INSPECTION MANUAL FOR SELF-CONSOLIDATING CONCRETE IN PRECAST MEMBERS

Product 0-5134-P1
TxDOT Project 0-5134: Self-Consolidating Concrete for Precast Structural Applications

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Chapter 1: Introduction

1.1 What is Self-Consolidating Concrete?

Self-consolidating concrete (SCC) is an advanced type of concrete that at the time of placement can flow and consolidate under its own mass without vibration, pass through intricate geometrical configurations, and resist segregation. Because of these unique workability characteristics, the use of SCC can result in increased construction productivity, improved jobsite safety, and enhanced concrete quality. In order to achieve SCC workability and realize the associated benefits, the materials and mixture proportions must be properly selected and the concrete quality must be carefully controlled.

1.2 How is SCC Different from Conventionally Placed Concrete?

SCC is defined in terms of its workability. Therefore, the differences between SCC and conventionally placed concrete are related to workability and to the changes in materials and mixture proportions required to achieve SCC workability.

The main difference between the workability of SCC and conventionally placed concrete is the ability of SCC to flow and consolidate under its own mass. This characteristics is best represented in the slump flow test (Figure 1.1). In contrast to the conventional slump test, where the change in height of the specimen is determined upon removal of the slump cone, the horizontal flow of SCC is measured. In addition, SCC must also be able to pass through tight spaces, such as between reinforcing bars, without the assistance of vibration and must resist segregation.

Figure 1.1: Flow Properties of Conventionally Placed Concrete (Left) and SCC after Removal of the Slump Cone

If water or high-range water-reducing admixture (HRWRA) were added to a conventionally placed concrete mixture to increase its flowability to a similar level as SCC, such a concrete mixture would not be able to flow through tight spaces, such as congested reinforcement, and would exhibit poor segregation resistance. Instead, the materials and mixture proportions must be modified to achieve the unique workability associated with SCC. SCC typically includes the same materials as conventionally placed concrete; however, a special HRWRA tailored for the production of SCC is typically used and a viscosity modifying admixture (VMA) may be used. Typical modifications to mixture proportions may include higher paste volume, increased sand-aggregate ratio (S/A), and reduced maximum aggregate size. In proportioning SCC, it is common to use a relatively low water-powder ratio, where powder is defined to consist of all particles finer than approximately the No. 200 sieve including cement, supplementary cementitious materials, and mineral fillers. The low water-powder ratio combined with the need for higher paste volume can result in higher powder contents.

The modifications to mixture proportions required to achieve SCC workability may, in turn, affect hardened concrete performance. The extent of the necessary changes in mixture proportions depends on the local materials and application requirements. In addition, different mixture proportioning procedures may result in different mixture proportions for a given set of local materials and application requirements. Therefore, the hardened properties of SCC should be evaluated on a case-by-case basis in reference to specific changes in mixture proportions. In addition, the increased dispersion of powder materials and improved consolidation of concrete may result in enhanced hardened properties.

SCC is much more sensitive to small changes in materials, mixture proportions, and production variables than conventionally placed concrete. The potential consequences of such variations can be severe. If conventionally placed concrete does not exhibit the intended flowability, the amount of vibration can be increased accordingly to ensure consolidation. With SCC, however, there is no opportunity to compensate for inadequate workability once the concrete is discharged from the mixer. The high flowability of SCC significantly increases the potential for severe segregation. Therefore, the control of workability is much more critical for SCC than for conventionally placed concrete.

It is important to remember that the term self-consolidating concrete represents a broad class of concrete mixtures. SCC can be proportioned to incorporate a wide range of materials and to meet a wide range of application requirements. SCC workability and hardened property requirements vary for different applications. SCC mixture proportions can vary widely depending on application requirements, the availability of local materials, and the mixture proportioning procedure. Therefore, the properties of SCC in both the fresh and hardened state should be evaluated on a case-by-case basis and not generalized to all SCC mixtures.

1.3 Purpose of this Document

This manual discusses quality control and testing procedures for SCC used in precast elements. It is intended for use by field inspectors responsible for pre-qualifying mixtures and assuring concrete quality. The information presented is of a general nature and may not be appropriate for all projects. The manual is written on the assumption that the reader already has basic background knowledge of general concrete material properties and construction practices. Chapter 2 provides basic background information on SCC. Guidelines for SCC quality control and quality assurance are presented in Chapter 3.

SCC is a specialized material and requires specialized knowledge to evaluate it. For more information on SCC and the research on which this manual is based, the reader is referred to the TxDOT Project 0-5134 Final Report entitled “Self-Consolidating Concrete for Precast

Structural Applications: Mixture Proportioning, Workability, and Early-Age Hardened Properties."

IMPORTANT NOTE:
Owner contract documents and specifications take precedence over this manual.

Chapter 2: SCC Background

2.1 Workability

The workability of SCC is defined in terms of three properties: filling ability, passing ability, and segregation resistance (Table 2.1). **Filling ability** describes the ability of concrete to flow under its own mass and completely fill formwork. It is essential because without it, concrete would not consolidate adequately. **Passing ability** describes the ability of concrete to flow through confined conditions, such as the narrow openings between reinforcing bars. Although increasing the filling ability typically increases passing ability, a high level of filling ability does not assure passing ability. **Segregation resistance** describes the ability of concrete to remain uniform in composition during placement and until setting. Segregation resistance includes both static and dynamic stability. Static stability describes segregation resistance when concrete is at rest. Dynamic stability describes segregation resistance with concrete is not at rest—such as during mixing and placing.

Each of these three workability properties should be evaluated independently. The extent to which SCC must exhibit filling ability, passing ability, and segregation resistance can vary widely depending on the application. In selecting target workability properties, it is important to only design for what is needed, with adequate tolerances for anticipated construction variations. Increasing the levels of filling ability, passing ability, and segregation resistance will often result in increased costs. Further, the susceptibility to segregation typically increases as the filling ability is increased.

Table 2.1: SCC Workability

	Definition	Application Requirements
Filling Ability	The ability of concrete to flow under its own mass and completely fill formwork.	Members with tight spaces—such as with narrow widths or congested reinforcement—and applications where concrete must flow long horizontal distances may require greater filling ability. High placement energy—such as that generated by pumping or by gravity acting on a large mass of concrete—may allow reduced filling ability requirements.
Passing Ability	The ability of concrete to flow through confined conditions, such as the narrow openings between reinforcement bars.	Applications may range from unreinforced or lightly reinforced sections with no passing ability requirements to narrow sections containing highly congested reinforcement with strict passing ability requirements.
Segregation Resistance	The ability of the concrete to remain uniform in composition during placement and until setting.	All mixtures must exhibit segregation resistance. Requirements for dynamic stability may be higher for sections with highly congested reinforcement, conditions where concrete subjected to vibration, or applications were concrete is dropped from vertical heights or required to flow long horizontal distances.

SCC workability can also be described in terms of rheology, which is defined as the scientific study of flow. In the context of concrete, rheology provides a scientific description of workability. The rheology of concrete is quantified in terms of the yield stress and plastic viscosity. The yield stress is the amount of stress needed to initiate or maintain flow. Plastic viscosity is the resistance to flow once the yield stress is exceeded. For SCC, the yield stress must be near zero to ensure that the concrete can flow and consolidate under its own mass. The plastic viscosity should not be too low, which would result in poor stability, or too high, which would result in concrete that is sticky and difficult to place.

Rheology is measured with a rheometer. Specially designed rheometers are available for measuring concrete. Rheometers determine the shear stress required for concrete to flow at different shear rates. The greater the speed at which a fluid flows (higher shear rate), the more stress that is required (higher shear stress). The relationship between shear stress and shear rate is used to compute the yield stress and plastic viscosity, as shown in Figure 2.1. The Bingham model is used to represent this relationship.

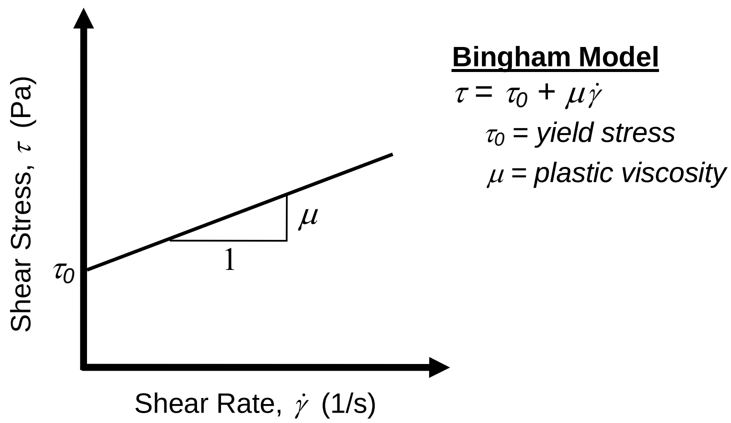


Figure 2.1: The Bingham Model for Concrete Rheology

2.2 Hardened Properties

Because SCC represents a broad class of concrete materials, the hardened properties of SCC mixtures should be evaluated on a case-by-case basis in view of the materials and mixture proportions. Potential changes in the hardened properties of SCC mixtures in reference to comparable conventionally placed concrete mixtures may be due to the changes in materials and mixture proportions made to achieve SCC workability and the improved powder dispersion and increased concrete consolidation associated with SCC. Conversely, requirements for hardened properties may result in limits on certain parameters important to achieving workability, such as powder volume, paste volume, and water-powder ratio.

Hardened properties can be measured with the same test methods used for conventionally placed concrete. The main exception, however, is that it is typically not necessary to consolidate test specimens with rodding or vibration.

2.3 Testing and Acceptance

2.3.1 Test Methods

Filling ability, passing ability, and segregation resistance should be evaluated independently. Filling ability should be evaluated with the slump flow test, passing ability with the j-ring test, and segregation resistance with the column segregation test (Figure 2.2). The procedures for each test are described fully in Appendix B.

The column segregation test measures static stability. At the time of this writing, no standardized test was available to measure dynamic stability directly.

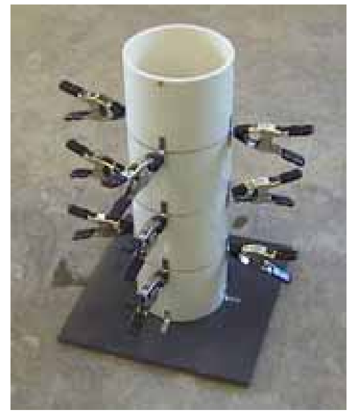
Filling Ability	Passing Ability	Segregation Resistance
Slump Flow Test	J-Ring Test	Column Segregation Test
		
Lab and Field	Lab Only	Lab Only

Figure 2.2: Test Methods for SCC Workability

Slump Flow Test. The slump flow test involves filling a slump cone with SCC, lifting the slump cone, and measuring the horizontal distance the concrete spreads. In addition, the time for the concrete to spread to a diameter of 20 in. or 50 mm (T_{50}) and the visual stability index (VSI), which is a qualitative rating of concrete stability on a scale of 0 to 3, are determined. The slump flow reflects the ability of concrete to flow under its own mass. The T_{50} measurement reflects the viscosity of the concrete. Higher viscosity (higher T_{50}) corresponds to increased resistance to flow. Concrete with high viscosity is often described as sticky and cohesive. The ability of concrete to flow under its own mass and viscosity are independent properties. Concrete with high viscosity can still flow under its own mass and completely fill formwork, it will just do so more slowly than concrete with lower viscosity. The visual stability index provides a quick but approximate indication of the stability of the mixture; however, an acceptable VSI does not ensure adequate stability nor does an unacceptable VSI mean the concrete will be unstable.

J-Ring Test. The j-ring test is conducted in the same manner as the slump flow test; however, a j-ring consisting of 16 equally spaced bars in a 12-inch diameter ring is placed around the slump cone. After the slump cone is lifted, the concrete flows though the bars in the j-ring. Instead of measuring the slump flow, the difference in height of concrete immediately inside and outside of the j-ring (Δheight) is measured. Lower j-ring Δheight measurements are associated with increased passing ability. The size and spacing of reinforcement bars is constant for all tests while the maximum value for the change in height should be established for the application.

Column Segregation Test. The column segregation test is conducted by filling concrete into a 26-inch tall, 8-inch diameter column, which is split into 3 sections. The top and bottom sections are 6.5 inches in height and the middle section is 13 inches in height. (In Figure 2.2, the test apparatus is split into four sections based on an earlier version of the test. In this case, the middle two sections can be used as a single section.) The concrete is left undisturbed for 15 minutes, after which the concrete in the top and bottom sections is collected and washed over a No. 4 sieve to retain all coarse aggregate. The relative amounts of coarse aggregate in the top and bottom of the column is used as an indication of segregation resistance.

2.3.2 Acceptance Criteria

Testing requirements vary between the laboratory (pre-qualification of mixtures) and the field (production quality control). For mixture pre-qualification testing, it is necessary to confirm that a proposed mixture exhibits adequate filling ability, passing ability, and segregation resistance and that the mixture is robust with respect to each of these properties. Once a mixture is pre-qualified, it is usually only necessary to confirm that the mixture has proper slump flow and T_{50} during field production quality control testing. It is not generally necessary to measure passing ability during production because passing ability mainly depends on the aggregates, paste volume, and slump flow. If the aggregates and paste volume remain reasonably constant and the slump flow is controlled during production, further testing of passing ability is not needed. Further, it is not generally necessary to measure segregation resistance during production because segregation resistance mainly depends on the paste rheology. If the paste rheology is controlled by ensuring that slump flow and T_{50} are within the ranges associated with acceptable segregation resistance established during mixture pre-qualification, further testing of segregation resistance is not needed.

General workability acceptance criteria are described in Table 2.2. The exact acceptance criteria should be selected for each application.

For slump flow, maximum and minimum limits should be established. The minimum limit is necessary to ensure that the concrete is able to flow and consolidate under its own mass. As the slump flow is increased, especially above 27 inches, the susceptibility to segregation increases. Therefore, a maximum limit on slump flow is needed. The value of the required slump flow depends on the application and can vary from approximately 21 to 30 inches, with slump flows of 24-27 inches appropriate for most applications. The ability to achieve higher slump flows than needed without segregation is one indication of robustness. Given the sensitivity of slump flow to small changes in materials and mixture proportions in general and HRWRA dosage in particular, a realistic range of slump flows—no less than 3 inches—should be used.

T_{50} should be measured to ensure the viscosity is appropriate for the application and to detect variations in materials or mixture proportions in a given mixture. In general, lower values of T_{50} are preferable because concrete with lower viscosity is generally easier to place (faster flow, less mixing energy, lower pumping pressure). However, if the T_{50} is too low, the concrete stability may be poor. Although low values of T_{50} are generally preferred, maximum limits on T_{50} are not necessary. T_{50} values between 2 and 7 seconds are appropriate for most applications. Target values of T_{50} should be set broadly because SCC mixtures with a wide range of T_{50} values can be placed successfully. During production, T_{50} can be used to monitor variations in materials and mixture proportions. If the HRWRA is adjusted to maintain a SCC level of slump flow, changes in T_{50} are likely to reflect variations in materials or mixture proportions. For instance, increased moisture content—such as from aggregate moisture content variations—results in lower T_{50} at a given slump flow.

Although it is advisable to monitor VSI to identify severe segregation, concrete should not be accepted or rejected on the basis of VSI.

For the j-ring test, a maximum j-ring Δheight should be specified based on the amount of reinforcement and clear spacing between reinforcement. There is no need to measure passing ability for unreinforced or lightly reinforced elements.

For the column segregation test, the maximum segregation should be less than 15% for most cases but may need to be reduced in some applications, such as sections with highly congested reinforcement or applications were concrete is dropped from vertical heights or required to flow long horizontal distances.

The robustness of each of these characteristics can be evaluated by varying the water content and slump flow over the ranges expected to be encountered in production. Mixtures should exhibit acceptable workability as the water content and slump flow are varied over these ranges. The water content and slump flow should be varied simultaneously (maximum and minimum slump flows with minimum water content, maximum and minimum slump flows with maximum water content).

Table 2.2: General Acceptance Criteria for SCC Workability

Slump Flow (in.)	21-24	Appropriate for members with light or no reinforcement, short lateral flow distances, or high placement energy (e.g. panels, barriers, coping)
	24-27	Ideal for most applications
	27-30	Appropriate for members with highly congested reinforcement, long lateral flow distances, or low placement energy (e.g. U-beams, I-beams, and other beams)
T_{50} (s)	<2	Poor stability
	2-7	Acceptable, should not vary over range of 3 s between batches
	>7	Possible, may reduce placeability
J-Ring Δheight (in.)	<0.5	Appropriate for members with highly congested reinforcement (e.g. U-beams, I-beams, and other beams)
	0.5-1.0	Appropriate for members with moderately congested reinforcement
	>1.0	Appropriate for unreinforced or lightly reinforced members (e.g. panels, coping)
Column Segregation (%)	<5	Highly segregation resistant
	5-10	Segregation resistant
	10-15	Borderline segregation resistant
	>15	Not segregation resistant

2.4 Materials

SCC is generally made with the same materials as conventionally placed concrete; however, the effects of material characteristics are often greater in SCC mixtures. Therefore, specifications for materials may not need to be changed but it is advisable to monitor material characteristics more frequently. When any changes in materials occur that could detrimentally affect workability or hardened properties, trial mixtures should be reevaluated for workability and hardened properties.

SCC mixtures always include HRWRA and in some cases a VMA. HRWRAs are typically polycarboxylate-based. Commercial HRWRA products may be tailored by the manufacturer for a given application, such as for SCC in precast concrete in certain regions of the country. The characteristics of HRWRAs can vary widely between individual commercial products. Therefore, it is suggested that concrete producers conduct testing with local materials to understand the characteristics of a HRWRA particularly with respect to rheology, workability retention, and setting time. In some cases, a water-reducing admixture (ASTM C 494 Type A or D) or mid-range water-reducing admixture can be used to reduce HRWRA demand. A retarder can be added to increase workability retention; however, it should be noted that not all retarders increase workability retention. Some commercial HRWRA products may include a retarder or VMA blended with the polycarboxylate-based HRWRA.

Viscosity modifying admixtures are used in certain cases, such as when high coarse aggregate contents, poorly shaped aggregates, or high water-powder ratios are used. They can enhance stability and reduce the effects of changes in materials and mixture proportions. VMAs tend to be most effective at higher w/p. The chemical formulation and effects on workability and hardened properties vary between commercial products.

A wide range of materials can be accommodated in SCC to meet a wide range of performance objectives. Proportioning SCC mixtures is an optimization process involving trade-offs between various materials and proportions. It is unlikely that any one material or condition can prevent the production of SCC. Instead, it may be necessary to make modifications to mixture proportions to produce an economical and well-performing SCC mixture with the available materials and for the given application.

2.5 Mixture Proportions

Mixture proportions can vary depending on the available materials and placement conditions, the workability and hardened property requirements, and the mixture proportioning procedure used. For a given set of materials and application requirements, there is commonly more than one acceptable mixture proportioning solution. Mixture proportions that perform successfully in one plant are likely to be of little relevance for a different plant with different materials.

The selection of mixture proportions should be the responsibility of the precaster and should be developed by someone experienced with SCC. Numerous mixture proportioning procedures for SCC are available. The suitability of mixture proportions should be evaluated in both laboratory and production trial batches.

In evaluating mixture proportions, SCC should be considered a suspension of aggregates in paste. Accordingly, the performance of the concrete depends on the properties of the combined aggregates, the paste volume, and the composition of the paste. The following indices should be considered when evaluating mixture proportions:

- **Aggregates.** Aggregates are defined in terms of maximum size, grading, and shape and angularity. All three of these factors should be considered together. For instance, adding a poorly shaped aggregate to improve grading may be adverse.
    - **Maximum Size.** The maximum aggregate size guidelines for conventionally placed concrete (such as ACI 211 requirements of one-fifth the narrowest dimension between side forms, one-third the depth of slabs, or three-fourth the minimum clear spacing of bars) are generally applicable to SCC. Reducing the maximum aggregate size may improve passing ability and segregation resistance; however, these benefits must be measured against any necessary increases in paste volume and the associated direct or indirect effects on hardened properties.
    - **Grading (Sand-Aggregate Ratio).** The combined grading of all aggregates should be considered. The S/A ratio is normally between 0.40 and 0.50 for SCC. Higher S/As are typically associated with improved passing ability and segregation resistance. Although the use of higher S/A results in lower coarse aggregate volume, it may allow a lower paste volume (and higher total aggregate

volume). Severely gap-graded aggregate blends should be avoided; however, slightly gap-graded mixtures can be acceptable and may be preferable to more uniform gradings. Although grading does affect segregation, the flow properties of the paste are likely to be significantly more influential.

  - **Shape and Angularity.** Aggregate shape and angularity significantly affect workability; however, aggregates of any shape and angularity can be accommodated in SCC. Well-rounded aggregates with few or no flat or elongated particles allow the use of lower paste volume and result in lower viscosity and lower HRWRA demand. Texture does not affect workability significantly; however, it can affect hardened properties substantially.

- **Paste Volume.** The paste volume, which can range from 28% to 40% in SCC, must be sufficient for ensuring filling ability and passing ability. SCC must have a minimum paste volume. Without the minimum paste volume, SCC workability cannot be achieved regardless of the admixtures used or the paste composition. The minimum required paste volume primarily depends on the aggregate characteristics. Well-shaped and well-graded aggregates with high packing density require significantly less paste volume. It is possible to use higher paste volumes than the minimum required, which increases flowability. The paste volume should be minimized, which generally results in improved hardened properties and economy. Increasing the paste volume can enhance robustness with respect to variations in aggregate properties.
- **Paste Composition.** The paste composition is defined in terms of the relative amounts of water, powder, and air and the blend of powder. The same volume of paste is needed regardless of the paste composition. The required paste composition for a given set of rheological characteristics depends on the aggregates and paste volume. Once the paste composition is set, the HRWRA dosage is established to achieve the target slump flow.
  - **Water Content.** The water content per unit volume of concrete in SCC is often similar to that in conventionally placed concrete.
    - **Water-Cement Ratio.** The w/c mainly relates to early-age hardened properties when SCMs and fillers with minimal early-age activity are used. In such cases, the w/c in SCC should normally be similar to that in conventionally placed concrete.
    - **Water-Cementitious Materials Ratio.** The w/cm, in conjunction with the powder blend, mainly relates to long-term hardened properties.
    - **Water-Powder Ratio.** The w/p, in conjunction with the powder blend, mainly relates to workability. Depending on the mixture proportioning approach, it may range from 0.25 to 0.45 or higher. The need for VMA increases as the w/p increases above 0.40. If no non-cementitious powders are used, the w/cm is equal to the w/p.
  - **Powder Content and Blend.** The powder content must be set in conjunction with the w/p to ensure proper workability. The blend of powders affects the workability and hardened properties.
    - **Cement Content.** The cement content should generally be minimized and the remainder of the powder content should be composed of SCMs, mineral fillers, or both.
    - **SCMs and Mineral Fillers.** As with conventionally placed concrete, the size distribution and shape of the SCMs and mineral fillers mainly affect

the workability. Due to their low reactivity at early ages, fly ash, slag, and mineral fillers typically reduce early heat of hydration as compared to cement. SCMs can increase long-term strength and durability.

- **Air Content**. SCC can be air entrained. For non-air entrained concrete, air contents of 1-2% are typical.

As the aggregates, paste volume, or paste composition are changed, the amount of HRWRA required to reach the target slump flow varies. HRWRA mainly affects slump flow. Therefore, the HRWRA dosage is typically adjusted to reach the target slump flow once the aggregates, paste volume, and paste composition are set. A certain target slump flow can usually be achieved with a wide range of aggregates, paste volumes, and paste compositions merely by adjusting the HRWRA dosage. In addition, VMA and other chemical admixtures may be added to assure adequate concrete performance.

The roles of aggregates, paste volume, and paste composition in achieving adequate filling ability, passing ability, and segregation resistance are summarized in Table 2.3. To achieve filling ability, concrete must have adequate paste volume and paste composition for the given combined aggregate. Sufficient paste volume ensures that voids between aggregates are filled and that sufficient spacing is provided between aggregates. If the concrete contains insufficient paste volume for filling ability, the paste will not convey the aggregates regardless of the characteristics of the paste. In this case, increasing the HRWRA dosage may result in severe bleeding. In the slump flow test, the concrete will not achieve the desired slump flow with adequate stability, if it at all (Figure 2.3). Even with the proper paste volume, concrete must also have proper paste rheology, which is affected by the paste composition. Proper paste rheology ensures that the paste can convey aggregates uniformly as the concrete flows and that the concrete can fill all corners of the formwork. As the paste volume changes, the paste rheology must also change. Concrete that is too viscous may be difficult to pump and place. Low concrete viscosities may result in poor dynamic stability. Harsh concrete mixtures can occur when the paste volume or paste viscosity is too low. In such a case, the concrete does not flow smoothly and may not completely fill all corners of the formwork and produce a smooth top-surface finish.

Passing ability is primarily affected by the aggregate characteristics and the paste volume. Reducing the maximum aggregate size and coarseness of an aggregate grading and improving the aggregate shape and angularity result in increased passing ability. Increasing the paste volume reduces the volume of aggregates and reduces the interparticle friction between aggregates. In addition, increasing the flowability of the paste improves passing ability, provided the mixture is stable.

Segregation resistance encompasses both static and dynamic stability. Static stability is affected by the relative densities of the aggregate and paste, the flow characteristics of the paste with time, the aggregate shape and grading, and the characteristics of the element (such as width and reinforcement spacing). Changing the paste flow characteristics is generally the most productive means of improving static stability. Improving the aggregate grading is also effective for reducing segregation resistance, though to a much lesser extent than changing the paste flow characteristics. An SCC mixture with an aggregate that is well-graded for segregation resistance can exhibit severe segregation if the paste flow characteristics are improper. Dynamic stability is mainly affected by the cohesiveness and passing ability of the concrete.

Table 2.3: Proportioning for SCC Workability

	Aggregates	Paste Volume	Paste Composition
Filling Ability	Improve shape and angularity to reduce interparticle friction; use finer grading to reduce harshness or coarser grading to reduce viscosity	Ensure sufficient minimum paste volume to fill voids between aggregates and reduce interparticle friction between aggregates	Ensure viscosity is not too high (sticky) or too low (instability); increase HRWRA dosage to increase slump flow
Passing Ability	Reduce amount of larger particles by reducing coarseness of grading or maximum aggregate size; improve shape and angularity to reduce interparticle friction	Increase paste volume to reduce aggregate volume and interparticle friction between aggregates	Reduce paste viscosity or increase HRWRA dosage to increase slump flow
Segregation Resistance	Use more uniform grading (avoid gap gradings); reduce coarseness of aggregate grading or maximum aggregate size	Increase paste volume	Ensure paste viscosity not too high or too low, reduce slump flow (lower HRWRA dosage); optimize workability retention (accelerate loss of slump flow in formwork); use VMA

Insufficient Paste Volume

The mixture exhibits severe bleeding and the aggregates are not uniformly distributed. Insufficient paste volume is available to mobilize and convey the aggregates. The rheology of the paste is improper, causing the paste to bleed from the concrete. Although the paste rheology can be modified by changing the paste composition, the paste volume must first be increased because without the minimum required paste volume, SCC workability cannot be achieved regardless of the paste composition. With the minimum paste volume provided, the paste composition can then be adjusted.

Sufficient Paste Volume

The mixture exhibits excellent filling ability, as evidenced by the uniform distribution of aggregates and the lack of bleeding. Both the paste volume and paste rheology are proper.

Figure 2.3: Illustration of Paste Volume for Filling Ability

2.6 SCC Performance During Production

2.6.1 Adjusting Workability During Production

During production, SCC is typically accepted on the basis of the slump flow test. If the slump flow is not within the target slump flow range, the concrete mixture can be adjusted. If the slump flow is less than the target range, HRWRA can be added. If the slump flow is greater than the target range, the mixture can be held until the slump flow is within the target range or VMA can be added (subject to maximum dosage limits). If the T_{50} is too low but the slump flow is within the target range, VMA can be added (subject to maximum dosage limits). It is advisable to pre-test mixtures to understand the effects of re-tempering with HRWRA or VMA on both workability and hardened properties. Modifications to mixture proportions during production should be kept to a minimum. The criteria for accepting and modifying mixtures should be clearly established and personnel responsible for evaluating mixtures and making changes should be well trained.

Whenever additions are made to the concrete mixture, the concrete must be remixed to ensure that the additions are fully dispersed. Whenever concrete is held until the slump flow is within the target range, the concrete must be remixed to restore homogeneity.

2.6.2 Horizontal Flow Distance and Free-Fall Height

Due to the cohesive nature and high segregation resistance of SCC, it may be possible to increase the permissible lateral flow distance and free-fall height. It is still advisable to minimize the lateral flow distance and free-fall height and to conduct tests to establish maximum permissible distances.

2.6.3 Vibration

Not only is vibration not needed for SCC, it may be detrimental. As soon as SCC comes to rest in forms, a three-dimensional structure of powder particles builds up in the paste, which causes the consistency of the concrete to thicken and increases segregation resistance. The application of vibration damages this three-dimensional structure and increases the susceptibility to segregation.

Vibration should only be used in cases where prior testing has demonstrated that vibration will not cause adverse results. Potential instances where vibration may be appropriate include the location of cold joints and in placements of concrete with low slump flow. Vibration should not be used as extra “insurance” to ensure full consolidation without prior testing.

2.6.4 Segregation During Transport

Vibration may be applied to SCC during transit, such as from jolts as the transport equipment passes over bumps. This vibration can cause segregation (one aspect of inadequate dynamic stability). Concrete that has segregated due to such vibration can be remixed to restore uniformity. It may be necessary to limit slump flows if the available transport equipment is not capable of remixing concrete prior to discharge.

2.6.5 Workability Retention

Workability retention and setting time are different properties and should be evaluated separately. Workability retention depends on the HRWRA type and dosage, retarder type and dosage, mixture proportions, concrete temperature, weather conditions, and degree of agitation. It is critical that SCC exhibit proper workability at the time of placement. The extent of workability retention should be tailored to the application because excessive workability retention is unnecessary and may increase formwork pressure and susceptibility to segregation.

Chapter 3: SCC Inspection

3.1 Overall Approach to Quality Control/Quality Assurance

Ensuring adequate SCC performance involves two tasks—mixture pre-qualification and quality control/quality assurance.

- **Mixture Pre-Qualification.** The performance of each proposed mixture—in terms of workability and hardened properties—must be demonstrated prior to placement in preliminary trial batches (conducted in laboratory) and in pilot test batches (conducted under production conditions).
- **Quality Control/Quality Assurance.** Proper quality control of all SCC batches is imperative due to the high sensitivity of SCC to small changes in materials, mixture proportions, and production variables, and to the potentially severe consequences of improper workability. In a quality control/quality assurance program, the producer is responsible for quality control and owner is responsible for quality assurance.

In pre-qualifying SCC mixtures and performing quality control/quality assurance, the respective responsibilities of the producer and the owner must be clearly defined. Preliminary trial batches and pilot test batches should be evaluated whenever there is a change in materials or mixture proportions. Changes in dosage of HRWRA or retarder do not require new trial batches; however changes in the commercial formulation of HRWRA or retarder do require new trial batches.

Prior to using an SCC mixture, the producer should submit a detailed work plan to owner. The work plan should include the following:

- Materials, mixture proportions, and relevant supporting test data
- Construction procedures (including batching, mixing, placing, and curing procedures and measures to adjust to ambient temperatures)
- Quality control plan (including test methods for material and concrete properties and target workability and hardened properties)

3.2 Selection of Allowable Workability Properties for Precast Elements

SCC mixtures should be accepted for workability on the basis of filling ability, passing ability, and segregation resistance. To pre-qualify mixtures prior to production, proposed mixtures should meet requirements for filling ability, passing ability, and segregation resistance. For production, it is usually only necessary to monitor filling ability. The allowable workability properties for each specific project should be obtained from owner specifications or other contract documents. Typical allowable workability properties are shown in Table 3.1.

For filling ability, the slump flow should typically be between 24 and 30 inches and the T_{50} should be greater than 2 seconds. Lower values of slump flow are permissible in lightly reinforced or unreinforced members. The concrete must exhibit adequate passing ability and segregation resistance at this range of slump flows. In general, as slump flow increases, the susceptibility to segregation also increases. Therefore, if the proposed mixture does not exhibit adequate segregation resistance over the full range of slump flows, it can be redesigned to exhibit greater segregation resistance or the precaster can limit the slump flow during production to only the range of slump flows associated with adequate segregation resistance.

Table 3.1: Typical Allowable Workability Properties for Precast Elements

		Specification Requirements	
		Mixture Pre-qualification	**Production Quality Control**
Filling Ability	Slump Flow (in.)	24-30 in. at the expected time of placement (lower slump flows permissible in lightly reinforced or unreinforced members)	24-30 in. at the time of placement (lower slump flows permissible in lightly reinforced or unreinforced members)
	T_{50} (s)	>2 s (inverted cone orientation)	>2 s (inverted cone orientation)
Passing Ability	J-Ring Δheight (in.)	<0.5 for highly congested reinforcement <1.0 for moderately congested reinforcement None for unreinforced or light reinforcement	None
Segregation Resistance	Column Segregation (%)	<15%	None
Note: Requirements for workability should be obtained for applicable owner specifications or other contract documents for each specific project.			

3.3 Preliminary Trial Batches (Laboratory)

The purpose of preliminary laboratory trial batches is to substantiate the performance of proposed SCC mixtures in terms of the following workability and hardened properties:

- Filling ability (slump flow, T_{50}, and retention of these properties to the time of placement)
- Passing ability (j-ring Δheight)
- Segregation resistance (column segregation)
- Air content
- Unit weight
- Setting time
- Compressive strength at release of tension age, 3 days, and 7 days
- ASTM C 1260 results (if applicable)
- Concrete rheology (optional)

The preliminary trial batches should be tested in the laboratory because of the greater control over mixture properties, which is important when evaluating the effects of variations in water content and slump flow. Accordingly, proper laboratory procedures are essential to evaluating mixtures. The workability can be evaluated at room temperature or at a temperature expected to be representative of placement conditions. Compressive strength can be evaluated in specimens cured at elevated temperatures expected to be representative of production conditions.

Due to the sensitivity of SCC workability to small variations—especially in water content and slump flow—the workability of mixtures (filling ability, passing ability, and segregation resistance) should be tested over the ranges of water contents and slump flows expected during production. Mixtures capable of demonstrating acceptable workability over these ranges of water contents and slumps flows are considered to be adequately robust. The water content should be varied by +/- 3% (unless otherwise specified or approved). The slump flow should be varied over the range of slump flows suitable for the application—such as 21 to 30 inches or 24 to 30 inches (unless otherwise specified or approved). If the mixture does not exhibit adequate workability over this range of slump flows, the proposed mixture can be used but the slump flow must be maintained during production to within the range over which the mixture exhibited adequate workability in the preliminary trail batches. (For instance, if the proposed SCC mixture segregates above a slump flow of 28 inches, the slump flow must be held below 28 inches during production.) The range of slump flows and water contents should be tested simultaneously (maximum and minimum slump flows with minimum water content, maximum and minimum slump flows with maximum water content).

The air content should be measured on preliminary trial batches whether or not the concrete is air entrained due to the potential for unexpected variations in air content related to the relatively high chemical admixture dosages associated with SCC.

3.4 Pilot Test Batches (Production Conditions)

Because laboratory concrete batches do not reflect all relevant field conditions, full-scale production trial batches (mock-ups) should be conducted for each proposed SCC mixture (new materials, new proportions, or both). These mock-ups should be conducted to demonstrate that the proposed mixture exhibits filling ability, passing ability, and segregation resistance, as evidenced by visual observations of the concrete flow around reinforcing bars and the lack of defects such as excessive honeycombing, aggregate or mortar pockets, and surface air voids (bugholes). The production conditions should be representative of those expected during normal production (including mixing, transport, and placement procedures). The elements should have similar dimensions and reinforcement configuration as the elements in which the concrete is to be used. Unlike laboratory trial batches where mixtures with a range of water content and slump flows are tested, only one batch within the range of target slump flows is necessary for the pilot test batches.

The trial batches should be conducted with typical procedures and personnel. The batch size should be at least 50% of the rated mixer capacity. SCC workability and hardened properties are affected by variations in weather conditions. It is likely that different mixtures will be proposed for different weather conditions. For example, the retarder dosage and fly ash rate may be adjusted to compensate for differences in weather conditions. As such, mixtures should be evaluated under weather conditions anticipated for use with a given mixture. Once the mixture has been pre-qualified under a given weather condition, it can continue to be used if the weather changes provided the performance is evaluated during production using the same criteria as for the pilot test batches.

The following properties should be determined when evaluating pilot test batches:

- Fresh Properties
  - Workability (slump flow, T_{50}, and retention of these properties to the time of placement)
  - Unit weight
  - Initial setting time
  - Ambient and concrete temperatures during curing (until release of tension time)

- Compressive strength at release of tension age, 3 days, 7 days, 14 days, and 28 days. (If concrete is to be accepted on the basis of 56-day strength, measure compressive strength at this age.) Match-cured cylinders are appropriate.
- Visual observations of workability during placement
    - Filling Ability (Does the concrete flow under its own mass? Does the concrete consolidate to the same extent as fully vibrated conventionally placed concrete? Does the concrete completely fill all corners of the formwork?)
    - Passing Ability (Does the concrete flow around reinforcement? Are there concentrations of aggregate behind reinforcing bars?)
    - Segregation Resistance (Is the concrete visually segregated as it is discharged from the transport equipment? Does the concrete remain uniform as it flows down the length of element? How far can the concrete flow laterally without segregating? Does the free fall drop cause segregation? After the concrete ceases flowing, are coarse aggregates present within the top 1 inch of the concrete?)
- Visual observations of formed surface finish
    - Is the formed surface finish comparable to or better than fully vibrated conventionally placed concrete?
    - Are there deficiencies such as excessive honeycombing, aggregate or mortar pockets, or surface air voids (bugholes)?

3.5 Quality Control (Production)

The producer should submit a detailed quality control plan as part of the work plan. This quality control plan should describe how the producer will ensure consistent quality for all batches by addressing the following:

- All pertinent specification requirements and target properties (workability and hardened properties).
- Production procedures and testing to ensure the initial batch of concrete is of adequate quality.
- Production procedures and testing to ensure that subsequent batches of concrete are of adequate quality.

The capabilities and qualifications of the producer to implement the quality control plan successfully should be evaluated by owner prior to the start of production. During production, owner should ensure the quality control plan is implemented fully. The quality control personnel designated by the precaster should have adequate experience with SCC. In addition to the specific requirements for SCC, the producer should use good general concreting practices.

The frequency of testing should be established by owner specifications or contract documents. Given the greater sensitivity of SCC workability to changes in materials and mixture proportions and the greater consequences of inadequate workability, workability tests during production should be performed with no less frequency for SCC than for conventionally placed concrete. At a minimum, all batches should be visually evaluated by qualified quality control personnel, who should be capable of deciding whether mixtures are acceptable and determining what measures should be taken to rectify non-performing mixtures. At a minimum, the visual observations should evaluate whether the concrete is sufficiently flowable and resistant to segregation. A certain minimum number of batches should be measured for slump flow and T_{50}

(e.g. first *X* batches and every subsequent Y^{th} batch). When starting production—with a new mixture, new materials, or different placement conditions—all batches should be tested for slump flow until satisfactory results can be obtained consistently. Other potential quality control measures include increased monitoring of moisture content and material properties, monitoring of mixer performance (amperage meter), and increased slump flow testing.

In addition, the quality control plan should address the frequency of testing of material characteristics, including aggregate grading and moisture content.

Concrete mixtures with slump flow, T_{50}, or both measurements outside the target range at the time of placement can be retempered, allowed to lose slump flow over time, or not used. If the slump flow is less than the target, the mixture can be retempered by adding HRWRA. If the slump flow is greater than the target, the mixture can be held until the slump flow is within the target or VMA can be added (subject to maximum dosage limits). If the T_{50} is too low, VMA can be added (subject to maximum dosage limits). Mixtures allowed to lose slump flow over time must be remixed prior to placement.

Appendix A: Glossary

Angularity (Aggregate): The sharpness of the corners and edges of a particle. (Shape describes a particle on the coarsest scale, angularity an intermediate scale, and texture the finest scale.) For SCC, the angularity characteristics of the aggregates and powder are relevant.

Filling Ability: The ability of concrete to flow under its own mass and completely fill formwork.

Passing Ability: The ability of concrete to flow through confined conditions, such as the narrow openings between reinforcing bars.

Paste Volume: The volume of water, air, and powder.

Plastic Viscosity: The resistance to flow once the yield stress is exceeded. Mixtures with high plastic viscosity are often described as "sticky" or "cohesive". Concrete with higher plastic viscosity takes longer to flow. It is closely related to T_{50} and v-funnel time (higher plastic viscosity $\rightarrow$ higher T_{50} and v-funnel time). It is computed as the slope of the shear stress versus shear rate plot from rheometer flow curve measurements.

Powder: Solid materials finer than approximately 75 μm (No. 200 sieve) including cement, supplementary cementitious materials (SCMs), and mineral fillers (e.g. finely ground limestone or other minerals and dust-of-fracture aggregate microfines). (There is not a discrete size for distinguishing solid materials that should be included in the powder; however, 75 μm is a reasonable and practical value.)

Rheology: The scientific study of flow. In the context of SCC, rheology refers to the evaluation and manipulation of yield stress, plastic viscosity, and thixotropy to achieve desired levels of filling ability, passing ability, and segregation resistance.

Robustness: The ability of concrete to maintain acceptable performance when variations occur in materials, mixture proportions, and other production variables.

Segregation Resistance: The ability of concrete to remain uniform in composition during placement and until setting. Segregation resistance encompasses both dynamic and static stability.

Self-Consolidating Concrete (SCC): An advanced type of concrete that at the time of placement can flow and consolidate under its own mass without vibration, pass through intricate geometrical configurations, and resist segregation.

Stability, Dynamic: The resistance to segregation when external energy is applied to concrete—namely during placement.

Stability, Static: The resistance to segregation when no external energy is applied to concrete—namely from immediately after placement and until setting.

Thixotropy: The reversible, time-dependent decrease in viscosity in a fluid subjected to shearing. For SCC, thixotropy is important for formwork pressure and segregation resistance.

Yield Stress: The amount of stress to initiate (static yield stress) or maintain (dynamic yield stress) flow. It is closely related to slump flow (lower yield stress → higher slump flow). It is calculated as the intercept of the shear stress versus shear rate plot from rheometer flow curve measurements.

Shape (Aggregate): The relative dimensions of a particle. Common descriptors of shape include flatness, elongation, and sphericity. (Shape describes a particle on the coarsest scale, texture the finest scale, and angularity an intermediate scale.) For SCC, the shape characteristics of the aggregates and powder are relevant.

Texture (Aggregate): The roughness of a particle on a scale smaller than that used for shape and angularity. (Shape describes a particle on the coarsest scale, texture the finest scale, and angularity an intermediate scale.) For SCC, the texture characteristics of the aggregates and powder are relevant.

Viscosity-Modifying Admixture (VMA): An admixture intended to mainly influence concrete viscosity in order to enhance the workability of the concrete. The exact effects of a VMA on viscosity can vary widely depending on the properties of the commercial VMA product.

Workability: The empirical description of concrete flow performance. For SCC, workability encompasses filling ability, passing ability, and segregation resistance. Workability is affected by rheology.

Workability Retention: The ability of a concrete mixture to retain workability properties over time.

Appendix B: Test Methods

The test methods described in this appendix are standardized by ASTM International; however, there are several important differences between the ASTM methods and those described in this appendix. It is strongly recommended that the test methods be conducted as described in this appendix.

Column Segregation Test – ASTM C 1610/C 1610M-06: “Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique”

J-Ring Test – ASTM C 1621/C1621M-06: “Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring”

Slump Flow Test – ASTM C 1611/C 1611M-05: “Standard Test Method for Slump-Flow of Self-Consolidating Concrete”

B.1 Column Segregation Test (Segregation Resistance)

Apparatus (Figure B.1)

1. PVC pipe sections, 8 inches in diameter, with seals and clips to accept clamps between top two sections (top and bottom sections 6.5 inches in height, middle section 13 inches in height)
2. Spring clamps (8)
3. Base plate (the bottom PVC pipe section is permanently attached to the base plate)
4. Collector plate
5. No. 4 sieve (at least 1, preferably 2)
6. Scoop or bucket to load concrete into column
7. Stopwatch
8. Drying containers or dishes, minimum 5 liters (2)
9. Oven or microwave
10. Balance

Concrete Volume

0.76 ft^3 (21.4 l)

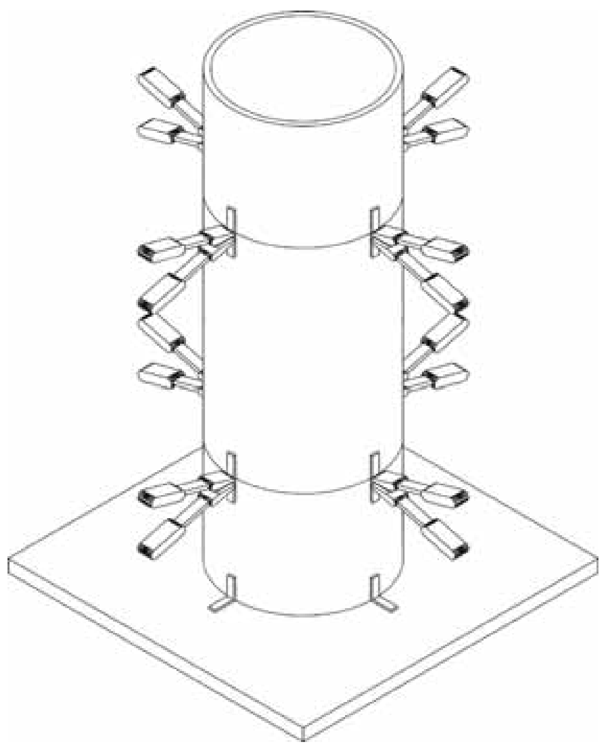


Figure B.1: Column Segregation Test (Collector Plate not Shown)

Procedure

1. Assemble the PVC pipe sections. Use the clamps to secure each PVC pipe section firmly and to ensure a water-tight seal.
2. Place the assembled apparatus on a firm, level surface.
3. Fill the column with concrete with no external compaction effort.
4. Allow the concrete to remain undisturbed for 15 minutes.

5. Use the collector plate to remove individually each PVC pipe section with the concrete material inside.
6. Individually transfer the contents of the top and bottom pipe section to separate No. 4 sieves. Discard the contents of the middle section. Wash each concrete sample over the No. 4 sieve to remove all paste and fine aggregate, leaving behind only clean coarse aggregates on each sieve.
7. Collect the coarse aggregates retained on each sieve in a separate container for each pipe section. Dry each sample in an oven or microwave until it reaches a constant mass.
8. **Measure** the mass of each sample of coarse aggregates.

Results

$$\text{Percent Static Segregation} = \begin{cases} \dfrac{M_{bottom} - M_{top}}{M_{bottom} + M_{top}} \times 100\% & \text{if } M_{bottom} > M_{top} \\ 0\% & \text{if } M_{bottom} < M_{top} \end{cases}$$

Where: M_{bottom} = mass of aggregate retained on No. 4 sieve from bottom pipe section
M_{top} = mass of aggregate retained on No. 4 sieve from top pipe section.

Notes

ASTM C 1610 allows aggregates to be dried to saturated-surface dry condition instead of oven-dried. In this case, towels are needed to dry surface moisture from aggregates.

B.2 J-Ring Test (Passing Ability)

Apparatus

1. J-ring (Figure B.2), 12-inch diameter with 16 equally spaced, 5/8-inch diameter smooth bars.
2. Rigid, non-absorbent plate, at least 32 inches square, with concentric circles marked at diameters of 100 mm (4 in.) and 300 mm (12 in.).
3. Slump cone (ASTM C 143)
4. Scoop or bucket to load concrete into slump cone
5. Measuring tape or ruler

Concrete Volume

0.20 ft^3 (5.6 l)

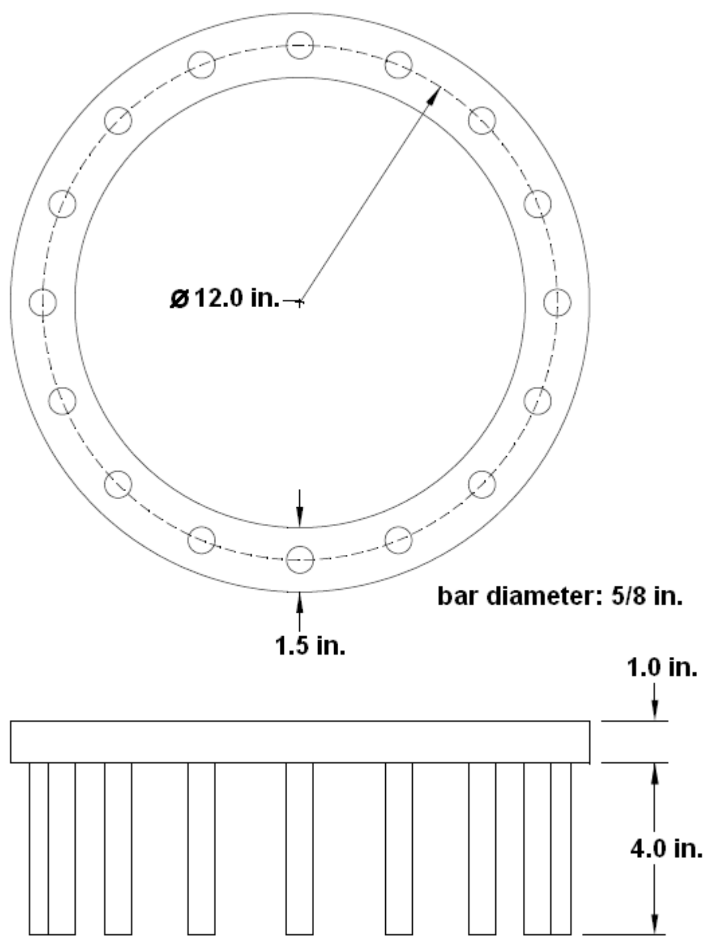


Figure B.2: J-Ring

Procedure

1. Dampen the slump cone and plate (ensure there is no standing water). Place the plate on firm, level ground. Center the j-ring on the plate (use the 12-inch concentric circle as a guide). Center the slump cone in the inverted position on the plate (use the 4-inch concentric circle as a guide) and hold down firmly.

2. Fill the slump cone with concrete. Do not apply any external compaction effort. Strike off any excess concrete above the top of the slump cone. Remove any spilled concrete on the plate.
3. Remove the slump cone by lifting it vertically upward, being careful not to apply any lateral or torsional motion. Allow the concrete to spread horizontally and cease flowing.
4. **Measure** the height of concrete inside the ring (H_{in}) and outside the ring (H_{out}) at four locations around the ring (See Figure B.3).

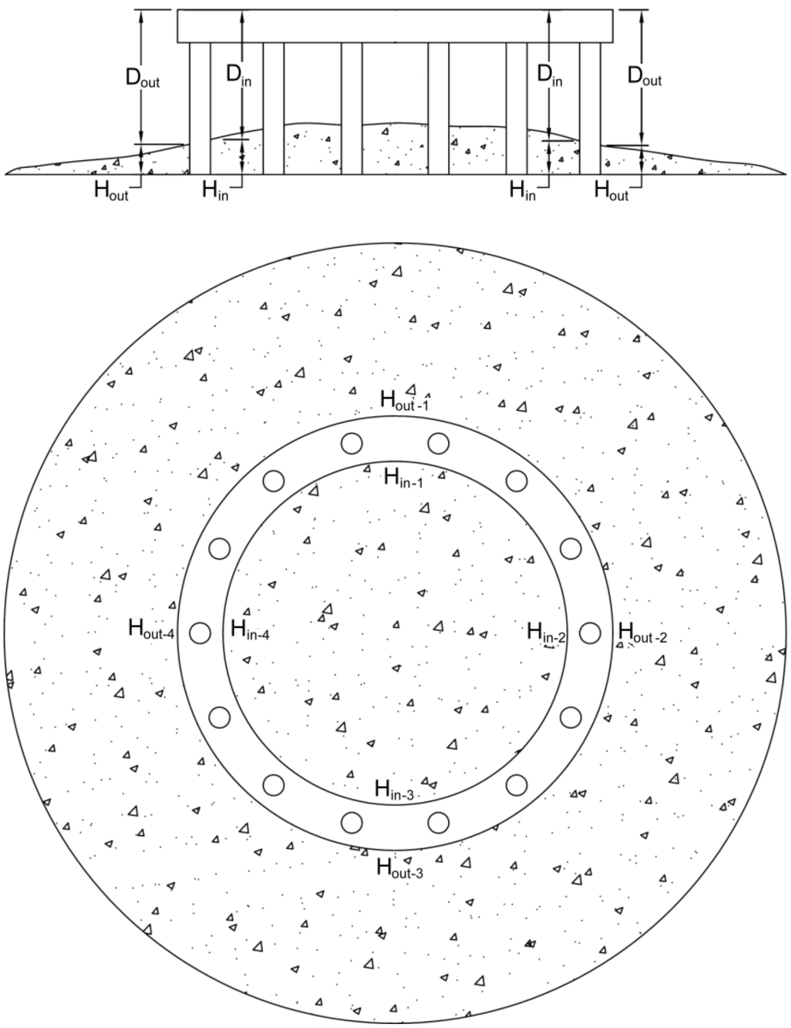


Figure B.3: J-Ring Measurement Locations

Results

J-ring Δheight = mean(H_{in}-H_{out}), in inches (to the nearest 1/8 inch)

B.3 Slump Flow Test (Filling Ability)

Apparatus

1. Rigid, non-absorbent plate (Figure B.4), at least 32 inches square, with concentric circles marked at diameters of 100 mm (4 in.) and 500 mm (20 in.)
2. Slump cone (ASTM C 143)
3. Scoop or bucket to load concrete into slump cone
4. Stopwatch
5. Measuring tape or ruler

Concrete Volume

0.20 ft^3 (5.6 l)

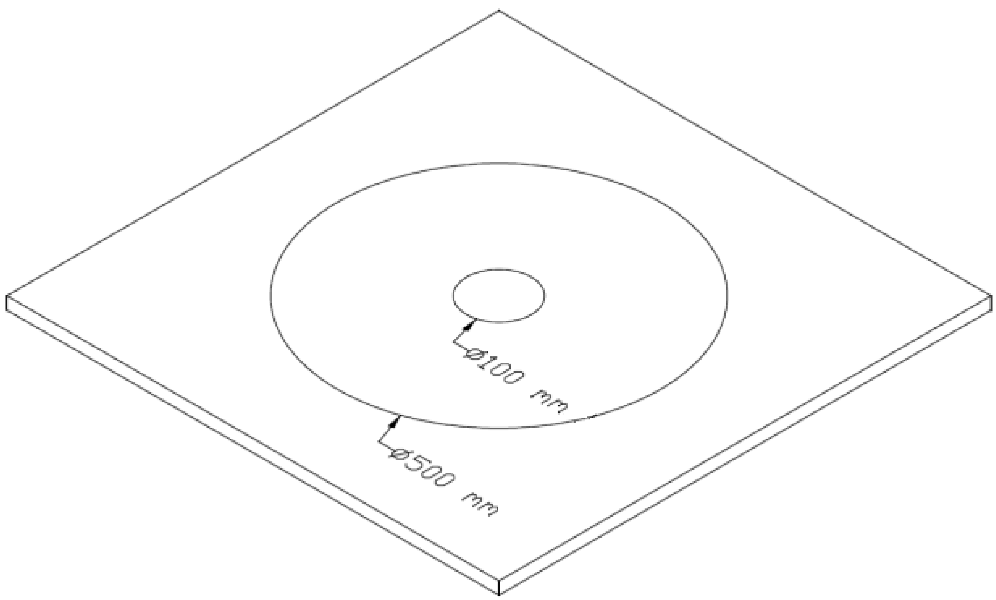


Figure B.4: Slump Flow Plate (500 mm = 20 in; 100 mm = 4 in)

Procedure

1. Dampen the slump cone and plate (ensure there is no standing water). Place the plate on firm, level ground. Center the slump cone in the inverted position on the plate (use the 4-inch concentric circle as a guide) and hold down firmly.
2. Fill the slump cone in one lift. Do not apply any external compaction effort. Strike off any excess concrete above the top of the slump cone. Remove any spilled concrete on the plate.
3. Remove the slump cone by lifting it vertically upward, being careful not to apply any lateral or torsional motion.
4. **Measure** the time for the concrete to spread to a diameter of 500 mm (T_{50})
5. **Measure** the final slump flow in two orthogonal directions after the concrete has ceased flowing.
6. **Assign** the visual stability index (VSI) to the nearest 0.5 based on the criteria in Table B.1.

Table B.1: Visual Stability Index Ratings (ASTM C 1611)

VSI	Criteria
0 = Highly Stable	No evidence of segregation or bleeding.
1 = Stable	No evidence of segregation and slight bleeding observed as a sheen on the concrete mass.
2 = Unstable	A slight mortar halo ≤ 0.5 in. and/or aggregate pile in the concrete mass.
3 = Highly Unstable	Clearly segregation by evidence of a large mortar halo > 0.5 in. and/or a large aggregate pile in the center of the concrete mass.

Results

1. Average slump flow, in inches (to the nearest ½ inch)
2. T_{50}, in seconds (to the nearest 0.1 s)
3. Visual stability index (to the nearest 0.5)

Notes

It is important that the slump flow test be conducted on a flat, level surface. The slump cone should be used in the inverted orientation, which makes it easier to fill the cone and increases the precision of the T_{50} measurement. The cone should be lifted in a consistent manner for each test.