC, but the trend was not consistently related to the height of the cast specimen or location within the cast specimen.
- The top-bar effect (ratio of average bottom-cast bar pullout strength to the lesser average strength of the other two pullout bar groups) ranged from 1.06 to 2.21 in nine SCCs of varying stability and equaled 1.22 and 1.68 in two conventional concretes.
- Pullout bond strengths decreased with height in a majority of walls in both conventional concrete and SCC, but the reduction was not consistently related to the height of the cast specimen.

5.2.3. Relationships from In-Situ Uniformity Results

- A reasonable correlation was found between the UPV segregation indices and top-bar effects measured during this research (r^2-value of 0.54).
- The rate of settlement determined by the surface settlement test was the only fresh stability test result in which reasonable correlations were found with both the UPV segregation index and top-bar effect (r^2-values of 0.44 and 0.65, respectively).

- The sieved fraction result from the sieve stability test and the VSI were found to exhibit reasonable correlations to the top-bar effect (r^2-values of 0.41 and 0.46, respectively).
- The results from the rapid penetration, column segregation, multiple-probe penetration, and surface settlement (maximum settlement) test methods did not exhibit reasonable correlations to either measure of in-situ uniformity.

5.3. Research Recommendations

5.3.1. Recommendations for Fresh Stability Testing

5.3.1.1. Surface Settlement Test

- The surface settlement test should be the primary test used to determine SCC mixture stability acceptance for prequalification.
- It is only necessary to measure the rate of settlement determined between 10 and 15 minutes while conducting the surface settlement test.
- A rate of settlement less than 0.15 percent per hour measured between 10 and 15 minutes during the surface settlement test should verify that the tested SCC will exhibit a top-bar effect less than 1.4.
- The surface settlement test should not be used for in-field QA mixture acceptance.

5.3.1.2. Sieve Stability Test

- Because it correlates well with pullout testing results and both the VSI and column segregation tests, and because it can be rapidly performed, the sieve stability test should be the primary stability test method used for QA mixture acceptance during production.

- A sieved fraction of less than 15 percent measured by the sieve stability test should verify that the tested SCC will exhibit a top-bar effect less than 1.4.
- Because it correlates well with the column segregation test, requires less time to conduct, and is better correlated to in-situ uniformity measurements, the sieve stability test should be used in place of the column segregation test when testing SCC stability.

5.3.1.3. Visual Stability Index

- Because it correlates well with the quantitative but more time-consuming sieve stability test, as well as with pullout testing results, the VSI is a viable quality assurance test method in the field.
- A VSI value of less than 2.0 should verify that the tested SCC will exhibit a top-bar effect less than 1.4.

5.3.1.4. Combined use of the Visual Stability Index and Sieve Stability Test Methods

Since it is quicker, but is subjective, the VSI test should be the first test method used to screen a load of SCC for quality assurance during full-scale production. If the load exhibits a VSI value of greater than 1, then the result of the sieve stability test should be waited upon to provide a quantitative result to determine the load's acceptance or rejection. While any VSI value less than 2 should ensure that the tested SCC will exhibit a top-bar effect of less than 1.4, using the sieve stability test result in borderline VSI situations will remove the subjectivity of the VSI from determination of batch acceptance or rejection. This approach will require that technicians simultaneously start the VSI and sieve stability test methods, but, if the SCC exhibits a VSI of 1 or less, then the sieve stability test can be discontinued.

5.3.2. Recommendations for Future Research

The observations of Section 5.2 and recommendations of Section 5.3.1 should offer conservative advice on the fresh and hardened stability testing of SCC. However, further research would be valuable to confirm the observations and recommendations established during this research project and study other potential relationships between fresh stability tests and measures of in-situ uniformity. Such research topics include

- Confirming correlations the surface settlement test, sieve stability test, and VSI exhibited with measures of in-situ uniformity,
- Evaluating if the sieve stability test results obtained after a shorter rest period (such as after 5 or 10 minutes) would provide a reasonable measure of stability,
- Determining the within-test repeatability of the sieve stability test through round-robin testing,
- Confirming the correlations obtained between the surface settlement, sieve stability, VSI, rapid penetration, and column segregation test methods within mixtures produced in the laboratory, and
- Evaluating the technician-friendliness of the surface settlement, sieve stability, and VSI test methods under actual plant conditions.

References

AASHTO. 2010. *AASHTO Bridge construction specifications.* 3rd ed. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. 2007. *AASHTO LRFD Bridge design specifications: Customary U.S. Units.* 5th ed. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO M 43. 2003. Sizes of aggregate for road and bridge construction. In *Standard specifications for transportation materials and methods of sampling and testing*. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO M 6. 2003. Fine aggregate for portland cement concrete. In *Standard specifications for transportation materials and methods of sampling and testing*. Washington, DC: American Association of State Highway and Transportation Officials.

Abo-Qudais, S.A. 2005. Effect of concrete mixing parameters on propagation of ultrasonic waves. *Construction and Building Materials* 19, no. 4:257-263.

ACI 232. 2003. Use of fly ash in concrete (ACI 232.2R-03). Farmington Hills, MI: American Concrete Institute.

ACI 234. 1996. Guide for the use of silica fume for concrete (ACI 234R-96). Farmington Hills, MI: American Concrete Institute.

ACI 237. 2007. Self-consolidating concrete (ACI 237R-07). Farmington Hills, MI: American Concrete Institute.

ACI 238. 2008. Report on measurements of workability and rheology of fresh concrete (ACI 238R-08). Farmington Hills, MI: American Concrete Institute.

ACI 318. 2008. Building code requirements for structural concrete (ACI 318-08) and Commentary. Farmington Hills, MI: American Concrete Institute.

ACI 408. 2003. Bond and development of straight reinforcing bars in tension (ACI 408R-03). Farmington Hills, MI: American Concrete Institute.

Alavi-Fard, M., and H. Marzouk. 2004. Bond of high-strength concrete under monotonic pull-out loading. *Magazine of Concrete Research* 56, no. 9:545-557.

Almeida Filho, F.M., M.K. El Debs, and A.L.H.C. El Debs. 2008. Bond-slip behavior of fresh self-compacting concrete and vibrated concrete using pull-out and beam tests. *Materials and Structures* 41, no. 6:1073-1089.

Assaad, J., K.H. Khayat, and J.A. Daczko. 2004. Evaluation of static stability of self-consolidating concrete. *ACI Materials Journal* 101, no. 3:207-215.

ASTM C 597. 2002. Standard test method for pulse velocity through concrete. *ASTM International*. West Conshohocken, PA.

ASTM C 1610. 2006. Standard test method for static segregation of self-consolidating concrete using column technique. *ASTM International*. West Conshohocken, PA.

ASTM C 1611. 2005. Standard test method for slump flow of self-consolidating concrete. *ASTM International*. West Conshohocken, PA.

ASTM C 1621. 2009. Standard test method for passing ability of self-consolidating concrete by J-ring. *ASTM International*. West Conshohocken, PA.

ASTM C 1712. 2009. Standard test method for rapid assessment of static segregation resistance of self-consolidating concrete using penetration test. *ASTM International*. West Conshohocken, PA.

Barnes, R.W., J.W. Grove, and N.H. Burns. 2003. Experimental assessment of factors affecting transfer length. *ACI Structural Journal* 100, no. 6:740-748.

Bartos, P.J.M. 2005. Assessment of key characteristics of fresh self-compacting concrete: A European approach to standardisation of tests. In *Second North American conference on the design and use of self-consolidating concrete and the fourth international RILEM symposium on self-compacting concrete*, ed. S.P. Shah, 807-829. Addison, IL: Hanley Wood.

BASF Construction Chemicals, LLC. 2007. Delvo Stabilizer product data sheet. Cleveland, OH: BASF Construction Chemicals.

Bonen, D., and S.P. Shah. 2004. The effects of formulation on the properties of self-consolidating concrete. In *Concrete science and engineering: A tribute to Arnon Bentur*, ed. K. Kovler, J. Marchand, S. Mindess, and J. Weiss, 43-56. Cachan Cedex, France: RILEM Publications s.a.r.l.

Bonen, D., and S.P. Shah. 2005. Fresh and hardened properties of self-consolidating concrete. *Progress in Structural Engineering and Materials* 7, no. 1:14-26.

Bui, V.K., E.K. Attiogbe, D. Vojtko, S. Schaef, and H.T. See. 2007. A rapid test for segregation resistance of self-consolidating concrete. In *2007 Concrete technology forum: Focus on high performance concrete*. Dallas: National Ready Mixed Concrete Association.

Bui, V.K., D. Montgomery, I. Hinczak, and K. Turner. 2002. Rapid testing method for segregation resistance of self-compacting concrete. *Cement and Concrete Research* 32, no. 9:1489-1496.

Castel, A., T. Vidal, K. Viriyametanont, and R. Francois. 2006. Effect of reinforcing bar orientation and location on bond with self-consolidating concrete. *ACI Structural Journal* 103, no. 4:559-567.

Cattaneo, S., G. Muciaccia, and G. Rosati. 2008. Bond strength in limestone self-compacting concrete. In *3rd North American conference on the design and use of self-consolidating concrete: Challenges and barriers to application*. Evanston, Illinois: Center for Advanced Cement Based Materials (ACBM). CD-ROM.

Chan, Y., Y. Chen, and Y. Liu. 2003. Development of bond strength of reinforcement steel in self-consolidating concrete. *ACI Structural Journal* 100, no. 4:490-498.

Cresset, Inc. 2008. CRETE-LEASE 880-VOC-Xtra Release Agent with Poly-Release specification sheet. Weston, OH: Cresset Chemical Company.

Cussigh, F. 1999. Self-compacting concrete stability control. In *First international RILEM symposium on self-compacting concrete*, ed. A. Skarendahl and O. Petersson, 153-167. Cachan Cedex, France: RILEM Publications s.a.r.l.

Daczko, J.A. 2003. Stability of self-consolidating concrete, assumed or ensured?. In *First North American conference on the design and use of self-consolidating concrete*, ed. S. Shah, J. Daczko, and J. Lingscheit, 245-251. Evanston, IL: Hanley-Wood.

El-Chabib, H., and M. Nehdi. 2006. Effect of mixture design parameters on segregation of self-consolidating concrete. *ACI Materials Journal* 103, no. 5:374-383.

Emborg, M. 1999. Rheology tests for self-compacting concrete: How useful are they for the design of concrete mix for full scale production? In *First international RILEM symposium on self-compacting concrete,* ed. A. Skarendahl and O. Petersson, 95-105. Cachan Cedex, France: RILEM Publications s.a.r.l.

EPG (Self-Compacting Concrete European Project Group). 2005. *The European guidelines for self-compacting concrete*. Farnham, UK: EFNARC.

Esfahani, M.R., M. Lachemi, and M.R. Kianoush. 2008. Top-bar effect of steel bars in self-consolidating concrete (SCC). *Cement and Concrete Composites* 30, no. 1:52-60.

Fang, W., C. Jianxiong, and Y. Changhui. 1999. Studies on self-compacting high performance concrete with high volume mineral additives. In *First international RILEM symposium on self-compacting concrete*, ed. A. Skarendahl and O. Petersson, 569-578. Cachan Cedex, France: RILEM Publications s.a.r.l.

Gaydecki, P.A., F.M. Burdekin, W. Damaj, D.G. John, and P.A. Payne. 1992. The propagation and attenuation of medium-frequency ultrasonic waves in concrete: A signal analytical approach. *Measurement Science and Technology* 3, no. 1:126-134.

Girgis, A.F.M., and C.Y. Tuan. 2005. Bond strength and transfer length of pretensioned bridge girders cast with self-consolidating concrete. *PCI Journal* 50, no. 6:72-87.

Hassan, A.A.A., K.M.A. Hossain, and M. Lachemi. 2010. Bond strength of deformed bars in large reinforced concrete members cast with industrial self-consolidating concrete mixture. 2010. *Construction and Building Materials* 24, no. 4:520-530.

Hosssain, K.M.A., and M. Lachemi. 2008. Bond behavior of self-consolidating concrete with mineral and chemical admixtures. *Journal of Materials in Civil Engineering* 20, no. 9:608-616.

Hwang, S., K.H. Khayat, and O. Bonneau. 2006. Performance-based specifications of self-consolidating concrete used in structural applications. *ACI Materials Journal* 103, no. 2:121-129.

Jeanty, P.R., D. Mitchel, and M.S. Mirza. 1988. Investigation of “top-bar” effects in beams. *ACI Structural Journal* 85, no. 3:251-257.

Kavanaugh, B. 2008. Creep behavior of self-consolidating concrete. Master of Science thesis, Auburn University.

Khayat, K.H., 1998. Use of viscosity-modifying admixtures to reduce top-bar effect of anchored bars cast with fluid concrete. *ACI Materials Journal* 95, no. 2:158-167.

Khayat, K.H. 1999. Workability, testing, and performance of self-consolidating concrete. *ACI Materials Journal* 96, no. 3:346-353.

Khayat, K.H., and J. Assaad. 2002. Air-void stability in self-consolidating concrete. *ACI Materials Journal* 99, no. 4:408-416.

Khayat, K.H., E.K. Attiogbe, and H.T. See. 2007. Effect of admixture combination on top-bar effect of highly flowable and self-consolidating concrete mixtures. In *Special Publication SP-247: Self-consolidating concrete for precast prestressed applications,* ed. A.K. Schindler, D. Trejo, and R.W. Barnes. Farmington Hills, MI: American Concrete Institute. CD-ROM.

Khayat, K.H., A. Ghezal, and M.S. Hadriche. 2000. Utility of statistical models in proportioning self-consolidating concrete. *Materials and Structures* 33, no. 5:338-344.

Khayat, K.H., K. Manai, and A. Trudel. 1997. In situ mechanical properties of wall elements cast using self-consolidating concrete. *ACI Materials Journal* 94, no. 6:491-500.

Khayat, K.H., and D. Mitchell. 2009. *National Cooperative Highway Research Program (NCHRP) Report 628: Self-consolidating concrete for precast, prestressed concrete bridge elements*. Washington, DC: Transportation Research Board.

Khayat, K.H., N. Petrov, E.K. Attiogbe, and H.T. See. 2003. Conventional flowable and self-consolidating concrete mixtures. In *Third international symposium on self-compacting concrete,* ed. O. Wallevik and I. Nielsson, 703-712. Bagneux, France: RILEM Publications S.A.R.L.

Koehler, E.P., and D.W. Fowler. 2008. Static and Dynamic Yield Stress Measurements of SCC. *Third North American conference on the design and use of self-consolidating concrete,* Chicago, IL. CD-ROM.

Koehler, E.P., and D.W. Fowler. 2010. Comparison of workability test methods for self-consolidating concrete. *Journal of ASTM International* 7, no. 2.

Koehler, E.P., D.W. Fowler, E.H. Foley, G.J. Rogers, S. Watanachet, and M.J. Jung. 2007. *Self-consolidating concrete for precast structural applications: Mixture proportions, workability, and early-age hardened properties*. CTR Technical Report 0-5134-1. Austin, TX: Center for Transportation Research.

Komlos, K., S. Popovics, T. Nurnbergerova, B. Babal, and J.S. Popovics. 1996. Ultrasonic pulse velocity test of concrete properties as specified in various standards. *Cement and Concrete Composites* 18, no. 5:357-364.

Kwan, A.K.H., and I.Y.T. Ng. 2009. Optimum superplasticizer dosage and aggregate proportions for SCC. *Magazine of Concrete Research* 61, no. 4:281-292.

Lange, D.A., ed. 2007. *Self-consolidating concrete: A white paper by researchers at the Center of Advanced Cement Based Materials*. Evanston, IL: ACBM.

Lemieux, G., S.D. Hwang, and K.H. Khayat. 2010. Effect of material constituents and mix design on performance of SCC for precast, prestressed girders. In *Design, production, and placement of self-consolidating concrete*, ed. K.H. Khayat and D. Feys, 25-35. New York, NY: Springer.

Lin, Y., S. Kuo, C. Hsiao, and C. Lai. 2007. Investigation of pulse velocity-strength relationship of hardened concrete. *ACI Materials Journal* 104, no. 4:344-350.

Lin, Y., C. Lai, and T. Yen. 2003. Prediction of ultrasonic pulse velocity (UPV) in concrete. *ACI Structural Journal* 100, no. 1:21-28.

Mehta, P.K., and P.J.M. Monteiro. 2006. *Concrete: Microstructure, Properties, and Materials*. 3rd ed. New York, NY: The McGraw Hill Companies.

Mindess, S., J.F. Young, and D. Darwin. 2003. *Concrete*. 2nd ed. Upper Saddle River, NJ: Pearson Education.

Mouret, M., G. Escadeillas, and A. Bascoul. 2008. Metrological significance of the column test in assessment of the static segregation of self-compacting concrete in the fresh state. *Materials and Structures* 41, no. 4:663-679.

Naik, T.R., V.M. Malhotra, and J.S. Popovics. 2004. The ultrasonic pulse velocity method. In *Handbook on nondestructive testing of concrete*, Second Edition, ed. V.M. Malhotra and N.J. Carino, chap. 8. Boca Raton, FL: CRC Press LLC.

Ng, I.Y.T., H.H.C. Wong, and A.K.H. Kwan. 2006. Passing ability and segregation stability of self-consolidating concrete with different aggregate proportions. *Magazine of Concrete Research* 58, no. 7:447-457.

Ozyildirim, C., and D.S. Lane. 2003. *Virginia Transportation Research Council (VTRC) Report: Evaluation of self-consolidating concrete.* Charlottesville, VA: VTRC.

PCI (Precast/Prestressed Concrete Institute). 2004. *Interim guidelines for the use of self-consolidating concrete in Precast/Prestressed Concrete Institute member plants*, 1st ed. Chicago: Precast/Prestressed Concrete Institute.

Peterman, R.J. 2007. The effects of as-cast depth and concrete fluidity on strand bond. *PCI Journal* 52, no. 3:72-101.

Roberts, J. 2005. Evaluation of self-consolidating concrete for use in prestressed girder applications. Master of Science thesis, Auburn University.

Saak, A.W., H.M. Jennings, and S.P. Shah. 2001. New methodology for designing self-compacting concrete. *ACI Materials Journal* 98, no. 6:429-439.

Sahmaran, M., O. Yaman, and M. Tokyay. 2007. Development of high-volume low-lime and high-lime fly-ash-incorporated self-consolidating concrete. *Magazine of Concrete Research* 59, no. 2:97-106.

Schindler, A.K., R.W. Barnes, J.B. Roberts, and S. Rodriguez. 2007. Properties of self-consolidating concrete for prestressed members. *ACI Materials Journal* 104, no. 1:53-61.

Schwartzentruber, L.D., and G.V.M. Broutin. 2005. Quantifying the segregation risk of self-compacting concrete by gammadensitometry. In *Second North American conference on the design and use of self-consolidating concrete and the fourth international RILEM symposium on self-compacting concrete*, ed. S.P. Shah, 713-720. Addison, IL: Hanley Wood.

Shen, L., L. Struble, and D. Lange. 2007. New method for measuring static segregation of self-compacting concrete. *Journal of Testing and Evaluation* 35, no. 3.

Solis-Carcano, R., and E.I. Moreno. 2008. Evaluation of concrete made with crushed limestone aggregate based on ultrasonic pulse velocity. *Construction and Building Materials* 22, no. 6:1225-1231.

Sonebi, M., and P.J.M. Bartos. 1999. Hardened SCC and its bond with reinforcement. In *First international RILEM symposium on self-compacting concrete*, ed. A. Skarendahl and O. Petersson, 275-284. Cachan Cedex, France: RILEM Publications s.a.r.l.

Sonebi, M., and P.J.M. Bartos. 2002. Filling ability and plastic settlement of self-compacting concrete. *Materials and Structures* 35, no.8:462-469.

Soshiroda, T., K. Voraputhaporn, and Y. Nozaki. 2006. Early-age inspection of concrete quality in structures by combined nondestructive method. *Materials and Structures* 39, no.2:149-160.

Soylev, T.A., and R. Francois. 2003. Quality of steel-concrete interface and corrosion of reinforcing steel. *Cement and Concrete Research* 33, no. 9:1407-1415.

Stocker, M.F., and M.A. Sozen. 1970. *Engineering Experiment Station bulletin 503: Investigation of prestressed reinforced concrete for highway bridges, part five: Bond* *characteristics of prestressing strand*, ed. V. Griffin. Urbana, IL: University of Illinois

Swords, J.S. 2005. Transfer length in prestressed self-consolidating concrete. Master of Science thesis, Auburn University.

Tregger, N., L. Ferrara, and S.P. Shah. 2010. Predicting dynamic segregation of self-consolidating concrete from the slump-flow test. *Journal of ASTM International* 7, no. 1.

Ye, Y., D. Bonen, and S.P. Shah. 2005. Fresh properties and segregation resistance of self-compacting concrete. In *Second North American conference on the design and use of self-consolidating concrete and the fourth international RILEM symposium on self-compacting concrete,* ed. S.P. Shah, 621-627. Addison, IL: Hanley Wood.

Zhu, W., J.C. Gibbs, and P.J.M. Bartos. 2001. Uniformity of in situ properties of self-compacting concrete in full-scale structural elements. *Cement and Concrete Composites* 23, no. 1:57-64.

Appendix A

Fresh Stability Test Methods

Testing instructions for the sieve stability, surface settlement, and multiple-probe penetration test methods are given in this appendix. The test procedures were derived from the most current version of test instructions available to the researcher at the beginning of testing, November 2009, and were not deviated from except as noted in Chapter 4. The test instructions are as follows:

- Appendix A.1: Sieve Stability Test, based on the European Guidelines for SCC (EPG 2005),
- Appendix A.2: Surface Settlement Test, based on NCHRP Report 628 (Khayat and Mitchell 2009), and
- Appendix A.3: Multiple-Probe Penetration Test, based on a publication by El-Chabib and Nehdi (2006).

A.1 Sieve Stability Test

The sieve stability test is recommended as the primary on-site quality assurance measure of stability for SCC projects in the European Union (EPG 2005). The test involves sampling fresh SCC and allowing it to stand for 15 minutes before pouring it onto a sieve, pan, and scale, usually with the assistance of a dumping apparatus. It then rests on the sieve for 2 minutes to allow separation of mortar and aggregate, after which the proportion of the sample passing through the sieve is used to assess stability.

A.1.1. Equipment

- **12 in. Diameter No. 4 Sieve,** at least 2 in. tall, complete with a pan from which the sieve can be easily removed by lifting vertically,
- **Scale,** having a flat platform to accommodate the sieve and pan, capacity of at least 22 lbs (10 kg), and calibrated increments of ≤ 0.02 lbs (10 g, or 0.35 oz),
- **Sample Container,** either plastic or metal, with an internal diameter of 12 in. ± 3/8 in. (300 mm ±10 mm) and a capacity of 3 gal ± 0.1 gal (11.5 L ± 0.5 L), and
- **Pouring Apparatus,** (optional), which may be used to support the sample container and ensure a constant pouring height of 20 in. ± 2 in.

A.1.2. Procedure

Place 2.6 gal ± 0.1 gal (0.35 ft^3, or approximately 50 lbs) of concrete in the sample container and allow it to stand in a level position undisturbed for 15 min. ± 30 seconds.

Weigh the pan while empty and record the mass (*pan*), and then add the sieve, weigh the empty sieve and pan, and record the mass (*sieve + pan*).

While the sieve and pan are still on the scale, and after the 15 minute standing period, pour 10.5 lbs ± 0.5 lbs of concrete (including bleed water) onto the center of the sieve from a height of 20 in. ± 2 in. above the sieve mesh. Record the total weight on the scale (*sieve + pan + SCC total*).

Allow the concrete to stand on the sieve for 120 s ± 5 s, and then remove the sieve vertically while avoiding any agitation. Record the mass of the pan and concrete that has passed into it from the sieve (*pan + SCC sieved fraction*).

A.1.3. Result

The segregation fraction (S) is calculated by dividing the weight of SCC passing onto the pan by the total weight of SCC tested according to the following equation:

$$S = \frac{[(pan + SCC\ sieved\ fraction) - (pan)]}{[(sieve + pan + SCC\ total) - (sieve + pan)]} \times 100$$

A.2 Surface Settlement Test

The surface settlement test is recommended by NCHRP Report 628 (Khayat and Mitchell 2009) as the primary stability test for SCC to be used in precast, prestressed bridge element production. The test involves measuring the settlement of a thin acrylic plate as it settles into a column of fresh SCC. Stability is then assessed by calculating either the maximum settlement or the rate of settlement as a percentage of the height of the sample.

A.2.1 Equipment

- **Column Mold,** as shown in Figure A.1. Made of Schedule 40 PVC, the column shall be 8 in. (200 mm) in diameter and 26 in. (660 mm) tall and shall be securely attached to the rigid, nonabsorbent base plate,
- **Dial Indicator,** with a 0.0004 in. (0.01 mm) precision and minimum travel length of 2 inches, or
- **LVDT,** with a minimum travel length of 2 inches,
- **Acrylic Plate,** as shown in Figure A.1. The plate shall be 6 in. (150 mm) in diameter and 0.15 in. (4 mm) in thickness. It shall have four ½ in. holes and four 1.4 in. (35 mm) screws that penetrate downward into the sample. The configuration of holes and screws is shown in the figure,
- **Sample Container,** of sufficient capacity to allow easy remixing of the entire sample, and
- **Shovel, Scoop, or Plastic Bucket,** used to fill the column mold.

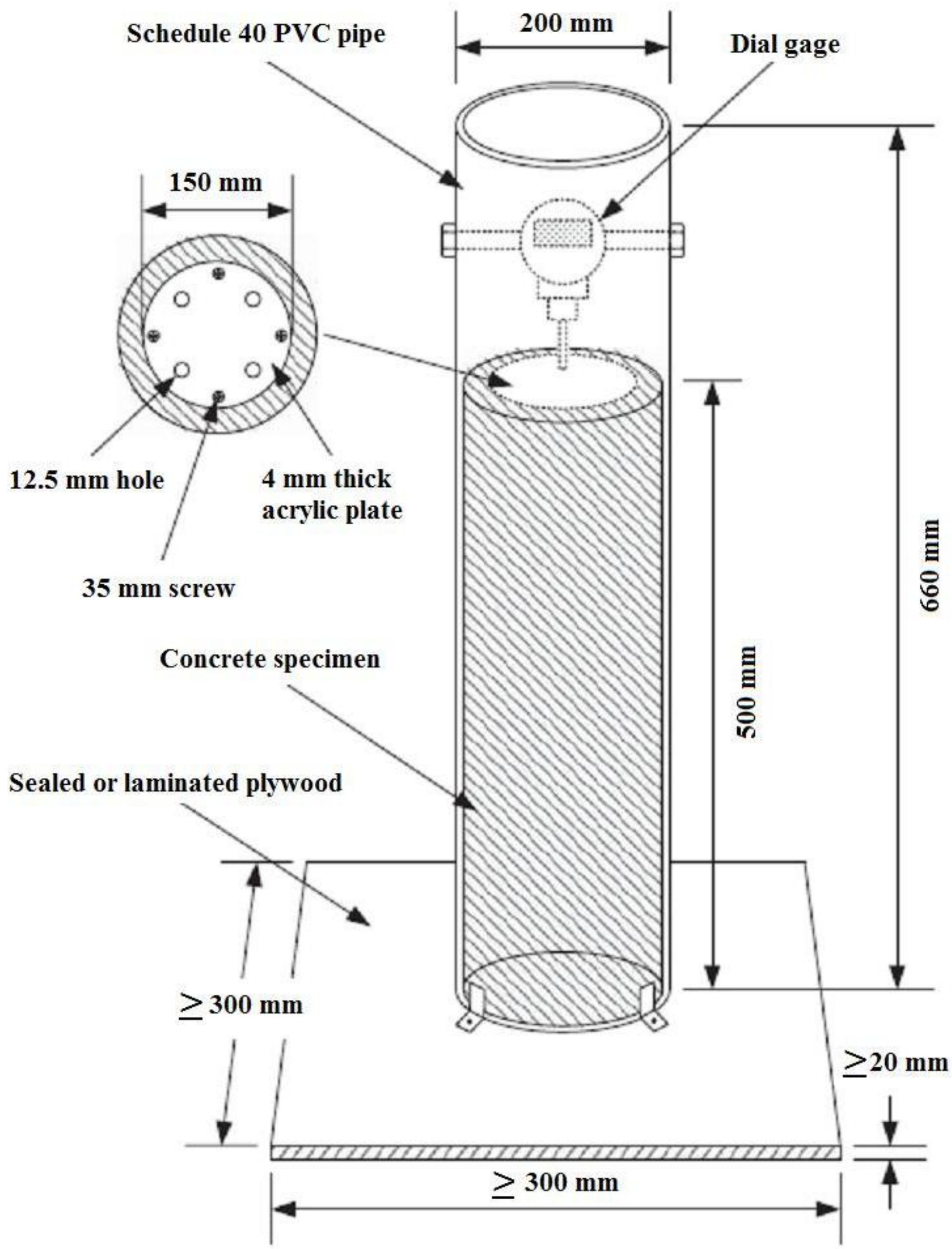

Figure A.1: Surface settlement test apparatus

A.2.2. Procedure

Avoid any vibration or disturbance of the sample throughout the test. Prior to filling of the column mold, mix the sample to ensure that the concrete is homogenous. Then, using a shovel, scoop, or plastic bucket, fill the column mold with concrete to a level of 19.7 in. (500 mm) within 2 minutes.

Install the acrylic plate with screws facing downward over the center of the column sample. Then install the dial indicator or LVDT over the center of the acrylic plate.

Take an initial reading of the dial indicator or LVDT 60 s after its installation. Then, continue to take readings at 5 minute intervals for the first 30 minutes and then every 2 hrs until hardening of the concrete.

A.2.3. Result

The rate of settlement is calculated using the readings at 10 minutes (S_{10}) and 15 minutes (S_{15}) according to the following equation, and the rate of settlement per hour is expressed as a percentage of the sample height:

$$rate\ of\ \ settlement\ (\%/hr) = \frac{\left[\dfrac{(S_{15} - S_{10})}{19.7\ in.}\right]}{5\ \text{min}} \times \frac{60\ \text{min}}{1\ hr} \times 100$$

The maximum settlement ($S_{\%}$) is calculated using the final reading taken after the concrete has hardened (S_{max}) and the initial reading ($S_{initial}$) according to the following equation, and the maximum settlement is expressed as a percentage of the sample height:

$$S_{\%}(\%) = \frac{(S_{\max} - S_{initial})}{19.7\ in} \times 100$$

A.3 Multiple-Probe Penetration Test

The multiple-probe penetration test was originally based on the rapid penetration test (El-Chabib and Nehdi 2006). The test involves measuring the penetration of four solid penetration probes as they penetrate a sample of SCC. The average penetration of the four probes is then used to assess stability.

A.3.1. Equipment

- **Column Mold,** made from PVC, 6 in. in diameter and 12 in. tall. The column mold shall be securely attached to a ¼ in. thick nonabsorbent, rigid base plate.
- **Penetration Probe, (four),** made from PVC or nonabsorbent plastic, 0.78 in. (20 mm) in diameter and 4.3 in. (110 mm) tall, and with a hemispherical head of 0.39 in. (10 mm) radius. The probe shall weigh 0.06 lb (25 g) and shall be marked with a millimeter scale along its height, beginning at the base of the cylindrical portion of the probe (to cover the upper 3.5 in.),
- **Probe-Supporting Frame,** made of metal or a rigid material, 13.25 in. tall with 1 in. openings as shown in Figure A.2. The openings shall allow the probes to fall freely into the sample, and
- **Sample Container,** with sufficient volume to gather a 0.25 ft^3 (2 gal).

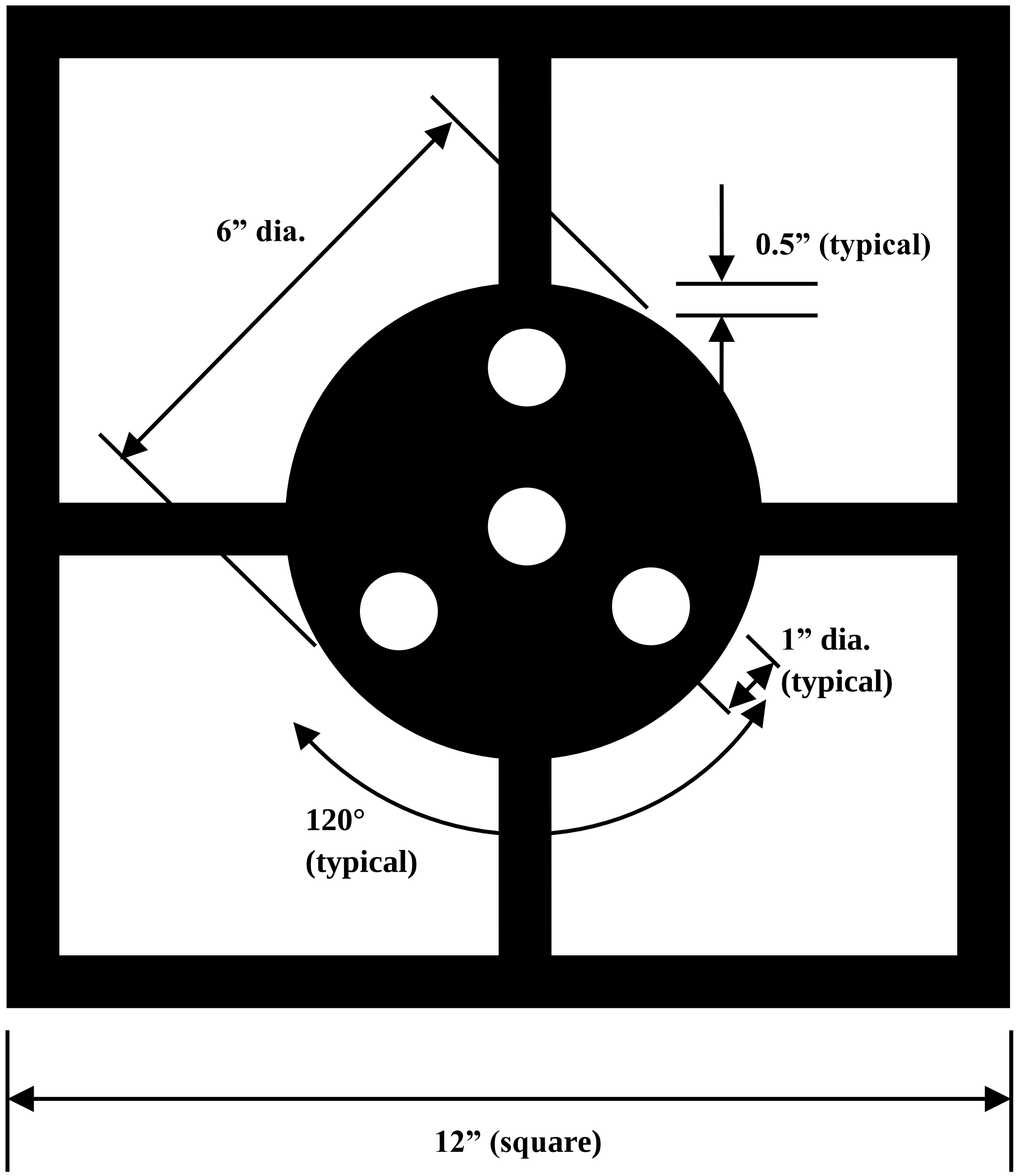

Figure A.2: Probe-supporting frame for multiple-probe penetration test

A.3.2. Procedure

Gather a homogenous sample in the sample container and fill the column mold in a single continuous lift. Strike off the sample and allow it to stand undisturbed for 2 minutes.

Place the probe-supporting frame over the column mold, and, after the 2 minute standing period, position the four probes in the four openings in the frame. One at a time, record the initial penetration (P_i) of the probe by reading from the scale at the level of the probe-supporting frame, and then release the probe into the sample.

After allowing the probes to settle for 30 s, read the final penetration (P_f) of each probe.

A.3.3. Result

The average penetration is calculated according to the following equation:

$$P_{avg} = \frac{\sum_{n=1}^{4} (P_f - P_i)_n}{4}$$

Appendix B

Fresh Stability Test Results

The fresh stability test results gathered during this research are presented in this appendix. The two test values averaged to achieve the results used in Chapter 4 are shown in Table B.1. More specific results for the surface settlement test method are given in Table B.2 (SCC-1 mixtures) and Table B.3 (SCC-2 mixtures), and more specific results for the multiple-probe penetration tests are given in Table B.4.

Table B.1: Mixture individual fresh stability test results

Mixture ID	VSI	Seg. Index (%)	Rapid Pen. (mm)	Sieve Fraction (%)	Rate of Set. (%/hr)	Max. Set. (%)	Multiple Probe (mm)
CTRL-1	N.A.	6.0 0.0	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-1A	1.5 2.5	8 3.2	8 5	*	0.16 -	0.60 -	5.3 2.8
SCC-1B	0.5 1	0.0 0.0	8 2	7.3 5.6	0.21 0.12	0.41 0.31	11.0 6.8
SCC-1C	1 1.5	8.7 8.0	3 3	9 7.4	0.15 0.06	0.04 0.03	18.3 11.8
SCC-1D	1 1.5	20.7 14.3	10 7	17.7 13.8	0.02 0.01	0.01 0.01	12.3 12.3
CTRL-2	N.A.	9.9 1.7	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-2A	1.5 2	8.6 7.4	12 6	13.9 13.6	0.06 0.02	0.03 0.02	24.0 16.8
SCC-2B	3 3	21.9 18.1	9 6	36.6 24.4	0.33 0.18	0.15 0.13	17.0 11.0
SCC-2C	1.5 2	5.2 0.8	5 2	9.2 8.7	0.15 0.09	0.1 0.07	23.8 17.5
SCC-2D	1.5 1	15.7 6.4	3 2	5.4 4.9	0.27 0.23	0.17 0.09	8.7 8.0
SCC-2E	2 1.5	18.4 14.7	4 3	15.2 13.3	0.19 0.15	0.23 0.12	11.8 9.0

Table B.2: Mixture individual surface settlement measurements: SCC-1 mixtures

Time (min.)	Settlement Reading (in.)									
	CTRL-1	SCC-1A		SCC-1B		SCC-1C		SCC-1D		
Initial	-	0.0000	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
5	-	0.0500	-	0.0330	0.0422	0.0015	0.0024	0.0005	0.0003	
10	-	0.0693	-	0.0560	0.0665	0.0033	0.0034	0.0009	0.0008	
15	-	0.0720	-	0.0580	0.0700	0.0057	0.0044	0.001	0.0011	
20	-	0.0800	-	0.0600	0.0750	0.0059	0.0045	0.0013	0.0012	
25	-	0.0930	-		0.0770	0.0061	0.0049	0.0014	0.0017	
30	-	0.0980	-		0.0800	0.0064	0.0050	0.0015	0.0019	
60	-	0.1182	-			0.0068		0.0018	0.0022	
105	-	0.1182	-							

Table B.3: Mixture individual surface settlement measurements: SCC-2 mixtures

Time (min.)	Settlement Reading (in.)										
	CTRL-2	SCC-2A		SCC-2B		SCC-2C		SCC-2D		SCC-2E	
Initial	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	-	0.0014	0.0018	0.0077	0.0109	0.0050	0.0023	0.0062	0.0090	0.0150	0.0130
10	-	0.0026	0.0030	0.0119	0.0181	0.0090	0.0043	0.0118	0.0186	0.0237	0.0200
15	-	0.0030	0.0040	0.0173	0.0210	0.0115	0.0057	0.0156	0.0230	0.0269	0.0225
20	-	0.0040	0.0043	0.0194	0.0233	0.012	0.0078	0.016	0.0286	0.0324	0.0219
25	-	0.0046	0.0044	0.022	0.0256	0.013	0.0092	0.0177	0.0330	0.0391	0.0221
30	-	0.0048	0.0047	0.0257	0.0280	0.0148	0.0098	0.0185	0.0340	0.0415	0.0224
60	-	0.0049	0.0048	0.0260	0.0300	0.0168	0.0118			0.0459	0.0230
105	-					0.0192	0.0146				

Table B.4: Mixture individual penetration depths from multiple-probe penetration test

Mixture ID	Multiple-Probe Penetration Test Apparatus 1 of 2				Multiple-Probe Penetration Test Apparatus 2 of 2			
	Probe Penetration Depths (mm)				Probe Penetration Depths (mm)			
CTRL-1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-1A	9	5	5	2	5	3	2	1
SCC-1B	13	13	13	5	12	6	5	4
SCC-1C	25	17	16	15	19	11	9	8
SCC-1D	17	14	10	8	16	13	12	8
CTRL-2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
SCC-2A	27	27	24	17	22	22	13	10
SCC-2B	20	17	15	15	24	9	7	2
SCC-2C	27	26	25	17	25	20	18	7
SCC-2D	14	8	7	6	9	8	8	7
SCC-2E	19	13	9	6	11	10	9	6

Appendix C

Hardened In-Situ Test Results

The hardened in-situ uniformity test results gathered during this research project are presented in this appendix. The measurements used to calculate the UPV segregation indices is presented in Table C.5, and the UPV measurements in each wall at a concrete age of two days are listed in Table C.1 through Table C.4. The measurements used to calculate the sixth-day UPV segregation indices is presented in Table C.10, and the UPV measurements in each wall at a concrete age of six days are listed in Table C.6 through Table C.9.

The measurements used to calculate top-bar effects are presented in Table C.14, and the pullout strength measurements in each wall are listed in Table C.11 through Table C.13.

Table C.1: Second-day horizontal row average measurements from UPV testing: 94 in. walls

Norm. Ht of 94 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.95	14.61	13.93	14.53	13.99	13.19	14.21	13.57	13.06	14.54	12.64	14.11
0.87	14.72	14.11	14.55	13.84	13.09	14.77	13.53	14.13	14.42	12.90	13.87
0.78	14.66	13.97	14.53	13.62	13.02	14.58	13.68	14.50	14.40	13.09	13.84
0.70	14.57	13.88	14.45	13.76	13.16	14.53	13.65	14.38	14.55	13.11	13.77
0.61	14.50	14.03	14.73	13.68	13.26	14.85	13.73	14.28	14.58	13.14	14.09
0.53	14.34	14.05	14.35	13.63	13.47	14.88	13.80	14.33	14.40	13.20	14.18
0.44	14.42	13.91	14.62	13.66	13.30	14.77	13.71	14.40	14.65	13.17	13.99
0.37	14.39	13.76	14.36	13.79	13.14	14.98	13.60	14.25	14.31	13.17	14.06
0.30	14.20	13.80	14.37	13.53	13.20	14.77	13.76	14.45	14.37	13.24	14.24
0.21	14.40	14.56	14.44	13.76	13.39	14.60	13.74	14.41	14.33	13.12	14.11
0.13	14.30	13.85	14.30	13.74	13.29	14.72	13.71	14.33	14.23	13.11	14.01
0.04	14.48	14.76	14.75	13.78	13.51	14.54	13.88	14.55	14.39	13.34	14.22

Table C.2: Second-day horizontal row average measurements from UPV testing: 72 in. walls

Norm. Ht of 72 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.94	14.29	14.00	14.34	13.93	13.17	13.75	13.25	14.03	14.40	12.69	13.89
0.83	14.69	14.20	14.52	13.95	13.11	14.26	13.44	14.32	14.37	13.07	13.81
0.74	14.66	14.28	14.56	14.04	13.22	14.36	13.45	14.36	14.52	13.22	13.76
0.63	14.68	14.16	14.57	13.90	13.05	14.59	13.63	14.21	14.50	13.12	13.84
0.53	14.51	14.36	14.74	13.87	13.02	14.65	13.65	14.10	14.31	13.25	13.77
0.42	14.47	14.39	14.82	13.92	13.40	14.47	13.65	14.12	14.30	12.95	13.90
0.33	14.29	14.33	14.71	13.80	13.28	14.53	13.63	13.99	14.34	13.01	13.93
0.25	14.35	14.39	14.55	13.89	13.27	14.47	13.55	13.92	14.27	12.97	13.93
0.17	14.46	14.24	14.53	13.99	13.45	14.36	13.48	14.09	14.33	13.19	14.05
0.06	14.59	14.46	14.90	14.20	13.50	14.22	13.80	14.34	14.45	13.31	14.12

Table C.3: Second-day horizontal row average measurements from UPV testing: 54 in. walls

Norm. Ht of 54 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.93	14.41	-	14.29	13.82	12.83	13.90	13.53	14.26	14.19	12.72	14.01
0.78	14.64	14.46	14.36	13.83	12.98	14.22	13.53	14.16	14.15	12.98	13.88
0.65	14.52	14.78	14.44	13.92	13.00	14.28	13.56	14.14	14.19	13.06	13.76
0.54	14.52	14.47	14.51	14.01	13.12	14.27	13.60	14.44	14.15	12.92	13.68
0.41	14.31	14.14	14.44	13.74	13.07	14.39	13.52	14.09	14.05	13.08	13.73
0.31	14.34	14.13	14.51	13.91	13.05	14.35	13.58	14.10	14.26	13.10	13.72
0.22	14.44	14.22	14.46	13.92	13.21	14.33	13.53	14.09	14.24	12.98	13.84
0.07	14.46	14.18	14.53	13.86	13.22	14.23	13.53	14.26	14.35	13.25	13.97

Table C.4: Second-day horizontal row average measurements from UPV testing: 36 in. walls

Norm. Ht of 36 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.89	14.50	13.86	14.43	13.62	13.15	14.08	13.45	14.01	14.24	12.63	13.83
0.67	14.48	14.24	14.45	13.63	13.24	14.37	13.57	14.08	14.27	12.94	13.80
0.50	14.57	14.03	14.38	13.66	13.04	14.47	13.63	14.12	14.23	12.96	13.77
0.33	14.60	14.05	14.55	13.46	13.03	14.47	13.58	14.13	14.22	13.19	13.67
0.11	14.40	14.26	14.58	13.45	12.97	14.45	13.57	14.39	14.17	13.25	13.79

Table C.5: Maximum and minimum horizontal row average measurements from second-day UPV testing, and calculated segregation indices

Mixture ID	94 in. Wall		72 in. Wall		54 in. Wall		36 in. Wall	
	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.
CTRL-1	14.72 14.20	1.036	14.69 14.29	1.028	14.64 14.31	1.023	14.60 14.40	1.014
SCC-1A	14.76 13.76	1.073	14.46 14.00	1.033	14.78 14.13	1.046	14.26 13.86	1.029
SCC-1B	14.75 14.30	1.031	14.90 14.34	1.039	14.53 14.36	1.012	14.58 14.38	1.015
SCC-1C	13.99 13.53	1.034	14.20 13.80	1.029	14.01 13.74	1.019	13.66 13.45	1.016
SCC-1D	13.51 13.02	1.038	13.50 13.02	1.036	13.22 12.98	1.019	13.24 12.97	1.021
CTRL-2	14.98 14.21	1.054	14.65 13.75	1.066	14.39 14.22	1.011	14.47 14.08	1.027
SCC-2A	13.88 13.53	1.026	13.80 13.25	1.042	13.60 13.52	1.006	13.63 13.45	1.014
SCC-2B	14.55 13.06	1.114	14.36 13.92	1.032	14.44 14.09	1.025	14.39 14.01	1.027
SCC-2C	14.65 14.23	1.030	14.52 14.27	1.017	14.35 14.05	1.021	14.27 14.17	1.007
SCC-2D	13.34 12.64	1.056	13.31 12.69	1.049	13.25 12.92	1.026	13.25 12.63	1.049
SCC-2E	14.24 13.77	1.034	14.12 13.76	1.026	13.97 13.68	1.021	13.83 13.67	1.011

Table C.6: Sixth-day horizontal row average measurements from UPV testing: 94 in. walls

Norm. Ht of 94 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.95	15.12	14.44	15.16	14.41	13.60	15.01	14.22	13.81	15.26	14.82	14.70
0.87	15.17	14.64	15.28	14.26	13.50	15.49	14.33	14.87	15.21	14.92	14.47
0.78	15.23	14.46	15.23	14.28	13.45	15.36	14.30	15.16	15.20	14.92	14.48
0.70	14.92	14.36	15.04	14.17	13.41	15.27	14.43	15.07	15.18	14.92	14.42
0.61	15.02	14.64	15.31	14.26	13.50	15.58	14.64	15.03	15.20	15.09	14.55
0.53	14.59	14.25	15.02	14.03	13.59	15.50	14.51	15.00	15.00	15.09	14.67
0.44	14.85	14.49	15.37	14.16	13.73	15.52	14.48	15.02	15.06	15.17	14.64
0.37	14.79	14.32	15.19	14.28	13.55	15.69	14.49	14.90	15.04	15.07	14.72
0.30	14.79	14.40	14.75	13.98	13.45	15.47	14.53	15.01	14.95	15.21	14.81
0.21	14.74	14.78	15.01	14.17	13.63	15.26	14.57	14.94	15.01	15.02	14.49
0.13	14.74	14.43	14.94	14.14	13.46	15.37	14.48	14.96	14.96	15.03	14.52
0.04	14.93	15.13	15.30	14.28	13.96	15.23	14.61	15.10	15.19	15.30	14.70

Table C.7: Sixth-day horizontal row average measurements from UPV testing: 72 in. walls

Norm. Ht of 72 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.94	15.11	14.66	14.96	14.38	13.58	14.59	14.09	14.86	15.16	13.84	14.58
0.83	15.25	14.80	14.99	14.43	13.54	15.00	14.07	14.95	15.14	13.82	14.44
0.74	15.21	14.78	15.11	14.35	13.42	15.00	14.17	15.04	15.08	13.88	14.46
0.63	15.29	14.86	14.99	14.31	13.36	15.21	14.26	14.92	15.01	13.91	14.40
0.53	14.91	14.89	15.15	14.22	13.45	15.22	14.21	14.71	14.98	13.89	14.27
0.42	14.98	14.89	15.26	14.18	13.50	15.17	14.36	14.76	15.01	13.91	14.54
0.33	14.80	15.00	15.23	14.16	13.53	15.13	14.38	14.62	14.94	13.87	14.41
0.25	14.69	14.94	15.08	14.29	13.56	14.94	14.40	14.62	14.98	13.78	14.46
0.17	14.73	14.90	15.12	14.38	13.74	14.98	14.28	14.79	15.01	13.87	14.55
0.06	14.75	15.01	15.37	14.40	13.89	14.87	14.53	14.95	15.09	14.12	14.63

Table C.8: Sixth-day horizontal row average measurements from UPV testing: 54 in. walls

Norm. Ht of 54 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.93	14.95	-	14.80	14.34	13.26	14.73	14.35	14.87	14.99	13.66	14.65
0.78	15.18	14.80	14.85	14.35	13.30	15.11	14.19	14.83	14.88	13.72	14.41
0.65	15.08	15.14	14.88	14.36	13.34	15.19	14.30	14.82	14.85	13.83	14.41
0.54	15.04	15.19	15.02	14.44	13.40	15.12	14.34	14.94	14.82	13.71	14.26
0.41	14.67	15.03	14.92	14.22	13.43	15.07	14.22	14.75	14.82	13.80	14.16
0.31	14.85	14.79	15.03	14.38	13.44	15.05	14.17	14.77	14.96	13.93	14.33
0.22	14.94	14.85	15.12	14.27	13.57	15.08	14.23	14.77	14.94	13.79	14.36
0.07	14.84	14.89	15.22	14.26	13.57	14.84	14.40	14.82	15.17	13.94	14.49

Table C.9: Sixth-day horizontal row average measurements from UPV testing: 36 in. walls

Norm. Ht of 36 in.	Average Measured Ultrasonic Pulse Velocity (10^3 ft/s)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.89	14.99	14.56	14.92	14.07	13.57	15.13	14.29	14.78	15.03	14.35	14.62
0.67	15.03	14.69	14.91	14.06	13.59	15.16	14.42	14.69	14.95	14.74	14.46
0.50	15.01	14.85	14.85	14.05	13.49	15.22	14.39	14.74	15.01	14.69	14.36
0.33	14.87	14.71	14.90	13.76	13.43	15.04	14.43	14.78	14.89	14.92	14.48
0.11	14.72	14.95	14.87	13.85	13.41	14.89	14.48	14.77	14.78	15.08	14.50

Table C.10: Maximum and minimum horizontal row average measurements from sixth-day UPV testing, and calculated segregation indices

Mixture ID	94 in. Wall		72 in. Wall		54 in. Wall		36 in. Wall	
	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.	Max, Min (10^3 ft/s)	UPV Unif.
CTRL-1	15.23 14.59	1.044	15.29 14.69	1.041	15.18 14.67	1.035	15.03 14.72	1.021
SCC-1A	15.13 14.25	1.061	15.01 14.66	1.024	15.19 14.79	1.027	14.95 14.56	1.027
SCC-1B	15.37 14.75	1.042	15.37 14.96	1.028	15.22 14.80	1.029	14.92 14.85	1.005
SCC-1C	14.41 13.98	1.031	14.43 14.16	1.019	14.44 14.22	1.015	14.07 13.76	1.023
SCC-1D	13.96 13.41	1.041	13.89 13.36	1.040	13.57 13.26	1.024	13.59 13.41	1.013
CTRL-2	13.96 13.41	1.041	13.89 13.36	1.040	13.57 13.26	1.024	13.59 13.41	1.013
SCC-2A	14.64 14.22	1.030	14.53 14.07	1.033	14.40 14.17	1.016	14.48 14.29	1.013
SCC-2B	15.16 13.81	1.098	15.04 14.62	1.029	14.94 14.75	1.013	14.78 14.69	1.006
SCC-2C	15.26 14.95	1.020	15.16 14.94	1.015	15.17 14.82	1.024	15.03 14.78	1.017
SCC-2D	15.30 14.82	1.032	14.12 13.78	1.025	13.94 13.66	1.021	15.08 14.35	1.051
SCC-2E	14.81 14.42	1.028	14.65 14.27	1.027	14.65 14.16	1.034	14.62 14.36	1.018

Table C.11: Eight-bar-group average pullout strength measurement: 94 in. walls

Norm. Ht of 94 in.	Average Measured Pullout Strength (lbs)										
	CTRL-1	SCC-1A	SCC-1B	SCC-1C	SCC-1D	CTRL-2	SCC-2A	SCC-2B	SCC-2C	SCC-2D	SCC-2E
0.91	8,324	6,230	8,779	5,507	3,724	4,364	4,905	3,646	7,003	3,050	3,490
0.49	7,479	4,855	9,632	5,839	3,811	5,885	3,532	6,867	7,533	3,407	4,182
0.08	8,294	7,106	10,212	6,381	4,058	7,625	5,701	7,091	7,908	4,004	5,454

Table C.12: Eight-bar-group average pullout strength measurement: 72 in. walls

Norm. Ht of 72 in.	Average Measured Pullout Strength (lbs)										
	CTRL-1	SCC-1A	SCC-1B	SCC-1C	SCC-1D	CTRL-2	SCC-2A	SCC-2B	SCC-2C	SCC-2D	SCC-2E
0.89	8,341	7,669	7,031	6,071	4,295	4,204	4,062	3,844	6,470	2,321	4,617
0.47	7,135	7,155	8,660	6,487	4,440	5,579	4,360	4,965	7,064	3,492	4,246
0.11	9,078	8,355	9,443	6,860	4,223	6,899	5,157	7,245	7,614	3,884	5,156

Table C.13: Eight-bar-group average pullout strength measurement: 54 in. walls

Norm. Ht of 54 in.	Average Measured Pullout Strength (lbs)										
	CTRL-1	**SCC-1A**	**SCC-1B**	**SCC-1C**	**SCC-1D**	**CTRL-2**	**SCC-2A**	**SCC-2B**	**SCC-2C**	**SCC-2D**	**SCC-2E**
0.85	8,749	6,157*	5,653	5,913	4,144	3,923	4,986	2,312	6,076	1,778	3,495
0.48	6,994	7,559	7,633	7,204	4,224	4,785	4,950	6,106	6,769	1,948	3,443
0.15	8,918	7,634	8,794	6,456	4,495	6,500	5,761	6,467	7,920	3,651	5,110

*Note: The recorded pullout strength was the average of four pullout specimens located at a normalized height of 0.78*h* (42 in.)

Table C.14: Average pullout strengths of bottom-cast bars and lesser of mid-height or top-cast bars, and calculated top-bar effects

Mixture ID	94 in. Wall		72 in. Wall		54 in. Wall	
	Bottom, Lesser (lbs)	Top-Bar Effect	Bottom, Lesser (lbs)	Top-Bar Effect	Bottom, Lesser (lbs)	Top-Bar Effect
CTRL-1	8,294 7,479	1.11	9,078 7,135	1.27	8,918 6,994	1.28
SCC-1A	7,106 4,855	1.46	8,355 7,155	1.17	7,634 6,157	1.24
SCC-1B	10,212 8,779	1.16	9,443 7,031	1.34	8,794 5,653	1.56
SCC-1C	6,381 5,507	1.16	6,860 6,071	1.13	6,456 5,913	1.09
SCC-1D	4,058 3,724	1.09	4,223 4,223	1.00	4,495 4,144	1.08
CTRL-2	7,625 4,364	1.75	6,899 4,204	1.64	6,500 3,923	1.66
SCC-2A	5,701 3,532	1.61	5,157 4,062	1.27	5,761 4,950	1.16
SCC-2B	7,091 3,646	1.94	7,245 3,844	1.88	6,467 2,312	2.80
SCC-2C	7,908 7,003	1.13	7,614 6,470	1.18	7,920 6,076	1.30
SCC-2D	4,004 3,050	1.31	3,884 2,321	1.67	3,651 1,778	2.05
SCC-2E	5,454 3,490	1.56	5,156 4,246	1.21	5,110 3,443	1.48

Appendix D

Coefficients of Determination for Nonlinear Models

Nonlinear regression models were evaluated for each relationship studied in this research. In each relationship, both datasets could reasonably be considered independent. Therefore, each relationship was evaluated twice—once with each dataset designated as the independent variable. The larger nonlinear r^2-values from each pair of evaluations is given in this appendix. The r^2-values for correlations between fresh stability test methods are given in Table D.1, and the values between fresh and hardened results are given in Table D.2.

Table D.1: Nonlinear regression coefficients of determination between fresh stability test results

Test Result	VSI	Column Seg.	Rapid Pen.	Sieve Stability	Surface Set. (rate)	Surface Set. (max)	Multiple Probe
	Nonlinear Regression Coefficient of Determination						
Multiple Probe	0.04	0.04	0.01	0.07	0.00	0.00	-
Surface Set. (max)	0.03	0.00	0.00	0.00	0.47	-	
Surface Set. (rate)	0.09	0.00	0.00	0.00	-		
Sieve Stability	0.66	0.53	0.46	-			
Rapid Pen.	0.13	0.05	-				
Column Seg.	0.29	-					
VSI	-						

Table D.2: Nonlinear regression coefficients of determination between measures of in-situ uniformity and fresh stability test results

Test Result	VSI	Column Seg.	Rapid Pen.	Sieve Stability	Surface Set. (rate)	Surface Set. (max)	Multiple Probe
	Nonlinear Regression Coefficient of Determination						
UPV Uniformity	0.19	0.16	0.01	0.17	0.43	0.15	0.00
Top-bar	0.41	0.16	0.00	0.32	0.70	0.13	0.00