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16. Abstract

Cast-in-drilled-hole (CIDH) concrete piles placed using the slurry displacement method require 2-inch (50 mm) inspection pipes be placed parallel to the longitudinal reinforcement. While these pipes are used to detect voids, the inspection pipes may also cause voids due to the limited spacing between the longitudinal reinforcing bars and the inspection pipe. The minimum specified spacing per Caltrans between the longitudinal reinforcing bars and the inspection pipe is 3 inches, which violates the bridge design specifications (BDS) for maximum reinforcement spacing. A separate effort has assessed the structural performance of CIDH piles with varying reinforcing bar spacing. This research will assess critical parameters of concrete to minimize voids in CIDH piles, including the influence of aggregate type and mixture proportions on concrete workability (i.e. flowability, stability, and passing ability). Results from this work indicate that increasing the paste volume and decreasing the voids in the aggregate can significantly increase slump flow. Concrete containing round coarse aggregate can also achieve higher slump flow values than concrete containing crushed coarse aggregate at the same paste volume. While initial results indicate the C-bar and J-ring test both seem to be reasonable approaches for assessing passing ability in the field, further work is needed. Based on the findings of this research, a methodology for proportioning mixtures was developed that provides adequate flowability, stability, and passing ability to minimize or eliminate voids in CIDH piles.

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The Kiewit Center for Infrastructure and Transportation

Assessing Highly Workable Concrete Mixtures for CIDH Pile Applications

by

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The United States Government and the State of California do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report.

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EXECUTIVE SUMMARY

Cast-in-drilled-hole (CIDH) concrete piles that are placed using the slurry displacement method are required to have 2-inch (50 mm) inspection pipes in place that are used to detect voids. However, the inspection pipes may cause voids due to the small spacing between the longitudinal reinforcing bars and the inspection pipe. The bridge design specifications (BDS) require a minimum reinforcing bar spacing of 8 inches (203 mm) center-to-center. The California Test 233 (2005), page 4, line 10 reports the minimum spacing between the longitudinal reinforcing bars and the inspection pipe is 3 inches (76 mm). If contractors are to maintain this clear spacing they must space the reinforcing bars in a manner that violates the BDS. The different specifications are conflicting.

Research is underway to assess the potential structural issues from varying reinforcing bar spacing. This research assesses the potential to place concrete to minimize void in CIDH piles. If voids or cavities form during the CIDH concrete pile placement, the repair or replacement costs could be significant. Schedule delays could also result. This research assesses the influence of aggregate type and mixture proportions on concrete workability (i.e. flowability, stability, and passing ability) for concretes used for CIDH pile applications. Creating a mixture with adequate flowability, stability, and passing ability can aid in achieving void free concrete for CIDH pile applications. Understanding the mixture proportions that influence these workability characteristics can aid in achieving highly workable (HW) concrete.

To better understand how mixture proportions influence workability mixture proportions were varied in this research. The mixture proportions varied for this research included the paste volume and fine to coarse aggregate ratio (FA/CA) for two 3/8-inch (9.5 mm) maximum size coarse aggregate types (crushed and round). A single fine aggregate was used throughout the study. The two coarse aggregates differ in shape and texture but have similar specific gravities and absorption values. Therefore, a comparison of the two aggregate types could be performed.

For this research slump flow and the K-slump tester are intended to assess flowability; the visual stability index and visual blocking index are intended to assess stability; and the L-box, J-ring, and C-bar test are intended to assess passing ability. In addition, different test configurations for J-ring and C-bar tests were evaluated to assess the influence of test configuration on the sensitivity of test results.

Based on the test results, increasing the paste volume and decreasing the voids in the combined fine and coarse aggregate can significantly increase slump flow. The round coarse aggregate can achieve higher slump flow values than the crushed coarse aggregate at the same paste volume. Increasing the paste volume can decrease stability and increasing the FA/CA can increase stability. The results for the influence of mixture proportions on standard J-ring and C-bar tests were unclear. The influence of paste volume on L-box test results showed an increase in L-box passing ability as paste volume increased. Although no recommendations for J-ring or C-bar configuration were identified, both the J-ring or C-bar tests are likely adequate to assess passing ability. The reinforcing bar clear spacing that is less than the clear spacing in the field could be used to conservatively assess the concrete’s passing ability.

1. INTRODUCTION

1.1. BACKGROUND AND PROBLEM STATEMENT

When ground water is present, cast-in-drilled-hole (CIDH) concrete piles are required to have a diameter of 2 feet (610 mm) or greater and be constructed using the slurry displacement method. The slurry displacement method involves introducing slurry (e.g., bentonite) into the drilled hole to prevent the hole from collapsing under the hydraulic pressure of the ground water. Also 2-inch (50 mm) polyvinyl chloride (PVC) inspection pipes are required to be placed along the circumference of the pile. One inspection pipe is required for every 1 foot (305 mm) of pile diameter. The inspection pipes are required so that a gamma-gamma logging device can be inserted into the pipe to detect homogeneity of the concrete density. Reduction in concrete density would indicate voids or cavities are present. Voids and/or cavities can affect the structural integrity of the piles.

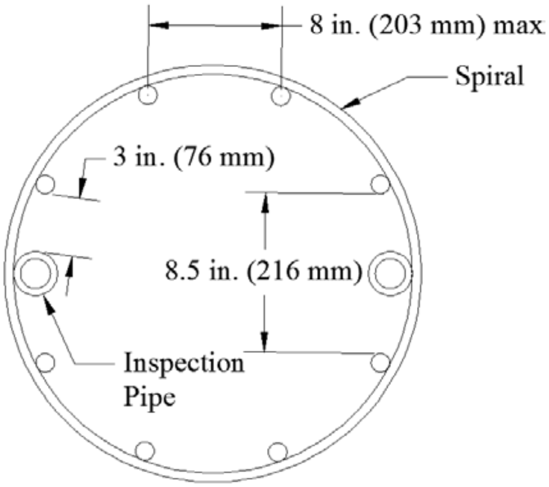

Figure 1.1. CIDH Pile Plan View

The California Department of Transportation (Caltrans) specifies that inspection pipes be placed in the pile with a clear spacing of 3 inches (76 mm) between the longitudinal reinforcement and the pipe (a typical CIDH pile layout is shown in Figure 1.1). To maintain this clear spacing the adjacent longitudinal bars must have a clear spacing of 8.5 (216 mm). This spacing violates the Bridge Design Specifications (BDS) of a maximum center-to-center spacing of 8 inches (203 mm). As a result of these specifications, the contractor constructing these CIDH piles is forced to violate either the minimum 3-inch (76 mm) clear spacing or the maximum center-to-center spacing of the longitudinal reinforcement.

Research is needed to better understand the factors that impact the fresh characteristics of concrete and a concretes ability to flow though different reinforcement spacing's, especially for highly workable (HW) concretes for CIDH pile applications. Understanding the influence of concrete mixture proportions and aggregate type that influence the fresh characteristics could aid highway agencies and contractors in achieving void free concrete in CIDH piles. Properly assessing these factors is critical to minimizing the potential of voids or cavities in CIDH piles. This research assessed the influence of aggregate type and mixture proportions on concrete workability. For the purpose of this research, workability is defined as the flowability, stability, and passing ability of a concrete mixture. In addition, this research evaluated different testing methods to assess the workability of concrete.

1.2. RESEARCH OBJECTIVES AND SCOPE

The objectives of this research are as follows:

1. Assess the influence of coarse aggregate type and mixture proportions on workability;
2. Assess the influence of the test configuration on the sensitivity of results;
3. Provide guidance on mixture proportioning that can meet the workability test requirements.

1.3. REPORT OUTLINE

This report consists of 6 chapters. Chapter 2 includes a literature review of concrete fresh characteristics, workability test methods, the influence of constituent materials on workability, and the influence of mixture proportions on workability. Chapter 3 provides an experimental plan, a description of the materials used, and the methods of testing. Chapter 4 presents the experimental results of the assessment on the workability of HW mixtures and the influence of test configurations on sensitivity of results. Chapter 5 presents a mixture proportioning process for HW concrete mixtures. Chapter 6 provides conclusions and recommendations.

2. LITERATURE REVIEW

2.1. INTRODUCTION

This chapter reviews and summarizes the literature relevant to the workability and rheology of concrete. This literature review focuses on the following four topics that are applicable to highly workable mixtures used for CIDH piles: the basic principles of concrete workability, the test methods used to assess workability, the influence of constituent materials on concrete workability, and the influence of material proportions on workability.

2.2. FRESH CHARACTERISTICS: BASIC PRINCIPLES

Concrete is a complex system of various constituent materials having a wide range of varying material characteristics. Ferraris (1999) reported that concrete is a concentrated suspension of solid particles in a viscous liquid or, more specifically, aggregate suspended in paste. Paste is a concentration of suspended cement grains in water (Ferraris 1999). For this complex system to be effectively placed in a reinforced concrete structure the material must maintain homogeneity and flow around the reinforcement, developing a composite system with the embedded reinforcement. Ideally, an effectively placed concrete would produce a hardened structure containing no voids or cavities.

A HW concrete mixture typically has a higher paste volume than conventional concrete. Higher paste contents are needed to convey aggregates and improve flowability. However, the increased paste must have adequate viscosity to uniformly suspend the aggregates (Koehler and Fowler 2006). Maintaining adequate paste viscosity can be a challenge because water content can vary in concrete mixtures throughout the batching, mixing, transportation, and placement process. Variations in water content can be caused by wash water in a truck mixer drum from the previous concrete loads; the batched water can be out of tolerance; an error can occur in estimating aggregate moisture contents; water can be added at the job site to increase slump; and a variety of other factors can change the water content in a concrete mixture (Obla and Lobo 2011). Changes in water content change the water-to-cementitious material ratio (*w/cm*) and can change viscosity, which can result in a heterogeneous mixture (El-Chabib and Nehdi 2006). Because concrete is a complex and variable system, it can be sensitive to segregation at increased paste volumes and can be sensitive to loss of workability. Therefore, it is important to monitor and assess concrete workability characteristics, especially for HW mixtures, before it is placed.

Workability is defined as the flowability, stability, and passing ability of a concrete mixture. Flowability is the ability of concrete to flow under its own weight without mechanical consolidation. Stability is the ability of concrete to flow and set in a homogeneous manner without separation of the aggregate from the paste and without excessive bleeding. Passing ability is the ability of concrete to flow freely through narrow spaces. Having adequate workability requires having adequate flowability, stability, and passing ability. Adequate workability can vary depending on the application. For CIDH applications, high workability is required and workability may have to be measured more frequently. Currently Caltrans Specifications (2010) requires contractors to produce a test batch (Section 49-3.02A(4)(c)) that must achieve the minimum required slump greater than 7 inches (178 mm) before placing concrete using the slurry displacement method. This is performed one time before concrete placement but this requirement may not be sufficient. Flowability, stability, and passing ability may need to be assessed throughout concrete placement..

To ensure HW concrete mixtures for CIDH applications have adequate workability it is important to identify a simple test or a suite of tests to measure a concrete's workability characteristics. Modeling concrete workability has been the subject of much research and the complexities of developing a simple test to characterize concrete workability is the focus of active research (Tattersall 1991, Wong and Kwan 2008, Chidiac and Mahmoodzadeh 2013). The American Concrete Institute (ACI) Committee 238 (2008) reported that hundreds of tests have been developed to assess concrete workability characteristics. However, no single test was reported to measure all aspects of workability. Also, the workability tests ranged in capabilities and effectiveness in measuring concrete workability characteristics.

Measuring and characterizing workability can be accomplished with several different tests, ranging from simple to highly complex. According to Tattersall (1991) there are three different categories or classes of terms used to characterize concrete workability. These classes and the associated terminology are shown in Table 2.1. Class I, qualitative (Q) descriptors of concrete workability, are used to provide a generalized qualitative description of concrete workability without providing a quantitative measure of the workability characteristics. Class II, quantitative empirical (QE) descriptors, assess the workability of concrete with simple tests that are commonly used in the field. QE tests are relatively fast, simple, and inexpensive to conduct but typically do not assess the basic physical characteristics of concrete workability. Class III quantitative fundamental (QF) tests assess fundamental physical characteristics of the concrete that are inherent to the concrete materials.

Table 2.1. Classes of Workability Terminology (Tattersall 1991).

Class	Terminology	Use
I – Qualitative (Q)	Workability, flowability, compactibility, stability, pumpability, consistency	To be used in a general descriptive way without any attempt to quantify
II – Quantitative Empirical (QE)	Slump, compacting factor, Vebe time, flow table spread	To be used as a simple quantitative statement of behavior in a particular set of circumstances
III – Quantitative Fundamental (QF)	Viscosity, mobility, fluidity, yield stress	To be used strictly in conformity with the definitions in the British Standards Glossary

Tests used to measure QF characteristics are often performed in specialized laboratories because the equipment used to measure these characteristics is relatively expensive and impractical to use in the field (Koehler and Fowler 2003). An example of a QF laboratory rheometer (used to measure QF characteristics) is shown in Figure 2.1. The QF characteristics of concrete are known as rheological characteristics of concrete.

Figure 2.1. Laboratory Rheometer (Banfill et al. 2000)

Rheology is defined as the theory of deformation and flow of matter (Irgens 2014). In rheological terms, fresh concrete flow behaves as a viscoplastic material. A viscoplastic material behaves as a solid when an applied stress is less than the yield stress and behaves as a fluid when the applied stress is greater than the yield stress. Figure 2.2 shows the typical viscoplastic flow behavior of concrete represented by the Bingham model. This model is known as a shear flow curve and displays the shear stress behavior of concrete with respect to shear rate. From the shear flow curve two concrete characteristics used to describe workability can be determined: yield stress and plastic viscosity. The yield stress represented in the Bingham shear flow curve is the intersection point on the shear stress axis and the plastic viscosity is the slope. The yield stress is the stress required to cause a viscoplastic material to flow. Plastic viscosity, in general, represents the resistance of a liquid to flow once flow is initiated (Hackley and Ferraris 2001). Using yield stress and plastic viscosity to describe concrete properties can provide a description of a mixture's flowability and stability. In general, if the yield stress is near zero concrete can flow under its own mass. However, if the yield stress is too low then segregation can occur. Plastic viscosity should also be low enough to allow an optimal rate of flow but adequately high for stability of the concrete mixture (Koehler and Fowler 2007).

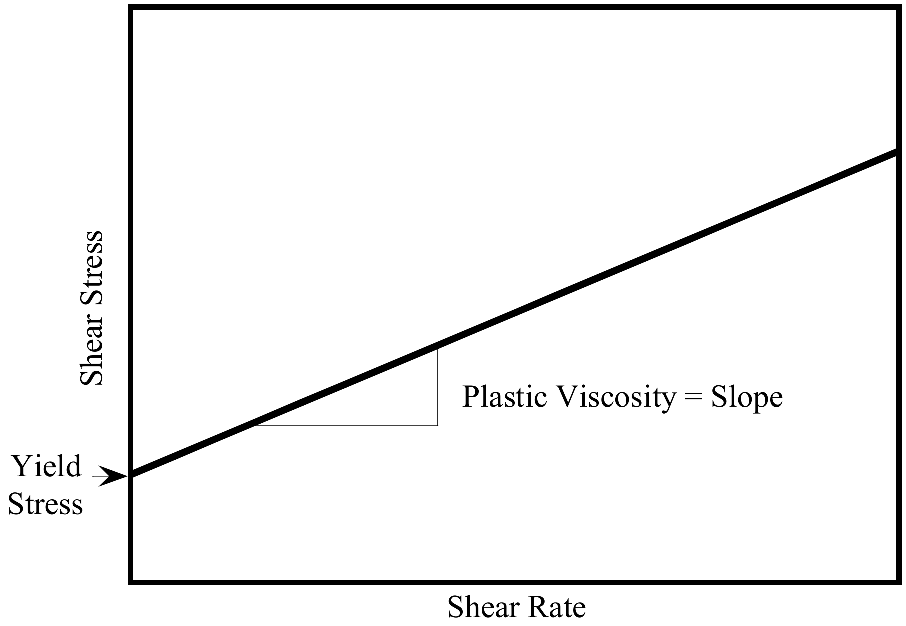

Figure 2.2. Bingham Model Used to Characterize Concrete Flow

Constitutive equations can be created to model concrete flow behavior based on the shear stress and shear rate relationship. The most widely used model for assessing concrete behavior is the Bingham model (Ferraris 1999). The Bingham model is as follows:

$$\tau = \tau_0 + (n) \times (\dot{\gamma}) \tag{2.1}$$

where τ = shear stress (force/area), τ_0= yield stress (force/area), n = plastic viscosity ((force/area) × time), and $\dot{\gamma}$ = shear rate (1/time). However, the Bingham model does not apply to all concrete. For instance, certain self-consolidating concretes (SCC) have exhibited behavior that is best modeled with the Herschel-Bulkley model (Ferraris et al. 2001). This model characterizes concrete mixtures as shear thinning or thickening. Shear thinning is a decrease in viscosity with increasing shear rate during steady flow and shear thickening is an increase in viscosity with increasing shear rate (ACI 238 2008). The Herschel-Bulkley model is as follows:

$$\tau = \tau_0 + (n) \times (\dot{\gamma}^a) \qquad (2.2)$$

where τ, τ_0, n, and $\dot{\gamma}$ were defined previously and a is a constant. The variable a is not a physical characteristic of the concrete but an empirical value determined to best fit the data to the equation. If a is less than 1 then shear thickening occurs. If a is greater than 1 then shear thinning occurs. If a is equal to 1, the Herschel-Bulkley model becomes the Bingham model. Shear flow curves for the Bingham and Herschel-Bulkley models are shown in Figure 2.3. Note that the Herschel-Bulkley model does not have a constant slope that can be used for calculating a single plastic viscosity value. Note that the yield stress is typically near zero for the Herschel-Bulkley model because concretes represented with this model typically exhibit high flow.

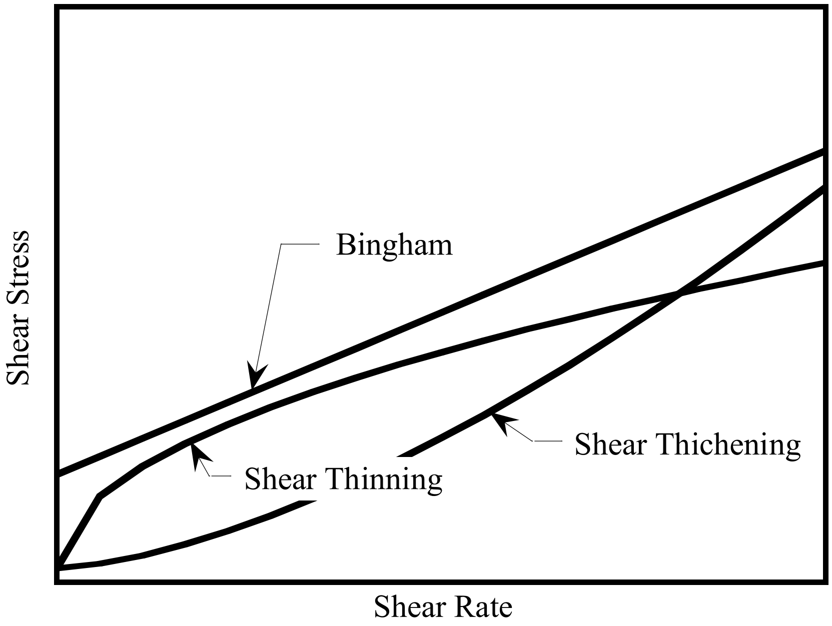

Figure 2.3. Shear Stress versus Shear Rate for Typical Models

Rheology test methods can provide a more complete description of concrete workability. However, until these tests become more economical and easier to use, common QE tests will likely continue to be used to assess workability. Although sometimes limited, these QE tests can provide a description for certain rheological characteristics.

2.3. QUANTITATIVE EMPIRICAL TEST METHODS TO ASSESS WORKABILITY

The effectiveness of QE workability tests to assess the fresh characteristics of concrete is reviewed. QE tests are reviewed to determine the suitability of these tests for evaluating the workability of HW mixtures for CIDH pile applications. These workability tests are designed to measure specific characteristics of workability (i.e., flowability, stability, and/or passing ability). The workability tests methods assessed as part of this literature review include slump flow, a K-slump tester, a J-ring test, and an L-box test. It should also be noted that this research investigated a new C-bar test but because this test is new, no information is available in the literature on the performance of this test.

2.3.1. Slump Flow

The American Society for Testing and Materials (ASTM) C1611-09 *Standard Test Method for Slump Flow of Self-Consolidating Concrete* is the most widely used method to assess the workability of SCC, but this test has also been used to assess other highly flowable concretes (ACI 238.1R-08 2008). This test is performed with a slump cone placed on a rigid, nonabsorbent surface and filled with concrete. The cone is then lifted and the slump flow diameter is measured in two perpendicular directions. The average of these perpendicular measurements is the slump flow. Koehler and Fowler (2009) reported that the slump flow diameter measurement is suitable to assess a concrete's flowability. In terms of rheological characteristics, slump flow has also been correlated to yield stress (Paisley University 2005, Nehdi and Al-Martini 2009). An example of a highly flowable concrete slump flow is shown in Figure 2.4.

Figure 2.4. Highly Flowable Concrete Slump Flow

The ASTM C1611-09 standard includes non-mandatory measurements of the T50 and visual stability index (VSI). The T50 test measures the time it takes for a slump flow to reach 20 inches (500 mm) from the time the cone is lifted. The T50 test has been shown to provide an indication of the concrete viscosity (Koehler and Fowler 2009). The VSI test is used to qualitatively assess the stability of a concrete mixture. The criteria used in the VSI rating system are shown in Table 2-1. A concrete mixture must have a VSI of 1 or less to be considered stable (ASTM C1611-09). In the field a visual assessment of concrete slump flow can provide a suitable assessment of a concrete's performance (University of Paisley 2005). However, Koehler and Fowler (2008) and Khayat et al. (2004) reported that stability should be assessed quantitatively in the laboratory or in the field before being assessed with the VSI test. The University of Paisley (2005) reported that a sieve stability test is a relatively simple and repeatable test that can be used to quantitatively measure the stability of concrete. The sieve stability method measures stability as the percent weight of mortar from concrete that has passed through a No. 4 sieve.

Table 2-1. Visual Stability Index Ratings (ASTM C1611-09)

VSI Value	Stability	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 inches (≤ 10 mm) and/or aggregate pile in the concrete mass.
3	Highly unstable	Clearly segregating by evidence of a large mortar halo > 0.5 inches (> 10 mm) and/or large pile in the center of the concrete mass.

2.3.2. K-Slump Tester

The K-slump tester is a device that is intended to measure nominal slump and a give a general description of concrete workability. The K-slump tester is shown in Figure 2.5. It consists of a hollow tube with a point on one end and a free moving plunger (measuring rod) inserted into the other end. A flat disc around the hollow tube is in place to indicate the proper depth to insert the K-slump tester into concrete. The holes and slots along the side of the tube allow concrete to flow into the tube. However, the holes and slots do not allow aggregate larger than 3/8 inches (9.5 mm) to enter. The K-slump tester is reported to not be appropriate for low slump concrete (ACI 238.1R-08 2008).

The K-slump tester is operated by inserting the pointed end of the device into concrete and waiting a minute before the plunger is lowered to rest on the concrete. Then a measurement value (K) is read off of the plunger. This K reading is intended to be an estimate of the nominal slump. The K-slump tester is then removed vertically from the concrete and a measurement of the workability (W) is reported from the plunger resting on the remaining concrete in the hollow tube. This W reading is a general description of the workability and compatibility of the concrete. The manufacturer recommends an upper limit of 2.0 be placed on the difference between the K and W values. This limit is recommended to minimize segregation (K-Slump Tester HM-65 2011).

Figure 2.5. K-Slump Tester (K-Slump Tester HM-65 2011)

The K-slump tester is a simple and relatively fast test that can be performed on cast-in-place concrete. Also, K and W are intended to provide more information on the workability than just the ordinary slump (ACI 238.1R-08 2008). However, Ferraris (1999) reported that the K-slump test results exhibit a high scatter when correlated with nominal slump. Also the test does not account for large aggregate and low slump mixtures (ACI 238.1R-08 2008).

2.3.3. J-Ring Test

The J-ring test (ASTM 1621-09) is intended to assess a concretes passing ability. The J-ring test consists of a ring of reinforcement as shown in Figure 2.6. The test is performed by placing a slump cone in the center of the J-ring, filling the cone with concrete, and lifting the cone to allow concrete to flow through the J-ring. Following lifting the cone, the diameter of the concrete flow is measured in two perpendicular directions. The average of these two measurements is known as the J-ring flow. The passing ability is determined by measuring the difference between the slump flow without the J-ring and the slump flow with the J-ring. The ASTM 1621-09 reports that a J-ring passing ability measurement equal to 2 inches (50 mm) or less has adequate passing ability. Koehler and Fowler (2009) reported that this measurement can be misleading and that other measurements should also be performed. Koehler and Fowler (2009) also report that passing ability should be measured as the difference in height of concrete directly outside and inside the J-ring circumference in four equally spaced locations. Researchers from the UK recommend that the average difference in height be equal to or less than 3/8 inches (10 mm) (University of Paisley 2005).

Daczko (2003) reported that a visual blocking index (VBI) rating system could be used in conjunction with the passing ability measurement to give a qualitative description of the concretes passing ability and stability. The VBI rating system is shown in Table 2-2. Researchers in the UK reported that a visual assessment, similar to the VBI, incorporated into the J-ring test could be a useful tool (University of Paisley 2005). These researchers also reported that the J-ring test is a suitable test to assess passing ability and that this test method was preferred over the L-box test (described next) because the L-box is difficult to clean and provides less of a visual assessment.

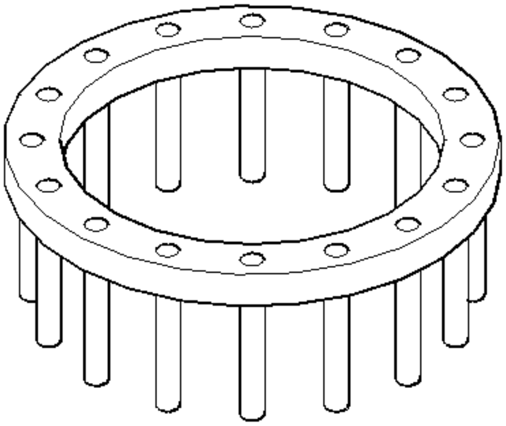

Figure 2.6. General Layout of J-Ring Test

Table 2-2. Visual Blocking Index Rating (Daczko 2003)

VBI	Description
0	No Evidence of blocking resulting in a pile of aggregate in the middle of patty and no evidence of bleed streaking behind the reinforcement obstacles.
1	A slight pile of coarse aggregate in the middle of the patty and slight evidence of bleed streaking behind the reinforcement obstacles.
2	A clear pile of coarse aggregate in the middle of the patty and significant bleed streaking.
3	Significant blocking of aggregate behind the reinforcement obstacles which will usually result in a significant decrease in flow value.

2.3.4. L-Box Test

The L-box test is intended to measure the passing ability of a concrete mixture. The L-box consists of a vertical section and a horizontal section as shown in Figure 2.7. The horizontal and vertical sections are separated by a movable gate and three vertical reinforcing bars evenly spaced in front of the gate. The vertical box is filled with concrete and left to rest for 1 minute. The gate is then lifted and the concrete is allowed to flow through the bars and into the horizontal section. The mean depth of concrete is then measured in the ends of the vertical (H1) and horizontal (H2) sections. The passing ability ratio is measured as the ratio of H2 to H1. A concrete mixture must have a passing ability ratio of at least 0.8 or greater to be considered passing (University of Paisley 2005). Koehler and Fowler (2009) reported that the L-box test did not provide well-defined passing ability results because both flowability and passing ability must be adequate to meet the L-box passing requirements. This means that the L-box does not measure only the concretes passing ability because concrete must also have high flowability to adequately flow the length of the horizontal section and meet the L-box passing requirements.

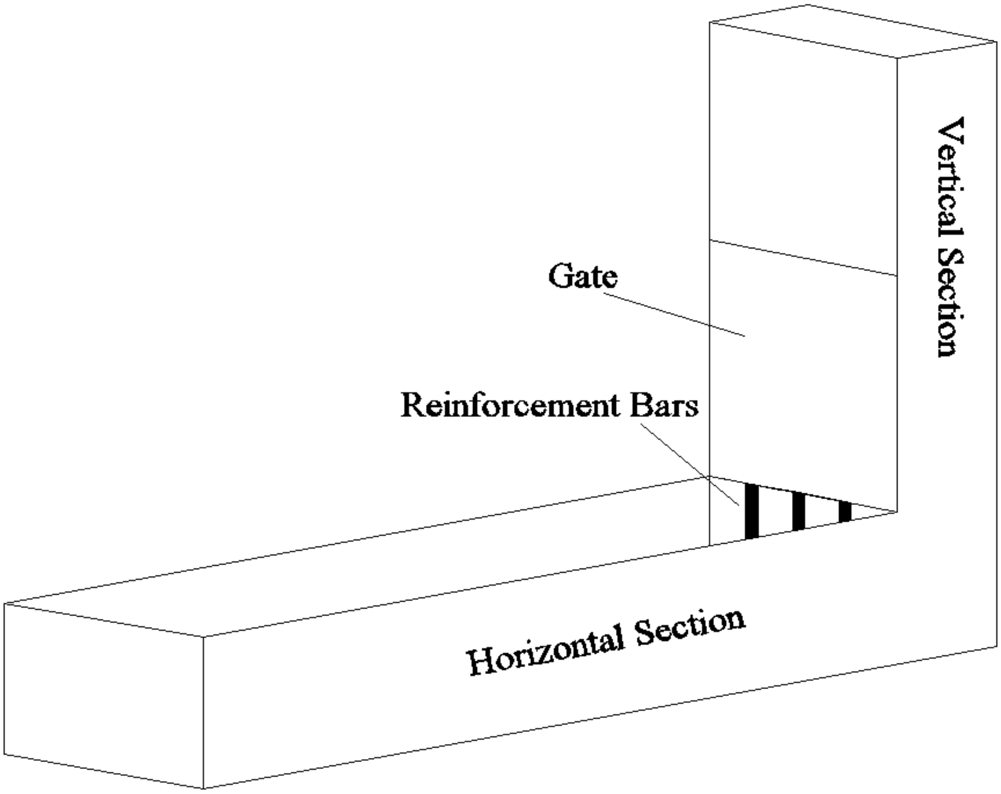

Figure 2.7.Configuration of L-Box

2.3.5. C-Bar Test

The C-bar test is intended to assess the passing ability of concrete. The C-bar test consists of a 14-inch (356 mm) diameter ring with six attached reinforcing bars and two

PVC pipes as shown in Figure 2.8. To perform this test a slump cone is placed in the center of the ring, filled with concrete, and lifted to allow the concrete to flow through the reinforcement and PVC pipes. The radii of the concrete flows are measured in the direction parallel to the PVC pipes (Y direction) and the direction perpendicular to the pipes (X direction). The preliminary standard specifies that all radii measurements must be greater than 9 inches (230 mm) for a concrete mixture to prequalify for this test.The effective flow (X' and Y') is then determined by subtracting the ring diameter (14 inches (356 mm)) from the diameter of the X and Y concrete flow values. The passing ability ratio is then determined by dividing X' by Y'. If the passing ability is greater than 1.67, then the concrete is considered to have adequate passing ability. If the passing ability ratio is between 1.67 and 2.0 the concrete is questionable (i.e., it may or may not exhibit adequate passing ability). If the passing ability is less than 2.0 then the concrete is unacceptable. Because this test is new, there is no literature regarding the suitability of this test to assess passing ability. Further research is needed.

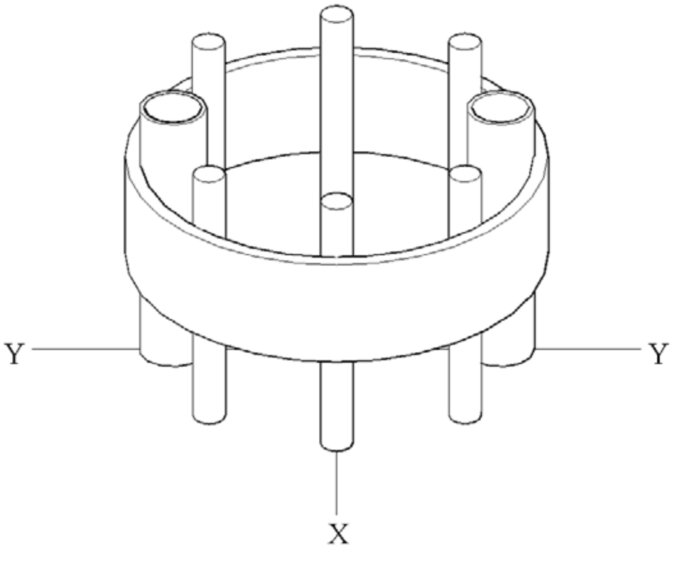

Figure 2.8. General Layout of C-Bar Test

2.3.6. Summary

Each QE workability test has advantages and disadvantages in terms of the test's suitability to measure certain characteristics of concrete workability (i.e., flowability, stability, and/or passing ability). Typically, workability tests are assessed in research regarding SCC. Research regarding SCC is paving the way and setting the foundation for other workability research. The suitability of these QE tests (J-ring, L-box, slump flow, and VSI) to assess SCC workability has been widely researched. These tests could be useful for assessing HW concrete workability. The suitability of these QE tests to assess the workability characterizes of HW concrete mixtures is an area that needs further research.

2.4. INFLUENCE OF CONSTITUENT MATERIAL CHARACTERISTICS ON CONCRETE WORKABILITY

The literature regarding material characteristics and how these may influence workability is presented in this section. This literature review includes a review of aggregate characteristics, cementitious and supplementary material type, and chemical admixture type and how these influence workability.

2.4.1. Aggregates

The coarse and fine aggregate characteristics can have a significant impact on concrete workability. These characteristics also influence mixture proportions which can influence workability. The aggregate characteristics reviewed here include the maximum size aggregate (MSA), gradation, shape, and texture.

Typically, the first aggregate characteristic to be selected for a concrete mixture is the MSA. The MSA is selected based on reinforcement spacing, availability, economy, and specifications. MSA values specified by Caltrans for CIDH concrete piles placed under slurry require 3/8 or 1/2-inch (9.5 mm or 12.5 mm) only (Caltrans 2010). No reasoning is provided on when one size should be used instead of the other. Hudson (2003) reported that the larger particle sizes reduce paste requirements because aggregate surface areas decreases with larger particle sizes. Required paste content is directly related to aggregate surface area. However, the maximum particle size must be decreased when passing ability is critical and clearance is minimal. Also, concretes containing aggregates with higher MSA's tend to have lower viscosities and have a higher risk of segregation (Bui and Montgomery 1999). Even so, for every MSA there is a range of acceptable gradations that are specified in the ASTM C33-13 *Standard for Concrete Aggregates*. Some state highway agencies (SHAs) also specify acceptable gradations for different MSAs (Caltrans 2010, Texas Department of Transportation 2004, Missouri Department of Transportation 2011, Oregon Department of Transportation 2008, New York Department of Transportation 2008).

It has been reported that the objective of the wide range of gradation specifications in ASTM C33-13 are to accommodate for availability of aggregate in different regions and to allow for the economical production of concrete (Graves 2006). However, the aggregate gradation can have significant influence on workability. The influence of gradation on workability has been the focus of much research (Shilstone 1990, Quiroga and Fowler 2004, Obla et al. 2007a, Obla et al. 2007b, Hahn et al. 2008). Shilstone (1990) reported that past versions of ASTM C33 placed regulations on coarse and fine aggregates individually and that aggregates complying with ASTM C33 could produce a gap-graded aggregate mixture. Gap-graded aggregates used in concrete can produce challenges with segregation, bleeding, and could result in unsatisfactory finishing characteristics. Uniformly graded aggregate mixtures tend to not have these challenges (Richardson 2005). Currently, the ASTM C33 standard allows for coarse and fine aggregate gradations to be assessed in combination to produce uniformly graded aggregate mixtures.

The combination or mixture of coarse and fine aggregate gradations can be optimized to satisfy a variety of objectives, such as slump requirements, aggregate packing density, aggregate gradation uniformity, or plastic viscosity (Quiroga and Fowler 2004). The aggregate packing density is a measure of the ratio of the solid aggregate volume to the bulk volume occupied by the aggregate. The packing density is a measure of the amount of voids in the aggregate mixture. Paste must fill these voids for the concrete to flow. In fact, to achieve adequate flow additional paste (beyond the measured minimum void content) is necessary to separate and provide lubrication between the aggregates. It is generally accepted that if the packing density is maximized (minimum voids), then a minimum paste content is required to produce a given slump.

There are different reports on the optimum gradation and maximum packing density required to produce a concrete mixture with minimal paste and adequate workability. Quiroga and Fowler (2004) reported that maximizing the packing density is an important parameter but may not result in optimal workability. Quiroga and Fowler (2004) reported that producing concrete mixtures with maximum aggregate packing densities (minimum void content) could result in concrete being prone to segregation. The authors also reported that segregation is thought to be due to a lack of fine aggregates in these concrete mixtures. Gap-graded mixtures can produce aggregate mixtures with relatively high packing densities but can also be susceptible to segregation (Koehler and Fowler 2007). Quiroga and Fowler (2004) and Shilstone (1990) reported that with a uniformly graded aggregate mixture and relatively high packing density is needed to produce concrete mixtures with adequate workability at minimum paste contents.

Shilstone (1990) reported that a uniform gradation can be achieved by using a volumetric individual percent retained plot, a coarseness factor chart, or a 0.45 power gradation plot. Obla et al. (2007a) noted that Shilstone's methods are useful tools to determine the proportion of fine and coarse aggregate but these methods do not necessarily yield a maximum aggregate packing density. Obla et al. (2007b) reported that proportioning aggregate using the ACI 211 procedure can also produce high packing densities and adequate workability characteristics.

The ACI 211 aggregate proportioning procedure uses the fineness modulus of sand and the dry rodded unit weight (DRUW) of the coarse aggregate to determine the proportions of the fine and coarse aggregates. Obla et al. (2007b) reported that gradation is an important factor because it is necessary to have adequate fine material to prevent segregation and high bleeding. The authors also explained that too much fine materials can produce a sticky mix that is difficult to finish. Goltermann et al. (1997) reported that concrete mixtures should have approximately 5 percent more fine aggregate than what is required for the maximum packing density. Higher fine aggregate contents are reported to reduce segregation. Hudson (2003) reported that gradation requirements, and therefore packing density, should be dependent on aggregate shape and texture.

Shape and texture of the coarse and fine aggregate influence packing density and workability. Aggregate shape can be measured with three characteristics: sphericity, roundness, and form. Sphericity is a measure of the equidimensionality of an aggregate particle. Roundness is the measure of the sharpness of the particle's edges or corners. Form is a measure of the relationship between the three dimensions of a particle and this is based on the ratios between the proportions of the long, medium, and short axes of the particle. It should be noted that different definitions of shape exist that may not correlate to the definition just provided, but this definition is used for the purpose of this report.

Aggregate texture is defined qualitatively as being either rough or smooth. Aggregate texture has been reported to have minimal influence on workability compared to aggregate shape (Bager et al. 2001). However, there are tests that provide a measurement of both the shape and texture characteristics (ASTM D3398-00).

Measuring and quantifying aggregate shape characteristics can be achieved using several different methods. The ASTM D4791-10 standard measures individual aggregate particles to quantify shape characteristics. Other methods include using a digital image processing (DIP) technique to analyze the shape characteristics of aggregate particles (Tongyan Pan 2002, Kwan et al. 1999, Kwan and Mora 2002). The DIP technique uses a video camera or scanner to capture a two-dimensional image of the aggregate. Kwan and Mora (2002) reported that shape characteristics can be successfully measured using the DIP technique along with weighing the aggregate. The measured shape characteristics can then be correlated with the packing densities of the aggregate. There is also an indirect method of quantifying shape characteristics based on measuring the voids, and therefore the packing density of the aggregate. The ASTM D3398-00 *Index of Aggregate Particle Shape and Texture* (IAPST) standard indirectly and quantitatively measures the shape and texture characteristics of an aggregate. This method measures the voids and rate of change of voids between aggregate sieve sizes, under standard compaction (Jamkar and Rao 2004).

The IAPST has been successfully used to characterize concrete aggregates, although it is more commonly used to characterize aggregate for asphalt concrete mixtures. Jamkar and Rao (2004) reported that rounded and smooth aggregate exhibit lower IAPST values. Measuring and quantifying the shape characteristics can provide an indication of the amount of paste required to meet workability requirements. Hahn et al. (2008) reported that aggregates having an angular shape required increased paste volumes to meet workability requirements compared to aggregates having a round shape. Jamkar and Roe (2004) reported that concrete composed of aggregate with a low IAPST values require a lower optimum volume fraction of fine aggregate (VFFA) in the total aggregate. The optimum VFFA is defined as the highest possible compaction factor value as per the ACI 211.3-75 *Recommended Practices for Selecting Proportions for No-Slump Concrete* standard. The compaction factor test is intended to assess workability for mixtures that have low slump values.

2.4.2. Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are commonly used to replace a percentage of the of the ordinary portland cement (OPC). Three SCMs commonly used in concrete mixtures include slag cement, silica fume, and fly ash. The influence of these SCMs on workability is reviewed in the following sections.

2.4.2.1. Slag

Slag is a glassy by-product of iron production that is created during the rapid cooling of iron in water. ASTM C989-13 provides specifications for slag and its use in concrete. Slag cement can be used to improve workability but has less of an effect on workability than other SCMs at similar replacement percentages (Tattersall 1991). Boukendakdji et al. (2009) reported that an optimum OPC replacement of 15% slag cement could improve concrete workability. However, Tattersall (1991) reported that the optimum slag replacement to improve workability depends on the slag type and characteristics. The author also reported that slag contents can have varying effects on yield stress and plastic viscosity depending on the type and quantity. Depending on the slag type and replacement levels, the effect on yield stress and plastic viscosity could be minimal; the yield stress could decrease while the plastic viscosity increases; or the yield stress and the plastic viscosity could both increase (Tattersall 1991). With such variability of effects on workability, slag should only be used by concrete producers that are highly knowledgeable about slag type and characteristics. Because of this, slag will not be assessed in this research.

2.4.2.2. Silica Fume

Silica fume forms as a by-product in electric-arc furnaces during the production of silicon metals and ferrosilicon alloys. ASTM C1240-14 provides requirements for using silica fume in concrete. Silica fume condenses from oxidized vapor that is created from the furnace. Silica fume can generally increase workability at lower replacement levels but can significantly reduce workability at higher replacement levels. Shi et al. (2002) reported that concrete mixtures with 3, 6, and 9% silica fume replacement levels produced lower yield stresses and plastic viscosities than concrete composed entirely of OPC. The authors also reported that replacement levels of 12% silica fume produced concrete with increased yield stress and plastic viscosity values. However, Hassan (2012) reported that silica fume replacement levels of 3 and 5% increased yield stress and plastic viscosity values but replacement levels of 8% had no effect on the plastic viscosity and increased the yield stress. The author also reported that silica fume replacement levels of 11% silica fume created concrete that required excessive amounts of chemical admixtures to create the desired workability characteristics. Silica fume has variable effects on workability depending on dosage. Therefore using silica fume to improve workability is a challenging task. Because of this, silica fume will not be assessed in this research.

2.4.2.3. Fly Ash

ASTM C618-12 *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete* divides fly ash into three classes: Class F , Class C and Class N. Class F and Class C fly ashes are by-products of electric power generating plants that combust pulverized coal. Class N is a relatively new class of fly ash that is produced from raw or calcined pozzolans. Because Class N fly ash is new it is not typically used by concrete producers. Class F fly ash has pozzolanic properties while Class C fly ash has pozzolanic and cementitious properties (ASTM C618-12 2012).

Fly ash has been reported to improve workability, long-term strength, resistance to sulfate attack, and durability (Owaid et al. 2012). Researchers have reported that fly ash can generally decrease yield stress and have variable effects on plastic viscosity. For example, Sonebi (2004a) reported that fly ash can reduce both the yield stress and the plastic viscosity. However, Park et al. (2005) reported fly ash can reduce the yield stress and increase the plastic viscosity (Park et al. 2005). Increasing the volume of fly ash can reduce the chemical admixture demand to achieve a given slump (Sonebi 2004a). For a given cementitious material content, *w/cm*, and chemical admixture content, an increase in fly ash has been shown to increase slump flow (Patel et al. 2004). Generally less bleeding is observed in concretes that incorporate fly ash into the mixture (Kosmatka and Wilson 2011). Increases in fly ash have also been reported to increase stability (Sonebi 2004a). Because the incorporation of fly ash into concrete has been shown to generally increase the yield stress and stability, this makes fly ash an ideal SCM to improve workability.

2.4.3. Chemical Admixtures

Chemical admixtures are generally used in concrete mixtures to decrease water demand, increase slump, delay setting time, modify viscosity, or entrain air. High range water reducing admixtures (HRWRAs), viscosity modifying admixtures (VMAs), and air-entraining admixtures (AEA) can influence the workability of concrete mixtures. The following sections will provide a brief overview of the effects of these chemical admixtures on concrete workability.

2.4.3.1. High Range Water Reducing Admixtures

HRWRAs can be used to reduce the amount of water, cement, or the *w/cm* required to achieve a given slump or slump flow. HRWRAs can also be used to increase the slump or slump flow when the water, cement, or the *w/cm* is kept constant (Hahn et al. 2008). However, concrete workability characteristics can vary depending on the type of HRWRA used. Polycarboxylate-based (PCB) HRWRAs are typically used in modern HW concrete mixtures as opposed to older sulfonate-based HRWRAs. Note that older sulfonate-based HRWRAs are seldom used in the concrete industry today.

The mechanism of dispersing cement particles differs for PCB and sulfonate-based HRWRAs. PCB HRWRAs have been shown to disperse cement particles by physically coating and separating the cement particles (i.e. steric hindrance) (Li et al. 2005). PCB HRWRAs consist of polycarboxylic backbones with polyethylene oxide side chains. The backbones absorb into the cement particles and the side chains extend out to physically separate the cement particles. PCB HRWRAs have also been shown to disperse cement particles by negatively charging the cement particles (i.e., electrostatic repulsion) and steric hindrance (Li et al. 2005, Yoshioka et al. 2002). Sulfonate-based HRWRAs typically only disperse cement particles by electrostatic repulsion (Collepardi 1998).

PCB HRWRAs are effective dispersing agents because these can be used to reduce the yield stress at relatively low dosages (Nehdi and Al-Martini 2009). Xu and Beaudoin

(2000) reported that PCB HRWRAs can produce a stable mortar mixture because of its dispersion method. PCB HRWRAs are typically used because increased slump values and a decrease in slump loss can be achieved with increased dosages (Hidalgo et al. 2008, Felekoglu and Sarikahya 2008). However, significant increases in PCB HRWRA dosages can decrease concrete stability (El-Chabib and Nehdi 2006).

In general, incorporating PCB HRWRAs into concrete mixtures decrease the yield stress and plastic viscosity but the *w/cm* has an effect on the degree to which yield stress and plastic viscosity decrease. Golaszewski and Szwabowski (2004) reported that reductions in plastic viscosity are minimal for concrete mixed with PCB in concrete mixtures with a low *w/cm*. Yamada et al. (2000) also reported that PCB HRWRA significantly decreased plastic viscosity at relatively high *w/cm*, but plastic viscosity decreased modestly at lower *w/cm*. Therefore, the incorporation of PCB HRWRAs can be used to improve workability at reduced water contents.

2.4.3.2. Viscosity Modifying Admixtures

VMAs are also known as anti-washout admixtures because they can be used for underwater concrete placements. VMAs are commonly used in underwater and SCC applications. VMAs can be used to increase stability and decrease bleeding in concrete (Khayat 1995). Khayat (1998) reported that VMAs increase the yield stress and the plastic viscosity of concrete. The author also reported that HRWRAs can be incorporated to decrease the viscosity and to maintain adequate workability. The author also reported that adequate combinations of HRWRA and VMA can produce concrete mixtures with high flowability and stability. Because VMAs are typically used in underwater and SCC applications, these will not be assessed in this research. However, VMAs have reported benefits that could be used for HW concrete mixtures.

2.4.3.3. Air Entraining Admixtures

Although AEAs are commonly used to improve a concrete’s resistance to freeze and thaw degradation, AEAs can have a significant influence on concrete workability. Tattersall (1991) reported that both yield stress and plastic viscosity decrease but the yield stress decreases at a lesser extent than the plastic viscosity with increased dosages of AEA. The author reported that 5% of entrained air reduced the yield stress by 30% and plastic viscosity by 70%. Chia and Zhang (2003) reported that increasing AEA dosages had minimal effect on reducing the yield stress and significant effect on reducing the plastic viscosity. Although AEAs have been reported to improve workability, AEAs also result in significant variations in fresh and hardened concrete properties. Because of this, specifiers and contractors are less likely to use AEA’s as an admixture to enhance workability. As a result of this, AEA’s will not be assessed in this research.

2.5. INFLUENCE OF MIXTURE PROPORTIONS ON WORKABILITY

Changes in mixture proportioning can significantly influence workability. As reported earlier, concrete is a concentrated suspension of solid particles in a viscous liquid or, more specifically, aggregate suspended in paste. Paste is a concentration of suspended cement grains in water (Ferraris 1999). The review of the influence of constituent material characteristics on workability has already been provided. However, the influence of proportions of these constituent materials (water, paste, and aggregate) on workability has yet to be reviewed. Therefore, because mixture proportions can influence workability this is reviewed. The water content (*w/cm*), paste, aggregate fraction, and proportions of fine and coarse aggregate are the material proportions reviewed.

Increasing the water content without increasing the cementitious materials content will increase the *w/cm*. Increasing the *w/cm* has been reported to reduce both the yield stress and plastic viscosity (Tattersall 1991). Sonebi (2004b) reported that increasing the *w/cm* has a greater effect on increasing slump flow than the fly ash quantity, HRWRA dosage, or paste content. However, increasing the *w/cm* has been reported to decrease the stability of concrete mixtures (El-Chabib and Nehdi 2006).

The proportion of paste can be varied depending on the desired workability characteristics. Note that paste may include SCMs and the type and quantity of SCM can alter workability characteristics. As noted earlier, the paste must fill the voids in the aggregate for the concrete to flow. In fact, to achieve adequate flow, additional paste (beyond the measured aggregate void content) is necessary to separate and provide lubrication between the aggregates. However, El-Chabib and Nehdi (2006) reported that increasing the paste content can decrease stability for concrete with high *w/cm*. The authors also reported that concrete with lower *w/cm* exhibited small increases in stability with increased paste contents. Sonebi (2004b) reported that increasing the paste content for a given *w/cm* increased slump flow. The author also reported that the plastic viscosity decreased to a greater extent than the yield stress with an increase in paste content. A report by the International Center for Aggregates Research (ICAR) (Research Report

108-1) reported that paste volume can typically range from 28% to 40% of the total concrete volume for SCC (Koehler and Fowler 2006).

To increase the paste content the total aggregate fraction must decrease. The total aggregate fraction and the proportions of fine and coarse aggregate can have an effect on concrete workability. Geiker et al. (2002) reported that increasing the total aggregate volume fraction by increasing the coarse aggregate volume fraction increased both the yield stress and plastic viscosity. Khayat (1999) reported that mixtures with relatively lower fine and coarse aggregate contents (increases in paste) had higher filling abilities than mixtures with higher coarse and fine aggregate contents. The author also reported that mixtures with higher coarse aggregate contents had higher yield stress and plastic viscosity values. Khayat (1999) reported that high coarse aggregate contents can decrease stability. However, El-Chabib and Nehdi (2006) reported that the coarse to total aggregate ratio only modestly impacts stability. The authors reported that an increase in the coarse to total aggregate ratio from 0.4 to 0.45 increased stability slightly and for increases beyond 0.45 the stability slightly decreased. Therefore, an optimum coarse to fine aggregate ratio can increase stability and this was reported to be approximately 0.45 for the aggregates used in their research. ICAR 108-1 reported that a fine to total aggregate ratio range of 0.40 to 0.50 is typically used in SCC (Koehler and Fowler 2006).

2.6. CALTRANS REQUIREMENTS AND NEEDS

Caltrans is funding research to assess the influence of constituent materials on workability. In addition, different tests used to assess the passing ability of HW concrete mixture for CIDH piles are being assessed. Concrete workability is being assessed for HW concrete mixtures for CIDH pile applications that will be placed under slurry. Caltrans (2010) specifies that concrete used for this application shall have a nominal slump of 7 inches (178 mm) or greater. Caltrans (2010) also requires a minimum of 675 lbs/cy (400 kg/m^3) of cementitious material to help prevent segregation and excessive bleed water in these concrete mixtures. There are also maximum cementitious materials limits placed on large diameter concrete piles. The maximum cementitious materials limits are shown in Table 2-3.

Table 2-3. Caltrans (2010) Cementitious Materials Limit Based on Pile Diameter

Pile diameter (D) (feet)	Maximum quantity of cementitious material (lb/cu yd)
$8 < D \leq 10$	750
$10 < D \leq 14$	720

As already noted, the MSA values are required to be 3/8 or 1/2-inch (9.5 mm or 12.5 mm). Although Caltrans Specifications (2010) allow 1/2-inch (12.5 mm) MSA, 3/8-inch (9.5 mm) is typically used in practice. The combined fine and coarse aggregate gradation requirements for the 3/8-inch and 1/2-inch (9.5 mm or 12.5 mm) MSAs are shown in Table 2-3. These Caltrans specifications are considered in this research and revisions may be recommended to achieve adequate workability for HW concrete for CIDH pile application.

Table 2-4. Caltrans (2010) Combined Aggregate Gradations for HW CIDH Concrete Mixtures

Sieve size	Percentage passing	
	1/2-inch (12.5 mm) max	3/8-inch (9.5 mm) max
3/4-inch (19 mm)	100	--
1/2-inch (12.5 mm)	90-100	100
3/8-inch (9.5 mm)	55-86	50-100
No. 4	45-63	45-63
No. 8	35-49	35-49
No 16	25-37	25-37
No. 30	15-25	15-25
No. 50	5-15	5-15
No. 100	1-8	1-8
No. 200	0-4	0-4

2.7. SUMMARY

The importance of assessing concrete workability has long been recognized. Concrete is a complex system consisting of aggregate suspended in paste. From the literature review it can be seen that mixtures with increased paste contents such as HW concrete mixtures typically can have an increasingly complex system. Therefore, monitoring and assessing workability for HW concrete mixtures is critical. However, the test methods used to assess concrete workability are vast and designed to assess different workability characteristics. Workability is defined as the flowability, stability, and passing ability of a concrete mixture for this study. Identifying a test or suite of tests that can assess these workability characteristics is critical. The Rheology test methods can provide a more complete description of concrete workability. However, until these tests become more economical and easier to use, common QE tests will likely continue to be used to assess workability.

The QE test methods presented in this literature review included slump flow, K-slump, J-ring, L-box, and C-bar. The slump flow test incorporating the VSI test is intended to assess the flowability and stability of concrete mixtures. The K-slump tester is intended to assess nominal slump and give a general assessment of workability. The J-ring test incorporating the VBI test is intended to assess the passing ability and stability of concrete mixtures. The L-box is intended to assess the passing ability of concrete mixtures. However, Koehler and Fowler (2009) reported that the L-box also assessed flowability. The C-bar test is intended to assess the passing ability of concrete mixtures. These tests will be assessed here for their suitability to assess workability characteristics.

The influence of constituent material characteristics on workability has been presented in this literature review. Based on the literature reviewed regarding aggregate characteristics there are three aggregate characteristics that can influence workability: MSA, gradation, and shape. Texture was reported to have little influence on workability. Aggregate characteristics are related to the voids in the aggregate or packing density. The voids in the aggregate can an influence concrete workability. Based on the literature reviewed for SCM's, fly ash may have the greatest influence on workability. The most effectively used admixture for increasing flowability is the PCB HRWRA. An admixture that could potentially be used in HW concrete mixtures is a VMA but this is typically used in underwater or SCC applications. A VMA was not assessed for HW concrete in this research. The AEA can increase workability but because it can result in variations in fresh and hardened concrete properties, it is not assessed in this research.

The influence of material proportions on workability was reviewed in this literature review. The *w/cm*, paste content, aggregate fraction, and fine and coarse aggregate proportions can influence workability. Generally, as the *w/cm* increases the flowability increases and the stability decreases. Also, in general, if the paste content increases the flowability increases and stability may increase or decrease depending on the *w/cm.* Decreasing the total aggregate fraction can increase flowability and increasing the coarse aggregate fraction can decrease stability. However, an optimum fine aggregate to coarse aggregate ratio exists to improve stability.

Caltrans has requirements for HW concrete mixtures placed under slurry for CIDH pile applications. These requirements are considered throughout the study and may need to be reevaluated based on the results of this study.

3. EXPERIMENTAL PLAN, METHODS, AND MATERIALS

The research consists of three tasks. The first task is to assess of the influence of coarse aggregate (CA) type and mixture proportions on workability. The influence of CA type and mixture proportions on workability is assessed using QE workability tests. The second task is to assess whether the J-ring and C-bar test results are sensitive to different test configurations. The third task is to provide guidance on proportioning concrete mixtures for HW concrete mixtures for CIDH pile applications.

3.1. EXPERIMENTAL PLAN

Initially, seven mixture proportions were supplied by Caltrans from concrete construction companies. These concrete construction companies included Mercer-Fraser (MF) Company, Granite (GR), Knife River (KR), Ghilotti Bros. (GB), Inc., Tutor-Saliba (TS) Corporation, Syar Concrete (SC), and Cemex (CX). These mixture proportions are shown in Table 3-1. An average of the mixture proportion weights was calculated as a starting point for trial mixtures. The average of these mixture proportions is shown in Table 3-2. However, the standard deviation of the mixture proportion average is relatively high, so the GR mixture was taken out. The mixture proportions average without the GR mixture is shown in Table 3-3. Starting with these mixture proportions, 66 trial mixtures were assessed for flowability and stability with slump flow and VSI tests. The mixture proportions were varied to determine how different material quantities influence the workability of concrete. The materials and quantities that were varied include the water-to-cementitious materials ratio (w/cm), percent cement paste volume (water, air, cement, and fly ash), and FA/CA. Several mixtures failed to meet either the flowability or stability requirements for testing. However, once a mixture exhibited adequate flowability and stability the experimental plan was developed.

Table 3-1. CIDH Pile Concrete Mixtures Supplied by Caltrans

		MF	GR	KR	GB	TS	SC	CX
Material	Unit	Material Quantity						
Cement	lbs	549	338	505	632	438	518	506
Water	lbs	308	250	295	367	235	300	300
Water/Cement		0.56	0.74	0.58	0.58	0.54	0.58	0.59
SCM								
Fly Ash F	lbs	185	169	169	211	236	173	169
Slag	lbs	-	169	-	-	-	-	-
Water/CM		0.42	0.37	0.44	0.44	0.35	0.43	0.44
Coarse Aggregate								
Max Size: 1"	lbs	-	-	-	-	-	-	1750
Max Size: 1/2"	lbs	-	1424	-	-	1538	-	-
Max Size: 3/8"	lbs	1395	-	1698	1281	-	1650	-
Max Size: 1/4"	lbs	-	176	-	-	-	-	-
Fine Aggregate								
Sand	lbs	1543	1454	1256	1337	1538	1333	1750

Table 3-2. Concrete Mixture Proportions Averages

Material	Unit	Avg. Qty.	Stnd. Dev.
Cement	lbs	498	92
Water	lbs	294	43
SCM	lbs	185	25
Water/Cement		0.60	0.07
W/CM		0.41	0.04
Coarse Aggregate	lbs	1586	167
Fine Aggregate	lbs	1459	168

Table 3-3. Concrete Mixture Porportions Averages without GR

Material	Unit	Avg. Qty.	Stnd. Dev.
Cement	lbs	525	64
Water	lbs	301	42
SCM	lbs	190.5	25
Water/Cement		0.57	0.02
W/CM		0.42	0.04
Coarse Aggregate	lbs	1583	668
Fine Aggregate	lbs	1460	184

The influence of *w/cm* on workability is a variable that is assessed as a part of a preliminary investigation. The influence of *w/cm* on workability was assessed for the crushed (CR) aggregate type and only one FA/CA of 1.26. For this preliminary study the influence of CR aggregate type on workability is not assessed. The workability characteristics assessed for these mixtures are slump flow (flowability) and VSI (stability). The mixtures used for this assessment are shown in Table 3-4.

Table 3-4. Concrete Mixtures Assessed for the Influence of w/cm and Paste Content on Flowability and Stability

	Paste Volume					
w/cm	35%	37%	38%	39%	40%	42%
0.36	X	X		X	X	
0.39		X	X	X	X	X
0.41	X	X	X	X		

To achieve task one, an experimental plan was developed to assess two types of coarse aggregate (crushed (CR) and round (RO)) and the mixture proportions used in the research program. The influences of paste (water, air, cement, and fly ash) volume and

FA/CA on workability are the mixture proportions assessed. The mixtures assessed for workability using standard QE workability tests are shown in Table 3-5. A replacement level of 28% fly ash (by weight) is maintained for all mixtures. Constant dosages of PCB HRWRA and set retarding admixture are used in each mixture. These quantities are determined based on the manufacture's recommendations. The percent paste of the total concrete volume is categorized as low paste (LP), medium paste (MP), and high paste (HP) volumes. It should be noted that none of these mixtures are suitable for CIDH piles with a diameter greater than 8 feet (2.4 m). This is because the LP mixtures contain 808 lb/cy (479 kg/m^3) cementitious materials. However, these mixtures are suitable for the study performed by UCSD because the proposed diameter is less than 8 feet (2.4 m) (the diameter of the piles is reported to be 2 feet (914 mm)). All of these mixtures have a *w/cm* of 0.39. The mixtures are assessed for flowability, stability, and passing ability.

Table 3-5. Mixtures Assessed with Standard QE Workability Tests

CA Type	FA/CA	Paste Volume	QE Workability Test				
			Slump flow w/VSI	J-ring w/VBI	C-bar w/VBI	L-box	K-slump
CR	1.13	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X
	1.26	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X
	1.38	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X
RO	1.00	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X
	1.10	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X
	1.20	38% (LP)	X	X	X	X	X
		40% (MP)	X	X	X	X	X
		42% (HP)	X	X	X	X	X

X: indicates mixtures are assessed

The first task is performed with standard configurations of the J-ring and C-bar tests. The second task is to assess the J-ring and C-bar test results with different test configurations. This analysis is performed by varying the spacing and number of reinforcing bars of the J-ring and C-bar tests. The experimental plan to assess the modified J-ring and C-bar tests is shown in Table 3-6. The standard and modified configurations of the J-ring and C-bar are shown in Tables 3-7 and 3-8, respectively. Note that the number of PVC pipes (2) for the C-bar test does not change for the all tests.

Table 3-6. Mixtures Assessed using Modified J-ring and C-bar Tests

CA Type	FA/CA	Paste Volume	QE Workability Test							
			J-ring w/VBI				C-Bar w/VBI			
			Standard	Mod. 1	Mod. 2	Mod. 3	Standard	Mod. 1	Mod. 2	Mod. 3
CR	1.13	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X
	1.26	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X
	1.38	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X
RO	1.00	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X
	1.10	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X
	1.20	38% (LP)	X	X	X	X	X	X	X	X
		40% (MP)	X	X	X	X	X	X	X	X
		42% (HP)	X	X	X	X	X	X	X	X

X: indicates mixtures are assessed

Table 3-7. J-ring Modifications

Test Version	J-ring Diameter, in. (mm)	Lineal Clear Spacing, in. (mm)	Bar Size, in. (mm)	No. of bars
Standard	12 (305)	1.73 (44)	0.625 (16)	16
Modification 1	12 (305)	3.11 (79)	0.625 (16)	10
Modification 2	12 (305)	1.47 (37)	0.625 (16)	18
Modification 3	12 (305)	2.07 (53)	0.625 (16)	14

Table 3-8. C-bar Modifications

Test Version	C-bar Diameter, in. (mm)	Lineal Larger Clear Spacing, in. (mm)	Lineal Smaller Clear Spacing, in. (mm)	Bar Size, in. (mm)	No. of Rebar
Standard	14 (356)	3.87 (98)	3.10 (79)	1.13 (29)	6
Modification 1	14 (356)	5.44 (138)	4.55 (116)	1.13 (29)	4
Modification 2	14 (356)	2.89 (73)	2.14 (54)	1.13 (29)	8
Modification 3	14 (356)	2.23 (57)	1.55 (39)	1.13 (29)	10

3.2. EXPERIMENTAL METHODS

To characterize the aggregates used in this research standard and modified standard test methods were used. Two CA types with 3/8-inch (9.5 mm) MSAs and a fine aggregate (FA) are used for the HW concrete mixtures in this research. The two CAs consist of a crushed (CR) granite rock and a round (RO) river gravel. The fine aggregate is a natural fine sand. Figures 3.1, 3.2, and 3.3 show the CR CA, the RO CA, and the FA. The aggregates are characterized using the following ASTM and Caltrans California Test (CT) standards:

- ASTM C136-06 – Sieve Analysis of Fine and Coarse Aggregates
- ASTM C29-09 – Bulk Density (Unit Weight) and Voids in Aggregate
- Modified ASTM C29-09 – Bulk Density (Unit Weight) and Voids in Combined Coarse and Fine Aggregate
- ASTM C127-12 – Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
- ASTM C128-12 – Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
- ASTM D3398-00 – Index of Aggregate Particle Shape and Texture
- CT 227 – Method of Test for Evaluating Cleanness of Coarse Aggregate
- CT 213 – Method of Test for Organic Impurities in Concrete Sand
- CT 217 – Method of Test for Sand Equivalent

Note that a modified ASTM C29-09 is used in this research, but this modified approach is not a standard. The modified test includes an assessment of the combined FA and CA instead of just the FA or CA alone. This test is performed to assess the void content for different FA/CA for the aggregates used in this research.

Figure 3.2. CR Coarse Aggregate

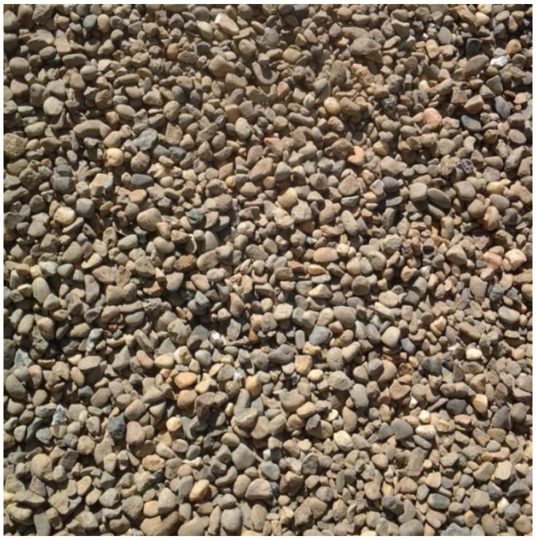

Figure 3.1. RO Coarse Aggregate

Figure 3.3. Natural Fine Aggregate

The QE workability tests used to assess flowability, stability, and passing ability are shown in Table 3-6. The first task included using standard equipment to assess flowability, stability, and passing ability. Note that the second task in this research is to assess the J-ring and C-bar tests with different configurations for their suitability to assess concrete passing ability. Therefore, the four versions of the J-ring and C-bar configurations are indicated in Table 3-9. The four C-bar test setups with dimensions are shown in the appendix.

Table 3-9. Workability Tests and the Intended Workability Characteristics Measured

Workability Test	Workability Characteristics Measured
Slump flow with VSI (ASTM C1611-09)	Flowability and stability
J-ring - 4 versions with VBI and different bar spacing's (ASTM 1621-09)	Passing ability and stability
California bar (C-bar) - 4 versions with VBI and different bar spacing's (CT 234)	Passing ability and stability
L-box	Passing ability and flowability
K-slump (ASTM C1362-09)	General workability (e.g. slump)

3.3. MATERIALS

The materials are characterized based on ASTM and CT test results. The aggregates used in this research are assessed with ASTM and CT tests as a prerequisite for use in concrete.

The ASTM C136-06 sieve analysis results are shown in Figures 3.4, 3.5 and 3.6 for the CA's and the FA. Note that the CR and RO CA's have very similar gradations. The fineness modulus for the fine aggregate is calculated to be 3.07. Each aggregate meets Caltrans individual gradations requirements for concrete. The combined coarse and fine aggregate gradations for the CR and RO aggregates are shown in Figures 3.7 and 3.8. For the CR combined aggregate at the FA/CA's of 1.26 and 1.38 the gradations are slightly above the No. 4 sieve size limit (by a maximum of 4 percent). For the RO combined aggregate at the FA/CA's of 1.1 and 1.2 the gradations are slightly above the

No. 4 sieve size limit by 2 percent at the most. All other gradations are within Caltrans limits.

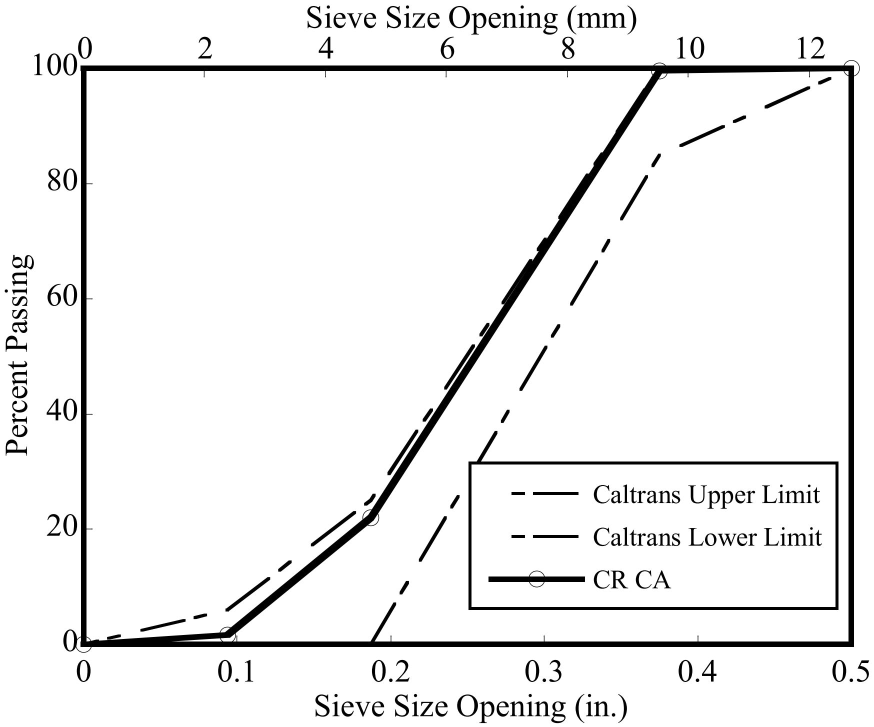

Figure 3.4. Sieve Analysis for the CR Coarse Aggregate

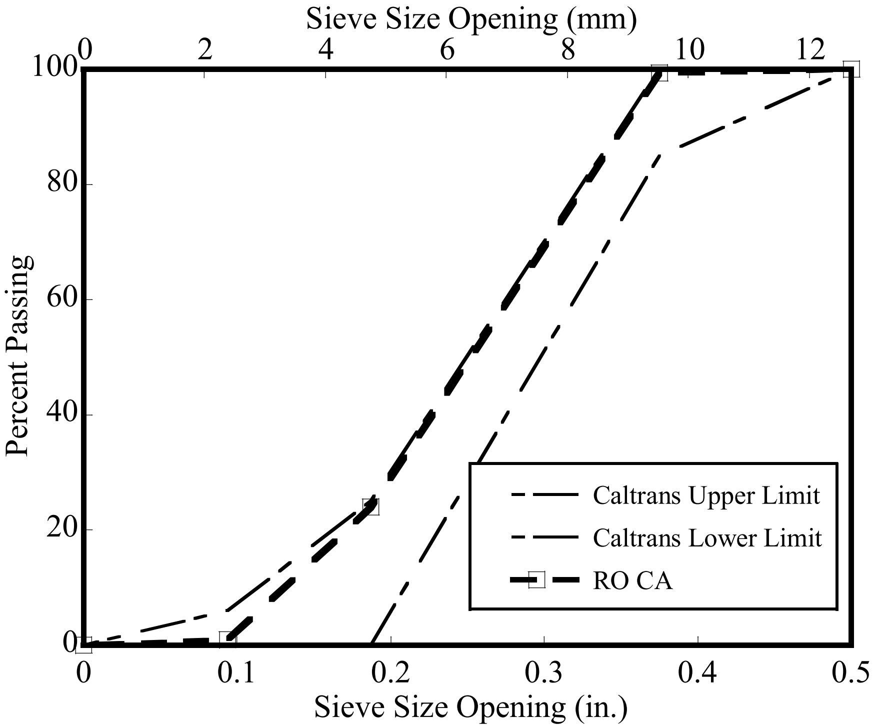

Figure 3.5. Sieve Analysis for the RO Coarse Aggregate

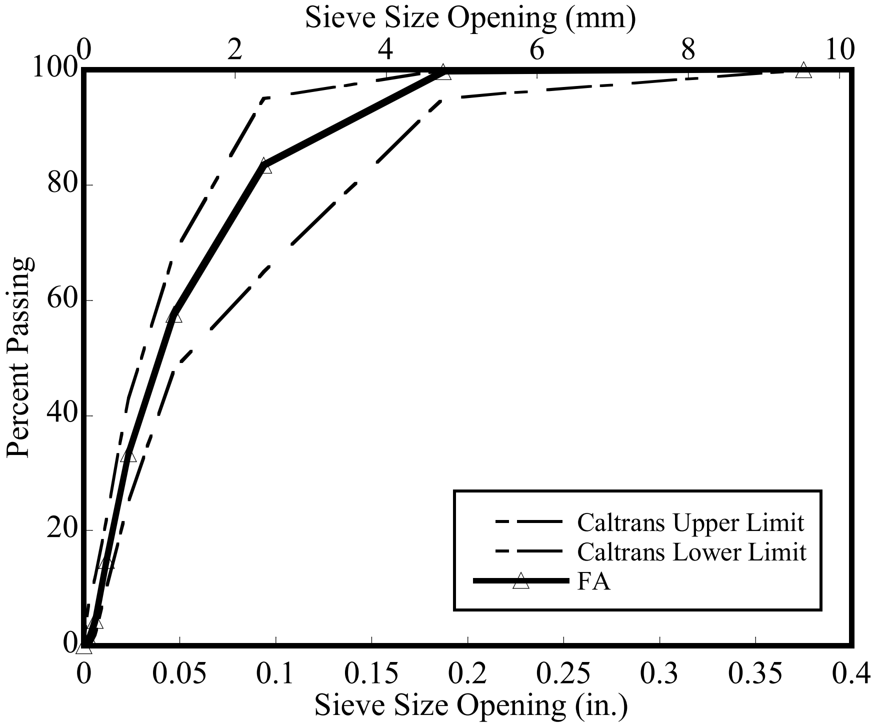

Figure 3.6. Sieve Analysis for Natural Fine Aggregate

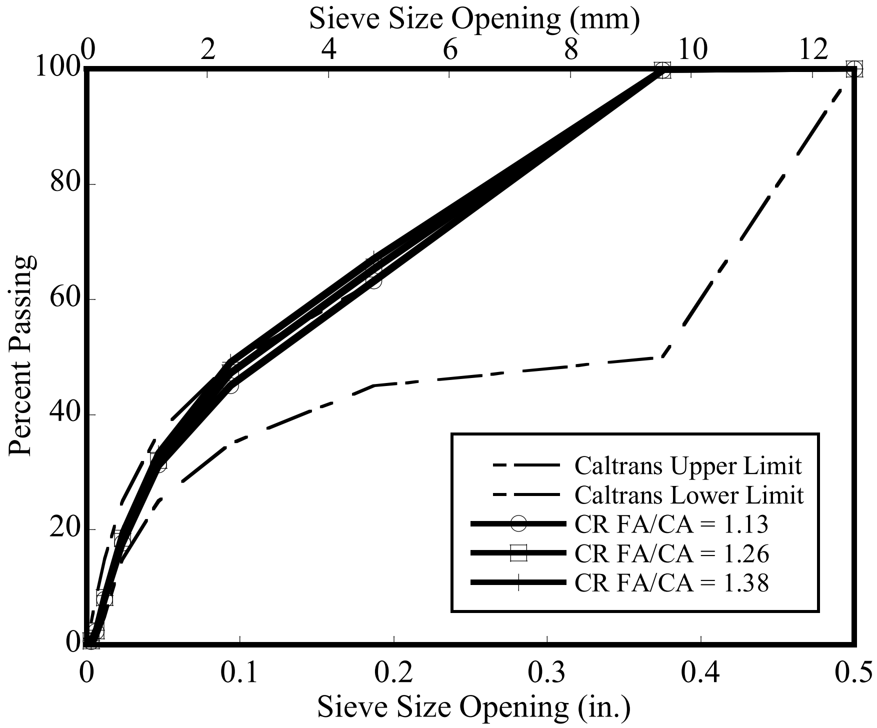

Figure 3.7. Sieve Analysis for CR Combined CA and FA

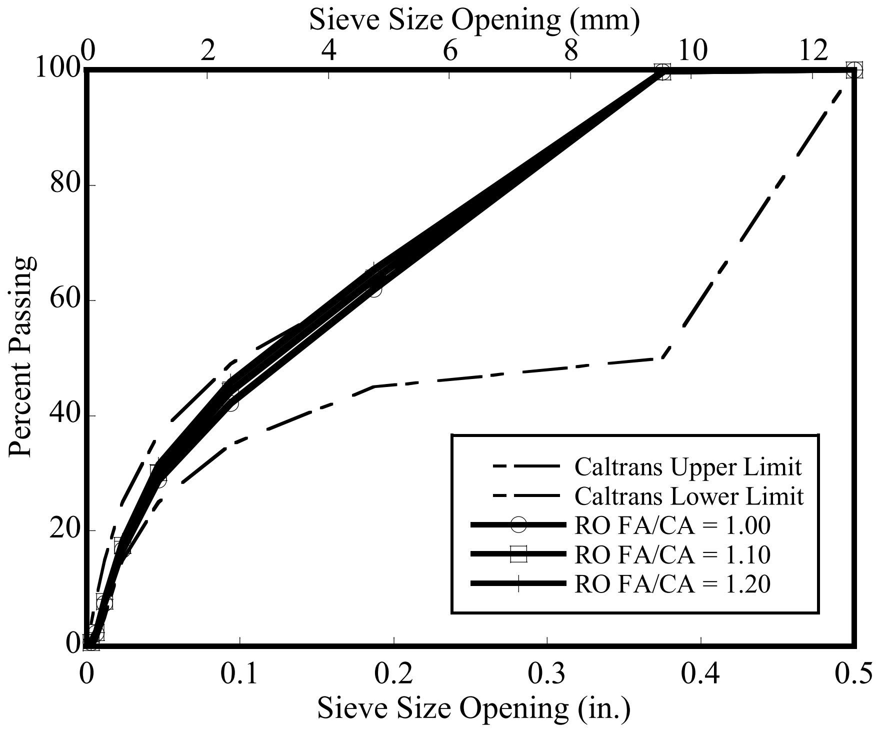

Figure 3.8. Sieve Analysis for RO Combined CA and FA

A summary of the ASTM standard aggregate characterization test results are shown in Table 3-10. The table shows that the oven dry, saturated surface dry (SSD) and apparent specific gravities of both the CR and RO CAs are relatively similar. The percent absorptions of both CAs are very similar. The main difference between the two CAs is the IAPST.

Table 3-10. Summary of ASTM Aggregate Characterization Test Results

	ASTM C29-09		ASTM C127/C128-12				ASTM D3398-00
	Bulk Density lb/ft^3 (kg/m^3)	Percent Void Content	Oven Dry Specific Gravity	SSD Specific Gravity	Apparent Specific Gravity	Percent Absorption	IAPST
CR CA	99.4	41.7	2.74	2.78	2.85	1.50	8.5
RO CA	106.2	35.5	2.64	2.68	2.76	1.60	5.0
FA	100.2	36.3	2.53	2.59	2.69	2.47	N/A

N/A: not applicable

The CT standard aggregate characterization test results are shown in Table 3-11. The Caltrans (2010) specification limits for these tests are shown in Table 3-11. These tables show that these aggregate meet Caltrans (2010) specifications. Note that fine aggregate developing a color lighter than the standard reference color (amber glass) is satisfactory when tested with the CT 213 standard.

Table 3-11. Caltrans CT Aggregate Characterization Test Results

	CT 227	CT 213	CT 217
	Cleanness	Organic	Sand

	Value	Impurities	Equivalent
CR CA	94	N/A	N/A
RO CA	92	N/A	N/A
FA	N/A	Satisfactory	94

N/A: not applicable

Table 3-12. Caltrans (2010) Aggregate Characterization Specification Limits

	CT 227	CT 213	CT 217
	Cleanness Value	Organic Impurities	Sand Equivalent
Operating Range	75 min	Satisfactory*	75 min

*Fine aggregate that develops a color darker than the standard color may be permitted for use if 95 percent of the relative mortar strength is achieved when tested under ASTM C87-10.

The results for the modified ASTM C29-09 are shown in Figure 3.9. The combine FA and CA void content is shown for both the CR and RO aggregates at different FA/CAs. The combined FA and CA aggregate void content will be referred to as the AV content for this report. From this figure it can be seen that the RO aggregate exhibits a lower AV content at a lower FA/CA than the CR aggregate. The circles shown in Figure 3.9 indicate the FA/CA values tested for HW concrete mixtures for this study. These FA/CA aggregate mixtures were chosen based on a number of trial mixtures in a preliminary study. Note that the AV content decreases as the FA/CA increases for the CR aggregate mixtures and the AV content increases as the FA/CA increases for the RO aggregate mixtures used for this study. The same fine aggregate is used for assessing both CAs.

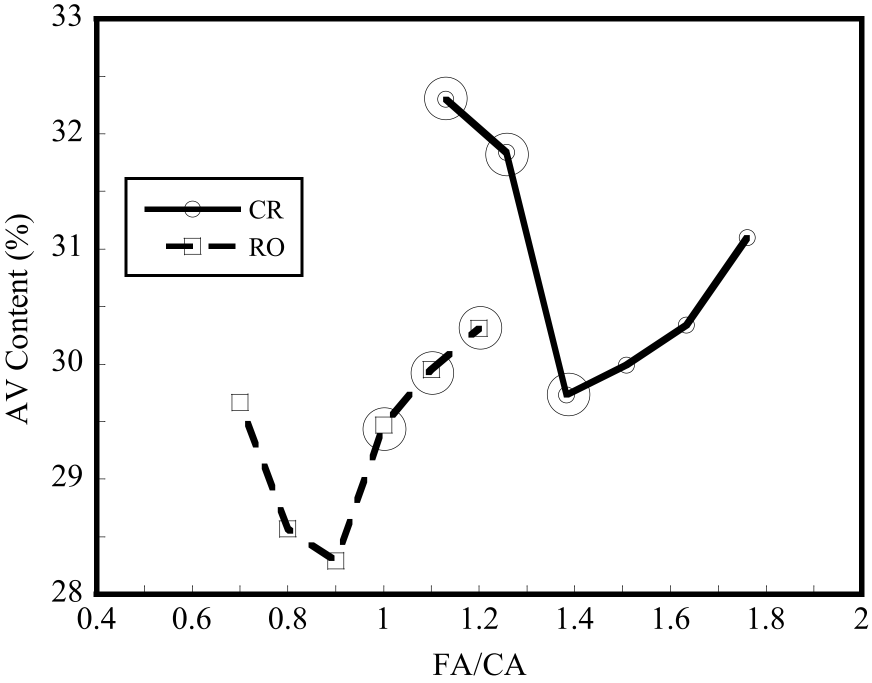

Figure 3.9. Modified ASTM C29-09 Percent AV Content versus FA/CA

A Type I/II cement from Lafarge is used for this research for all concrete mixtures. However, the Type I/II used for concrete containing the CR CA is obtained from a different batch than the concrete containing the RO CA. The cement is obtained from the same Lafarge location. The chemical and physical analysis for the cement used for the concrete containing the CR CA is shown in Tables 3-13 and 3-14. The chemical and physical analyses for the cement used for the concrete mixtures containing the RO CA are shown in Tables 3-15 and 3-16.

Table 3-13. Chemical Analysis of Cement Used in CR CA Concrete Mixtures

Item	Test Results (%)
SiO_2	20.0
Al_2O_3	4.8

Fe_2O_3	3.5
CaO	63.4
MgO	0.8
SO_3	3.1
Loss on ignition	2.8
Insoluble residue	0.02
CO_2	1.8
Limestone	4.1
$CaCO_3$ in limestone	98.1
C_3S	51
C_2S	19
C_3A	7
C_4AF	11
$C_3S+4.75\times C_3A$	83

Table 3-14. Physical Analysis of Cement Used in CR CA Concrete Mixtures

Item	Test Results
Air content of mortar (%)	5
Blaine Fineness, ft^2/lb (m^2/kg)	1826 (374)
Passing 325 (%)	98.1
Autoclave expansion (%)	0
3 day compressive strength, psi (Mpa)	3860 (26.6)
7 day compressive strength, psi (Mpa)	4870 (33.6)
28 day compressive strength, psi (Mpa)	6300 (43.4)
Time of setting vicat initial (minutes)	90
Time of setting heat of hydration, btu/lb (KJ/Kg)	155 (361)
Colour (Lafarge Index)	29
Mortar bar expansion (%)	0.005

Table 3-15. Chemical Analysis of Cement Used in RO CA Concrete Mixtures

Item	Test Results (%)
SiO_2	20.0
Al_2O_3	4.7
Fe_2O_3	3.5
CaO	63.6

MgO	0.8
SO_3	3.1
Loss on ignition	2.7
Insoluble residue	0.12
CO_2	1.9
Limestone	4.5
$CaCO_3$ in limestone	96.8
C_3S	51
C_2S	19
C_3A	7
C_4AF	11
$C_3S+4.75\times C_3A$	83

Table 3-16. Physical Analysis of Cement Used in RO CA Concrete Mixtures

Item	Test Results
Air content of mortar (%)	8
Blaine Fineness, ft^2/lb (m^2/kg)	1831 (375)
Passing 325 (%)	98.1
Autoclave expansion (%)	-0.01
3 day compressive strength, psi (Mpa)	3840 (26.5)
7 day compressive strength, psi (Mpa)	4830 (33.3)
28 day compressive strength, psi (Mpa)	6270 (43.2)
Time of setting vicat initial (minutes)	100
Time of setting heat of hydration, btu/lb (KJ/Kg)	155 (361)
Colour (Lafarge Index)	28
Mortar bar expansion (%)	0.005

A Class F fly ash SCM is used in this research for all concrete mixtures. The chemical and physical analyses of the fly ash are shown in Tables 3-17 and 3-18, respectively.

Table 3-17. Chemical Analysis for Class F Fly Ash

Item	Test Results (%)
SiO_2	48.7

Al_2O_3	18.4
Fe_2O_3	5.4
$SiO_2+Al_2O_3+Fe_2O_3$	72.5
SO_3	0.8
CaO	13.4
Magnesium oxide	4.3
Moisture content	0.11
Loss on ignition	0.26
Available alkali as equivalent Na_2O	1.10

Table 3-18. Physical Analysis for Class F Fly Ash

Item	Test Results
Fineness retained on No. 325 sieve (%)	18.8
% of control at 7 day compressive strength	88
% of control at 28 day compressive strength	109
Water requirement, % of control	98
Autoclave expansion (%)	0.00
Specific gravity	2.59

4. EXPERIMENTAL RESULTS

The influence of aggregate type and mixture proportions on workability are assessed in this section. Assessment of the suitability of the existing and modified J-ring and C-bar tests for assessing passing ability of HW concrete mixtures follows. Note that the measurements performed in this experiment are presented in inches and that an exact conversion to millimeters is performed.

The influence of aggregate type, paste volume, and FA/CA on flowability, stability, and passing ability are assessed. Aggregate types included the CR and RO CA's described previously. Concrete containing the CR CA type is referred to as the CR mixture and concrete containing the RO CA type is referred to as the RO mixture in this research. The influence of *w/cm* on flowability and stability is also assessed in a limited investigation. For this investigation, the paste content varied with *w/cm*.

4.1. PRELIMINARY INVESTIGATION: INFLUENCE OF W/CM ON FLOWABILITY AND STABILITY

A preliminary study is performed to assess the influence of *w/cm* on flowability and stability. Note that mixtures with different *w/cm* values also have different paste contents. El-Chabib and Moncef Nehdi (2006) reported that the influence of paste volume on stability can vary depending on the *w/cm*. However, that report was focused mainly on the stability of SCC mixtures. Therefore, a preliminary study is conducted here to assess the influence of *w/cm* and paste volumes on the flowability and stability of HW concrete mixtures.

One aggregate type (CR) and one FA/CA (1.26) are used in this study to assess the influence of *w/cm* and paste volume on flowability and stability. The influence of *w/cm* and paste volume on measured slump flow and VSI are shown in Figures 4.1 and 4.2, respectively. Figure 4.1 shows that increasing the paste volume can significantly increase the slump flow. The figure also shows that increasing the *w/cm* (above 0.36) results in increased slump flow values. The figure also shows that increasing the *w/cm* from 0.36 to 0.41 can increase slump flow by approximately 5 inches (127 mm) at 37.5 percent paste volume. This was the largest increase in slump flow from increasing the *w/cm* at a constant paste volume. At a paste volume of 35% no increase in slump flow was observed. Results show that *w/cm* can influence slump flow but it is dependent on paste volume.

Increasing the paste volumes from 37 to 39 percent has the greatest influence on the change in slump flow. However the rate of change in slump flow varies depending on the *w/cm*. When changing the paste volume from 37 to 39 percent, mixtures with a *w/cm* of 0.36, 0.39, and 0.41 had a change in slump flow of approximately 5 inches (127 mm), 4 inches (102 mm), and 3 inches (76 mm) per 1 percent change in paste volume. This indicates that paste volume may have a greater influence on slump flow at lower *w/cm's* in the 37 to 39 percent range for these mixtures.

Mixtures are also assessed for stability. Figure 4.2 shows that increasing the *w/cm* and paste volume can decrease stability. Decreasing the *w/cm* and increasing paste volume can improve stability. The stability of concrete mixtures with a high *w/cm* can become more sensitive to high paste volumes and caution should be taken when changing *w/cm* and paste volume to higher values.

For this study a HW concrete mixture is considered to have adequate flowability and stability if it has a slump flow of at least 20 inches (510 mm) and a VSI of 1 or less. The data indicates that some minimum paste volume is needed to achieve a minimum flow value. In addition, if the paste volume becomes too high, the mixture can become unstable. Therefore, a minimum paste volume is likely dependent on the minimum required flow and the maximum paste content is likely dependent on the required stability. Table 4-1 shows the minimum paste requirements to achieve a 20-inch (510 mm) slump flow and maximum paste limit to achieve a VSI of 1 or less based on values from Figures 4.1 and 4.2. The results indicate that decreasing the *w/cm* provides for larger acceptable variations in *w/cm*.

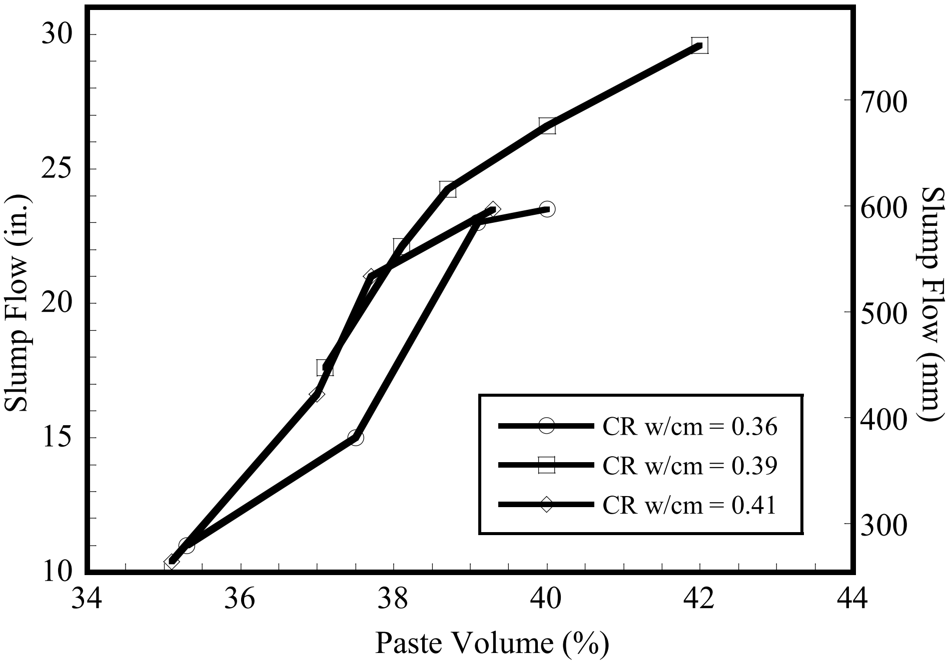

Figure 4.1. Slump Flow versus Percent Paste Volume for Different *w/cm* values

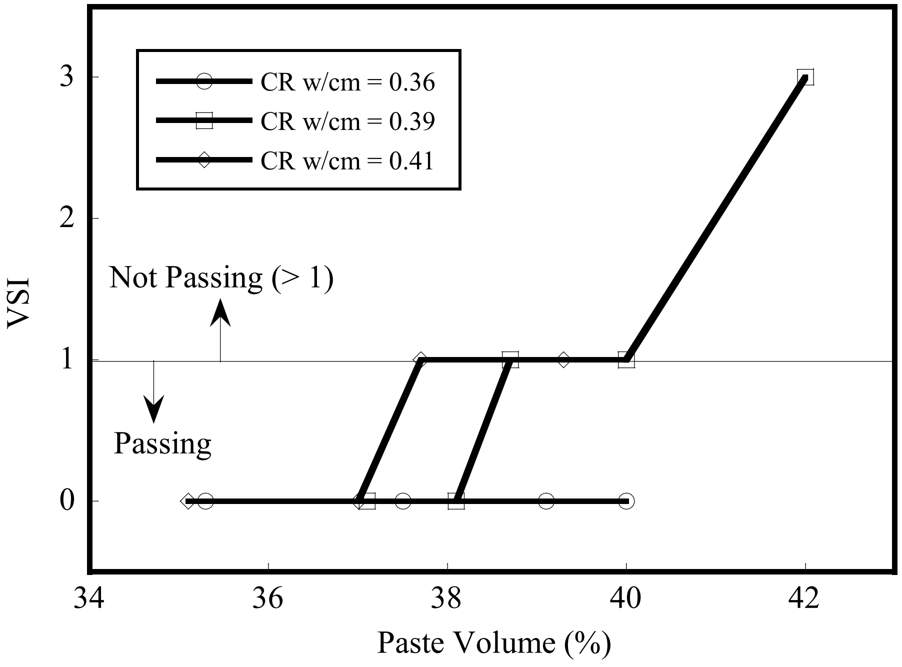

Figure 4.2. VSI versus Percent Paste for Different *w/cm* values

Table 4-1. Minimum and Maximum Percent Paste Volumes for Adequate Flowability and Stability

w/cm	Minimum Paste Volume (%) Based on Slump Flow	Maximum Paste Volume (%) Based on Stability
0.36	38.5	N.A.
0.39	37.5	40
0.41	37.5	39.5*

* Estimated value
N.A. indicates not available

This preliminary investigation indicates that increasing the *w/cm* and paste volume can increase slump flow. However the *w/cm* influence on slump flow is dependent on paste volume. Paste volume has a greater influence on slump flow than *w/cm*. However, increasing the *w/cm* and paste volume can decrease stability. The stability of concrete mixtures with a high *w/cm* can become more sensitive to high paste volumes. Therefore, to create a HW concrete mixture with adequate flowability (slump flow of 20 inches (510 mm) or greater) and stability (VSI of 1 or less) it is recommended that a minimum and maximum paste volume be identified for the desired *w/cm*.

4.2. INFLUENCE OF AGGREGATE TYPE AND MIXTURE PROPORTIONS ON WORKABILITY

The influence of aggregate type, paste volume, and FA/CA on flowability, stability, and passing ability for HW concrete mixtures are assessed using different standard tests in this section. The slump flow and K-slump tests are used to assess the flowability of HW concrete mixtures. The stability of HW concrete mixtures is assessed with the VSI and the VBI tests. For this report, VBI data from the J-ring test will be indicated as VBI_J and data from the C-bar test will be indicated as $\mathrm{VBI_C}$. To assess the passing ability of HW concrete mixtures the J-ring, C-bar, and L-box tests are used in this study.

4.2.1. Slump Flow Loss as a Function of Time

During testing slump flow loss can occur at a rapid rate. High flowability is a critical characteristic for HW concrete mixtures. Therefore, to minimize slump flow loss, all mixtures are mixed in triplicate batches which allows for testing to be completed within one-half hour after mixing is complete. Larger mixture batches would require more time for testing and slump loss would be greater. Even with these shorter test periods, slump flow loss was observed.

Because slump flow is compared with other test results, the researchers examined the slump flow as a function of time after mixing. To correct for slump loss, a preliminary study investigating the slump flow loss of five mixtures was performed. Figure 4.3 shows results from the five trial mixtures. The results indicate that the average slump flow loss for the five trial mixtures is linear and can be estimated as follows:

$$SF = k_1 - (k_2) \times (t) \tag{4.1}$$

where SF = slump flow (inches or cm), t = time (min.), k_1 = slump flow at t = 0 minutes (inches or cm), and k_2 = slump loss (inches/min. or cm/min.). It is important to note that slump flow loss can be estimated using a linear function. Because initial slump flow values vary and because the rate of slump loss can vary, this research assesses slump flow values immediately after mixing and immediately after casting of all specimens are complete. Slump loss values between these times are estimated using a linear function. The slump flow loss function is then used to estimate the slump flow at each test time (e.g., J-ring, C-bar, and L-box). Estimated slump flow values are identified as SF_{etv} (estimated time variant slump flow) and the initial measured slump flow values are identified as SF_i (initial slump flow). Note that SF_i is not k_1 because it is not always measured at t = 0 minutes. Figures 4.4, 4.5, and 4.6 show the initial and estimated slump flow values for the tested CR mixtures. Figures 4.7, 4.8, and 4.9 show the initial and estimated slump flow values for the tested RO mixtures.

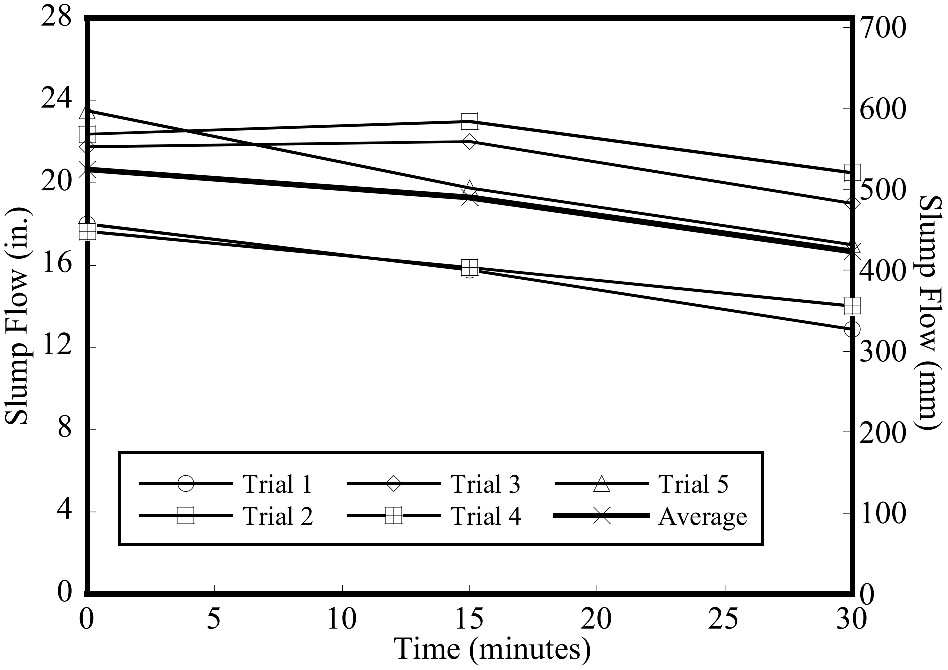

Figure 4.3. Slump Flow Loss as a Function of Time for Five Trial Mixtures

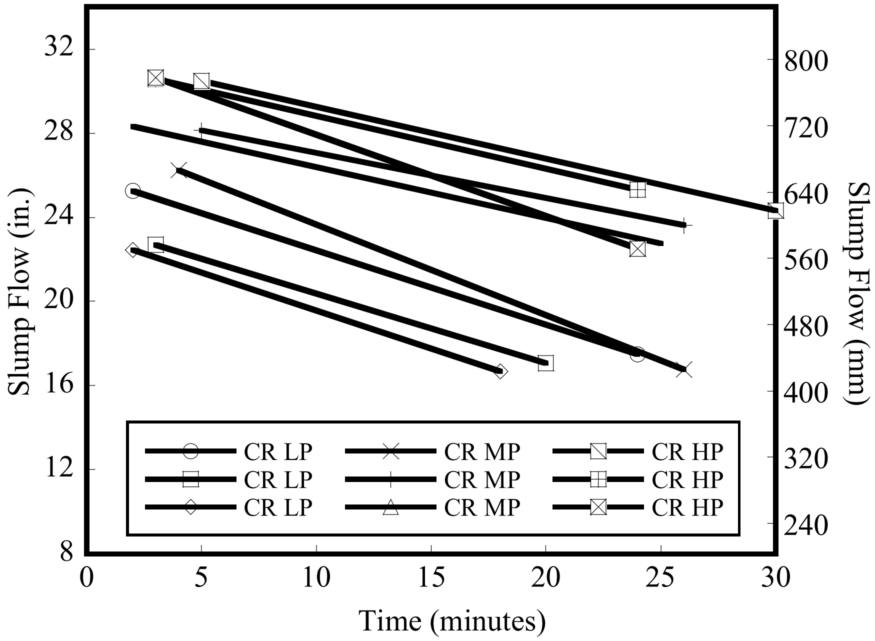

Figure 4.4. Estimated Slump Flow Loss as a Function of Time for CR Mixtures with 1.13 FA/CA

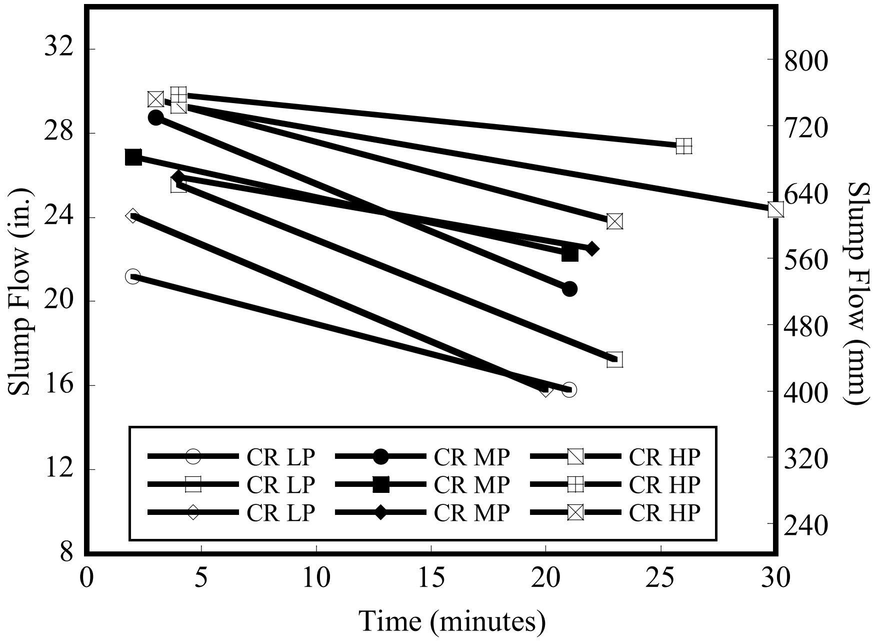

Figure 4.5. Estimated Slump Flow Loss as a Function of Time for CR Mixtures with 1.26 FA/CA

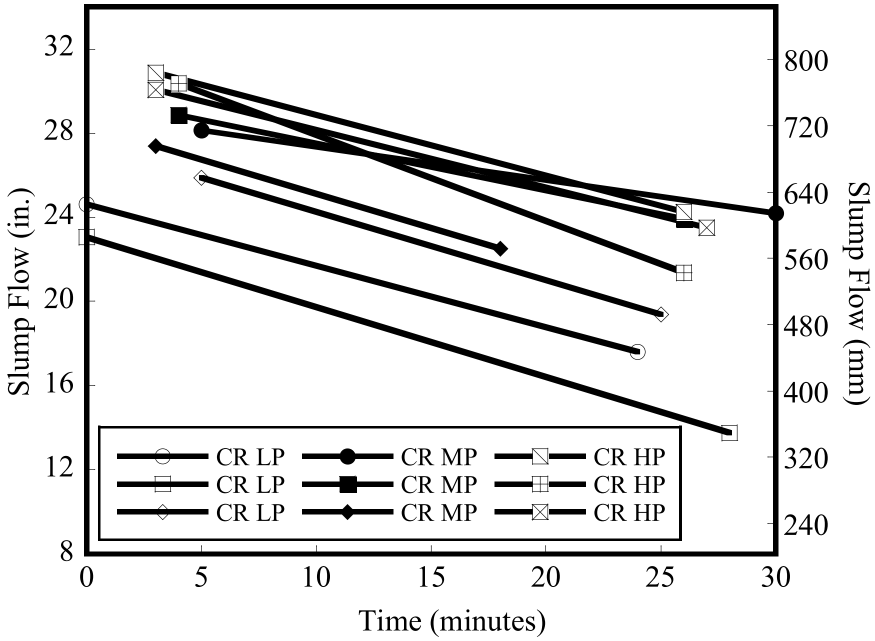

Figure 4.6. Estimated Slump Flow Loss as a Function of Time for CR Mixtures with 1.38 FA/CA

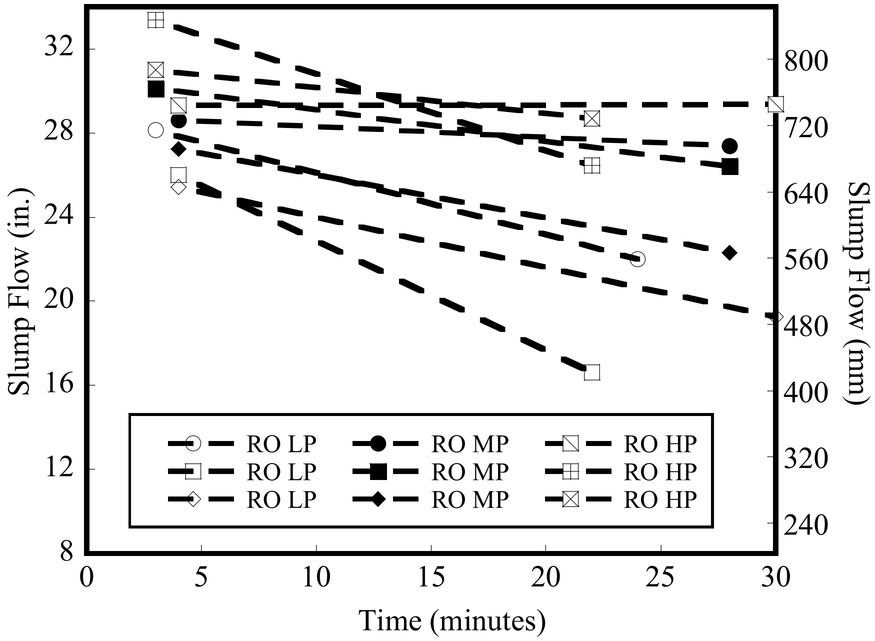

Figure 4.7. Estimated Slump Flow Loss as a Function of Time for RO Mixtures with 1.00 FA/CA

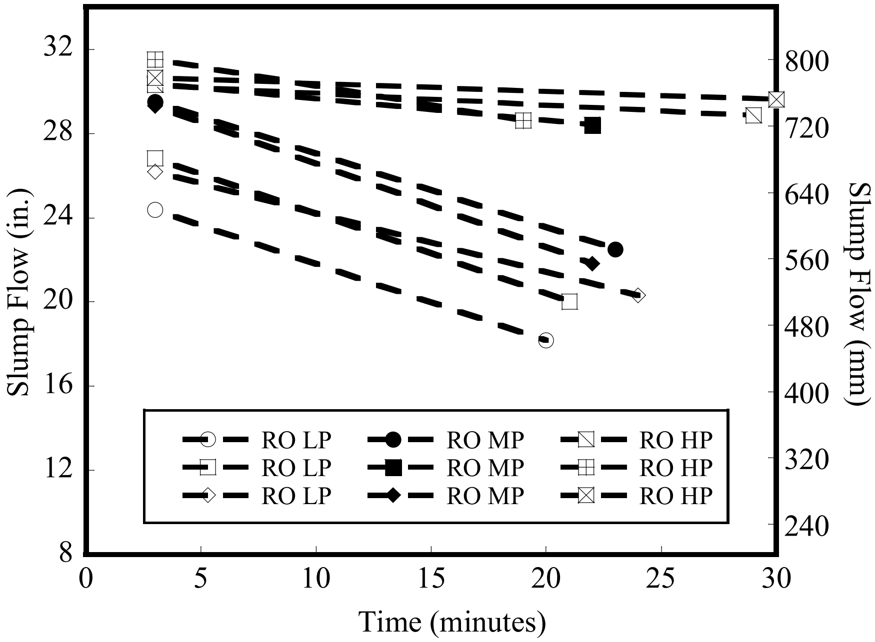

Figure 4.8. Estimated Slump Flow Loss as a Function of Time for RO Mixtures with 1.10 FA/CA

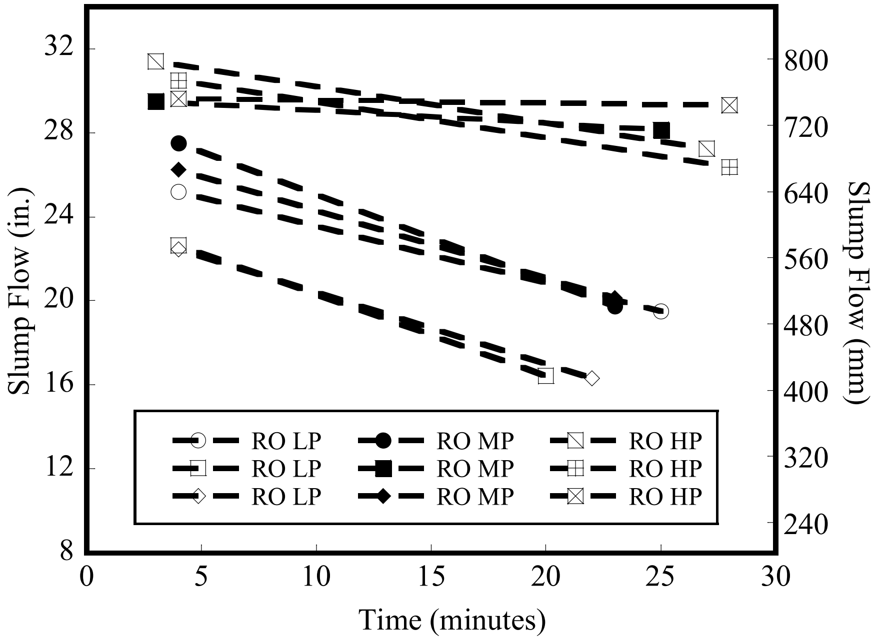

Figure 4.9. Estimated Slump Flow Loss as a Function of Time for RO Mixtures with 1.20 FA/CA

To determine if slump flow loss varies between mixtures the average slump flow loss and standard deviation (SD) data are shown in Tables 4-2 and 4-3. These tables show that slump flow loss generally increases as the paste volume decreases with the exception of the CR mixture containing the 1.38 FA/CA and the RO mixture containing the 1.00 FA/CA. The FA/CA showed no influence on slump flow loss. The aggregate type has little influence on slump flow loss for mixtures containing low and medium paste volumes. However, the RO mixtures containing high paste volumes exhibited less slump loss than CR mixtures containing high paste volumes. This may be the result of low stability. The SD was as low as 0.01 (0.38) and as high as 0.19 (4.73) for all the HW concrete mixtures tested in this study.

Table 4-2. Average Slump Flow Loss for CR Mixtures

	FA/CA					
	1.13		1.26		1.38	
	Avg SF loss, in./min. (mm/min.)	SD	Avg SF loss, in./min. (mm/min.)	SD	Avg SF loss, in./min. (mm/min.)	SD
LP	-0.35 (-8.83)	0.01 (0.38)	-0.39 (-9.96)	0.10 (2.42)	-0.32 (-8.04)	0.02 (0.55)
MP	-0.30 (-7.51)	0.12 (3.01)	-0.29 (-7.46)	0.14 (3.52)	-0.24 (-5.98)	0.08 (2.14)
HP	-0.29 (-7.41)	0.08 (2.10)	-0.20 (-5.01)	0.09 (2.29)	-0.32 (-8.21)	0.07 (1.89)

Table 4-3. Average Slump Flow Loss for RO Mixtures

	FA/CA					
	1.00		1.10		1.20	
	Avg SF loss, in./min. (mm/min.)	SD	Avg SF loss, in./min. (mm/min.)	SD	Avg SF loss, in./min. (mm/min.)	SD
LP	-0.35 (-8.89)	0.15 (3.81)	-0.34 -8.66	0.05 (1.35)	-0.33 (-8.45)	0.06 (1.48)
MP	-0.14 (-3.43)	0.08 (1.97)	-0.28 -7.18	0.16 (3.98)	-0.26 (-6.71)	0.18 (4.57)
HP	-0.16 (-4.09)	0.19 (4.73)	-0.09 -2.30	0.08 (1.97)	-0.12 (-3.02)	0.09 (2.33)

4.2.2. Influence of Aggregate Type and Mixture Proportions on Flowability

The influence of aggregate type and mixture proportions on flowability is presented here for concrete containing both coarse aggregate types (CR and RO). The influence of paste volume on measured slump flow is also assessed. Therefore, the initial measured slump flow (SF_i) will be plotted against the paste volume for the different FA/CA values used in this experiment. The average SF_i data are plotted for the CR and RO mixtures in Figures 4.10 and 4.11, respectively. Because mixtures are mixed in triplicate an average of the three SF_i values is represented in these figures. These figures show that the paste volume significantly influences the average SF_i. As paste volume increases the average SF_i increases for both CR and RO mixtures.

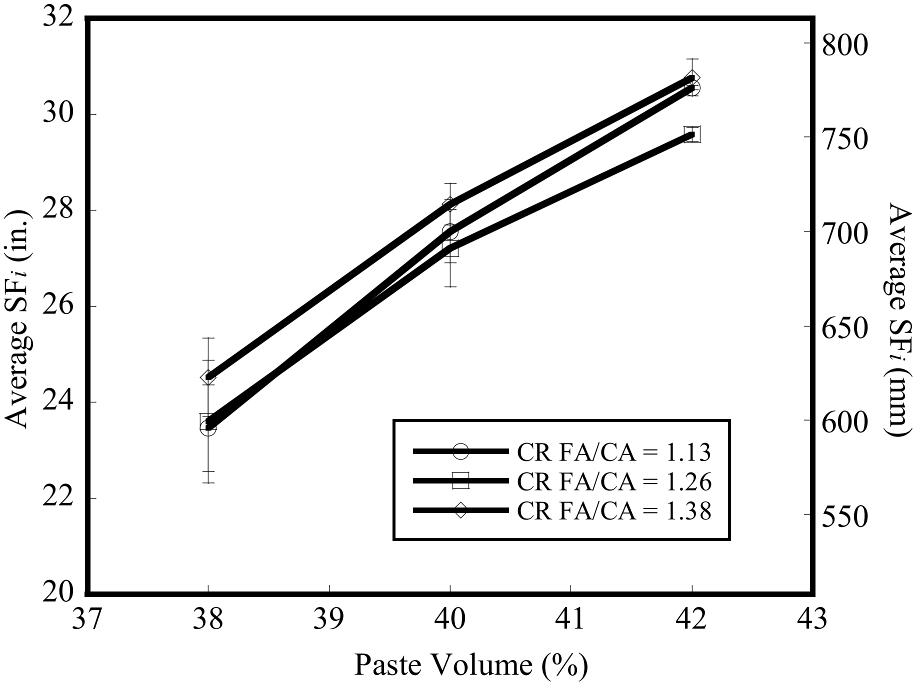

Figure 4.10. Average SF$_i$ versus Percent Paste Volume for CR Mixtures

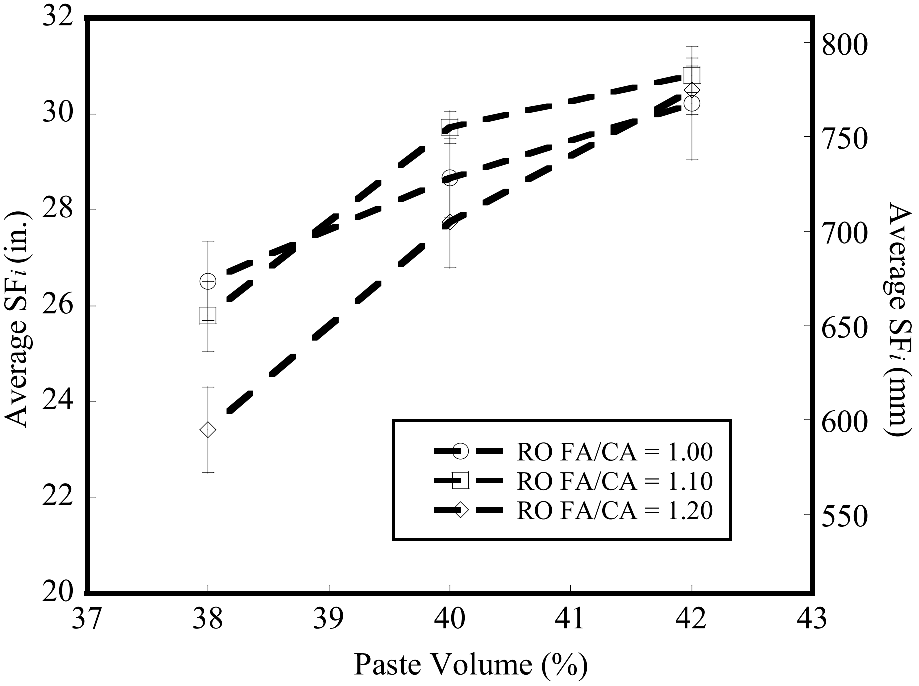

Figure 4.11. Average SF$_i$ versus Percent Paste for RO Mixtures

To compare the general SF_i values of the concretes containing the different aggregate types, the average SF_i values for all FA/CA values containing each type were determined and compared as a function of paste volume. Figure 4.12 shows the average SF_i values as a function of paste volume for the CR and RO mixtures. The RO mixtures generally have higher average SF_i values than the CR mixtures at the same paste volume. However, the difference between the average SF_i values decreases with increasing paste volumes for the CR and RO mixtures. Results indicate that concrete producers wanting to reduce the amount of paste volume could use a rounded CA such as the RO aggregate used in this research. Using the mixtures containing RO aggregate resulted in higher slump flow values than mixtures containing the CR aggregate at the same paste volumes.

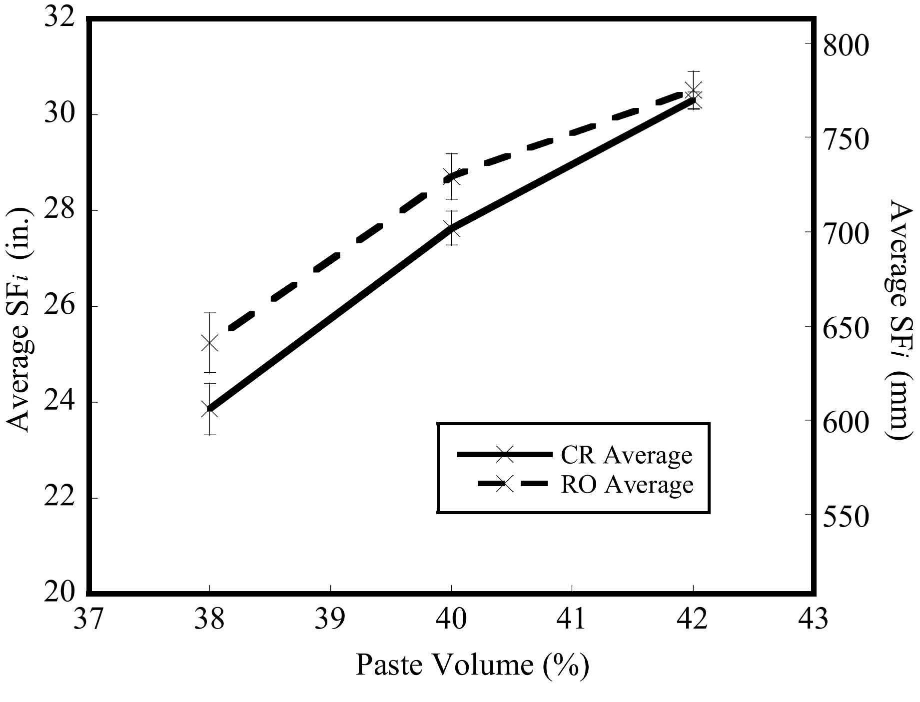

Figure 4.12. Average SF_i for CR and RO Mixtures

The influence of FA/CA on the average SF_i is also assessed in this research. For these cases, the average SF_i is plotted as a function of FA/CA for different paste volumes. The average SF_i values for the CR and RO mixtures are shown in Figures 4.13 and 4.14, respectively. However, these figures show that FA/CA has a small influence on the SF_i. For CR mixtures containing low paste volumes the average SF_i increases as the FA/CA increases. For the RO mixtures containing low paste volumes the average SF_i decreases as the FA/CA increases. However, the paste volume has a more significant influence on SF_i than the FA/CA.

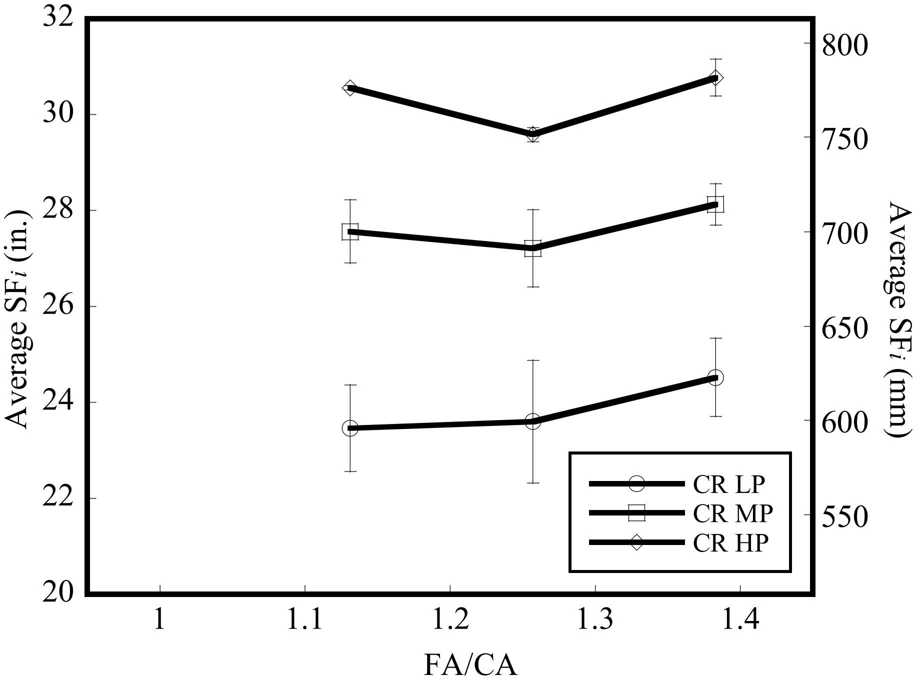

Figure 4.13. Average SF_i versus FA/CA for CR Mixtures

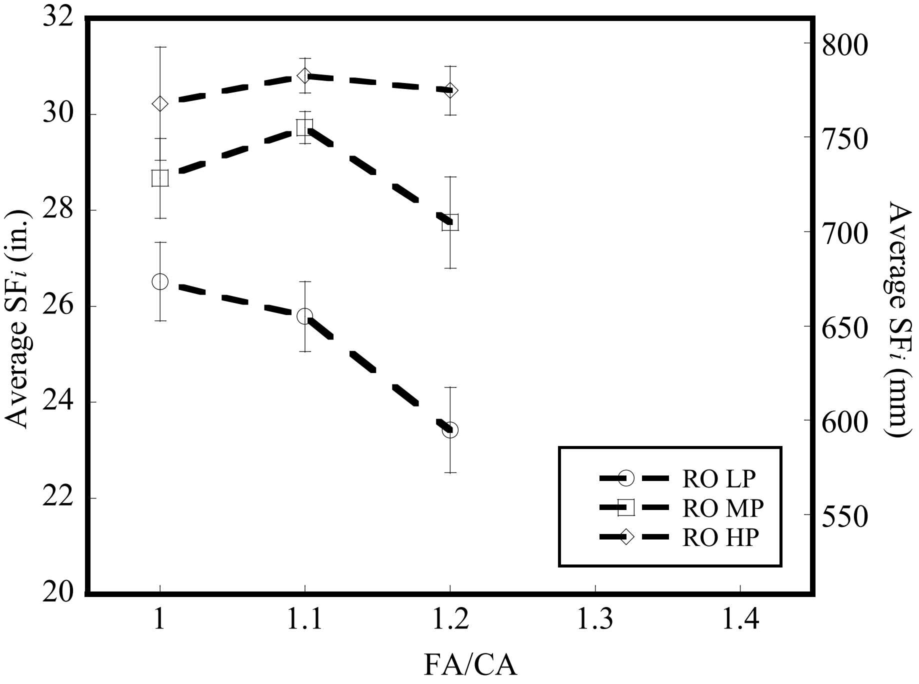

Figure 4.14. Average SF$_i$ versus FA/CA for RO Mixtures

One characteristic that changes with a change in the FA/CA is the AV content. The 1.38 FA/CA aggregate mixture exhibited the lowest AV content for the CR aggregate and the 1.00 FA/CA aggregate mixture exhibited the lowest AV content for the RO aggregate (Figure 3.3). For mixtures with the lowest paste volumes, the highest average SF$_i$ values were observed at the lowest AV content as shown in Figure 4.15. This figure shows that mixtures containing the lowest paste volumes exhibit increased SF$_i$ values as the AV content decreases for both the CR and RO mixtures.

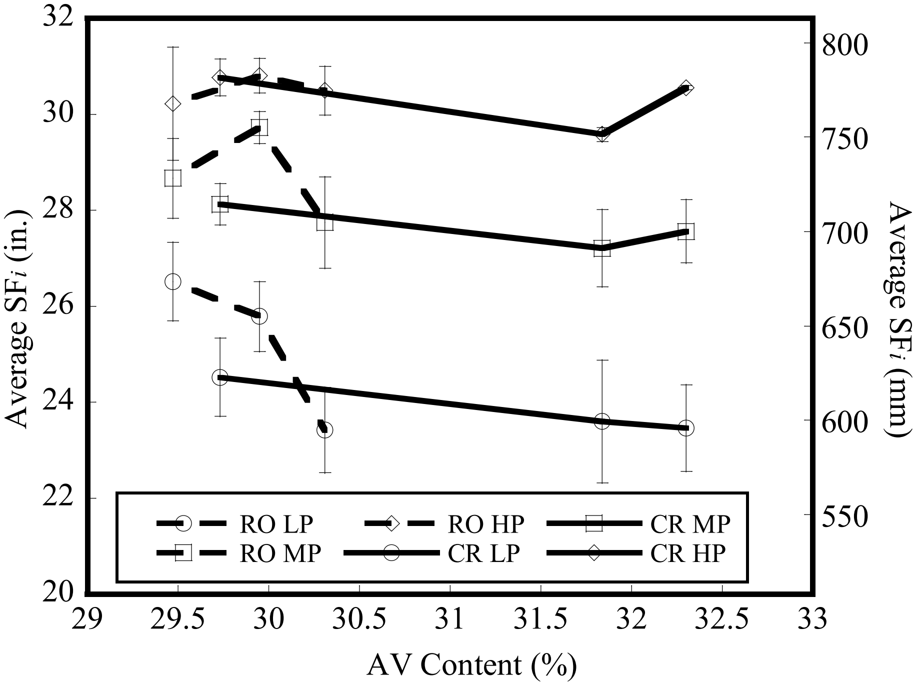

Figure 4.15. Average SF$_i$ versus AV Content for CR and RO Mixtures

For the CR and RO mixtures containing medium and high paste volumes the influence of the AV content on slump flow is unclear. However, the paste volume and the AV content are likely both influencing factors. Because of this, the ratio of the paste volume and AV content (PV/AV) is plotted versus the average SF$_i$ in Figure 4.16. This figure indicates that the SF$_i$ is significantly influenced by the PV/AV.

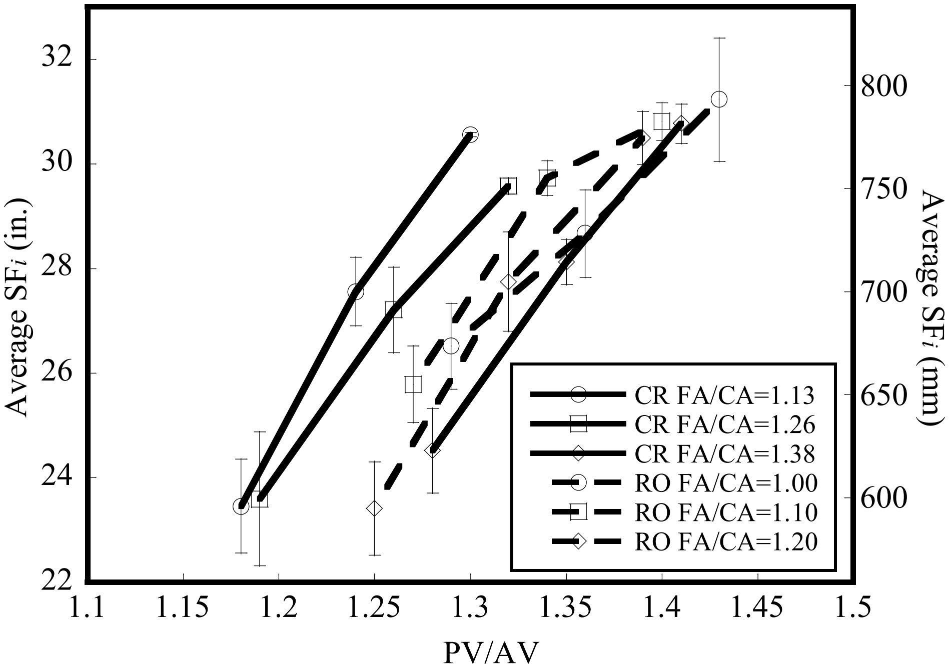

Figure 4.16. Average SF$_i$ versus PV/AV for CR and RO Mixtures

In addition to the slump flow measurements, K-slump tests were also performed. The K-slump tester is intended to estimate nominal slump. In this research the applicability of using the K-slump test to estimate the flowability of the HW concrete mixtures was assessed. The K-slump test is simple, uses smaller equipment, and can be performed in a relatively short time period (60 seconds) and therefore could add value for field investigations. The influence of paste volume on K-slump results are assessed in this research. The average K-slump results are shown in Figures 4.17 and 4.18 for the CR and RO mixtures, respectively. All mixtures were mixed and tested in triplicate. The figures show that the average K-slump values increase with increasing paste volumes. This general trend was also observed with the average SF$_i$ values.

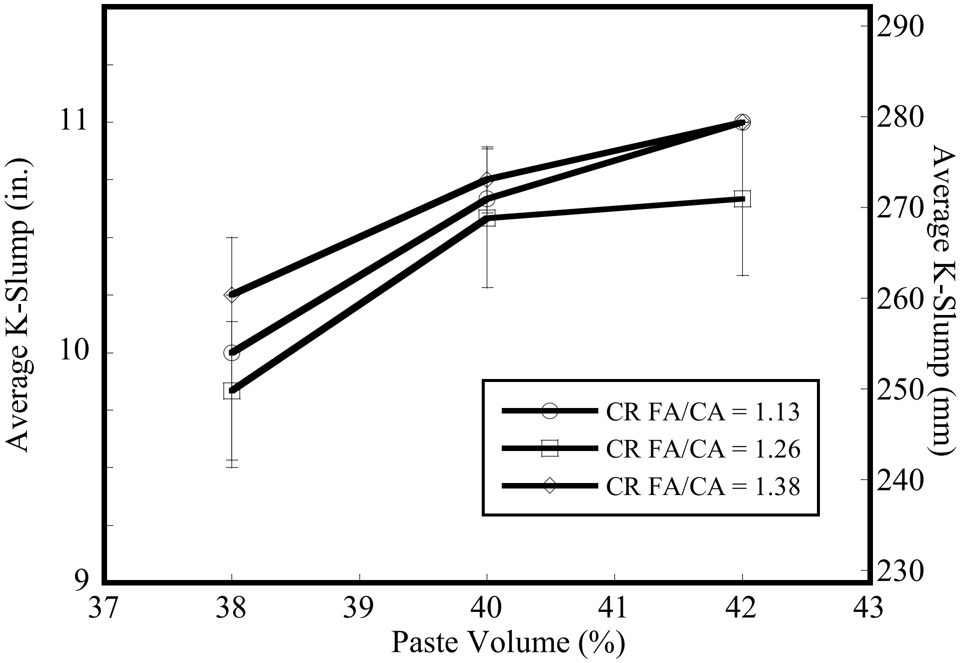

Figure 4.17. K-slump versus Percent Paste Volume for CR Mixtures

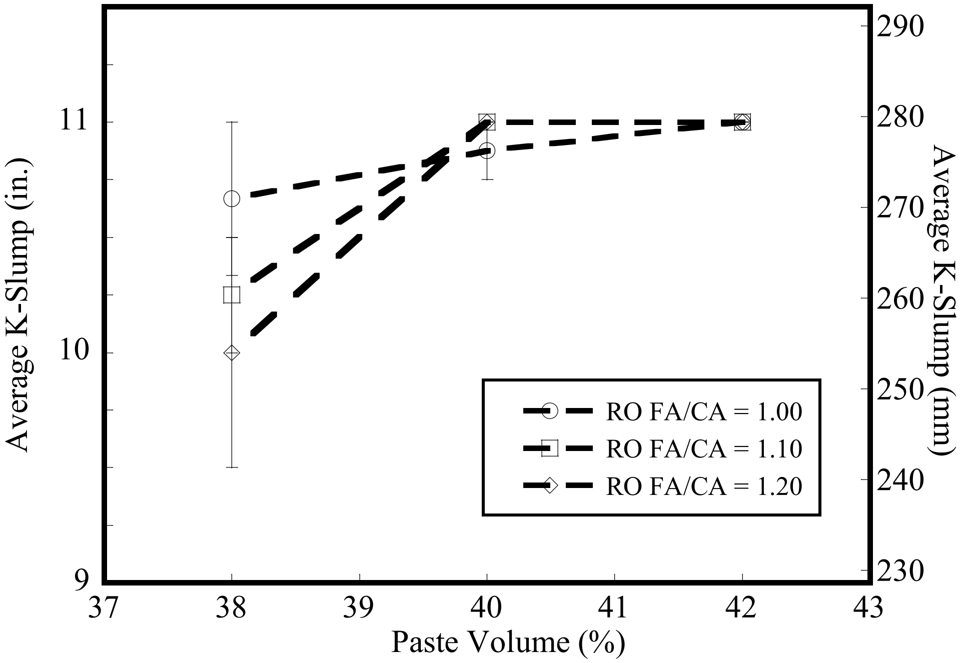

Figure 4.18. K-slump versus Percent Paste Volume for RO Mixtures

To determine if the K-slump test can assess flowability a correlation between SF_i and K-slump is assessed. The correlation between SF_i and K-slump is shown in Figures 4.19 and 4.20 for the CR and RO mixtures, respectively. The correlation between SF_i and K-slump exhibits a near linear trend. However, the K-slump instrument is limited to measuring 11 inches (280 mm) of nominal slump and this prevents the prediction of high SF_i values, especially for RO mixtures. In addition, a relationship between SF_i and K-slump for a concrete mixture with a specific FA/CA would have to be established so that K-slump could be used to estimate SF_i. Because the correlation between SF_i, and K-slump is limited by the max readings of the K-slump tester, further analysis will not be performed as part of this report. Further research is needed to assess its applicability.

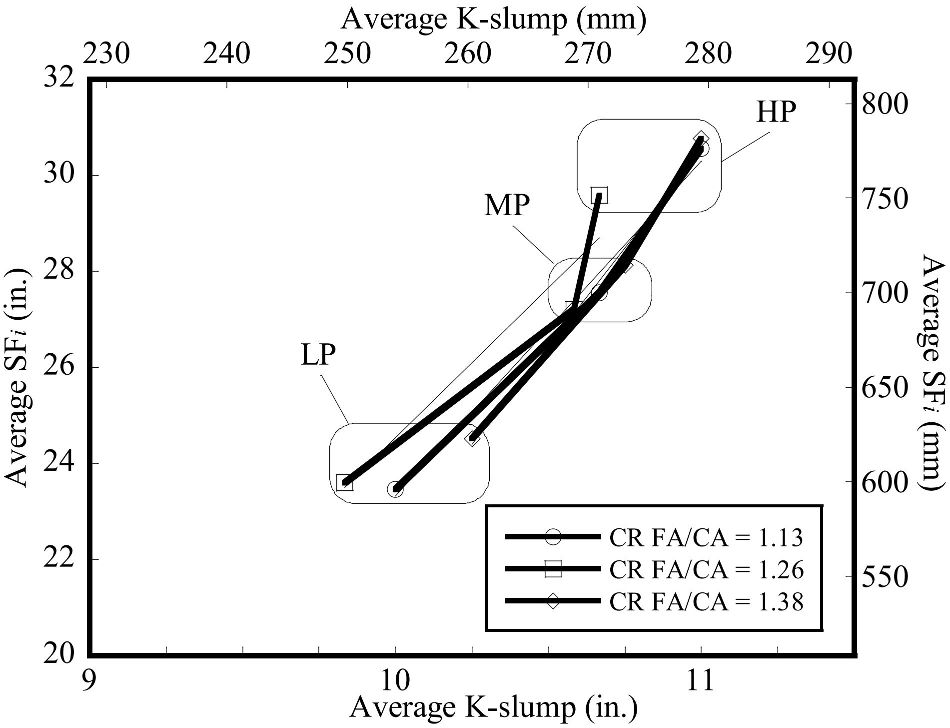

Figure 4.19. Slump Flow versus K-slump for CR Mixtures

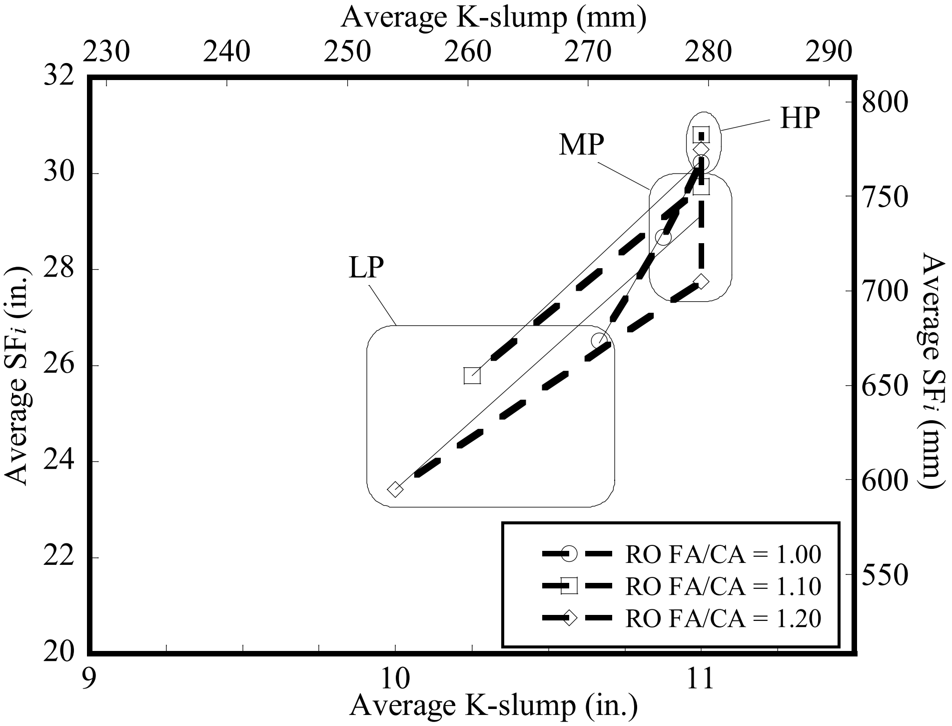

Figure 4.20. Slump Flow versus K-slump for RO Mixtures

4.2.2.1. Summary

The results for this section indicate that both the paste volume and AV content influence SF_i. The K-slump test has potential to be correlated to SF_i but the instrument has limitations that require further research to assess its applicability. The FA/CA influences the AV content and therefore, a modified ASTM C29-09 test including both FA and CA aggregates at various FA/CA could be a useful test to assess the AV content and predict flowability. For the FA/CA values used in this study the RO aggregate exhibited the lowest AV content. Also the results indicate the RO mixtures exhibited greater SF_i values than the CR mixtures at the same paste content.

4.2.3. Influence of Aggregate Type and Mixture Proportions on Stability

The stability of HW concrete mixtures is qualitatively assessed here with VSI. The influence of paste volume on VSI is assessed first. The VSI with respect to paste volume is shown in Figures 4.21 and 4.22 for the CR and RO mixtures, respectively. Concrete mixtures that exhibit a VSI of 1 or less are considered to have adequate stability. These figures show that increasing the paste volume can decrease stability. These results are consistent with the results observed in the preliminary investigations on the influence of *w/cm* on stability. It should be noted the VSI is measured at the beginning of concrete workability testing.

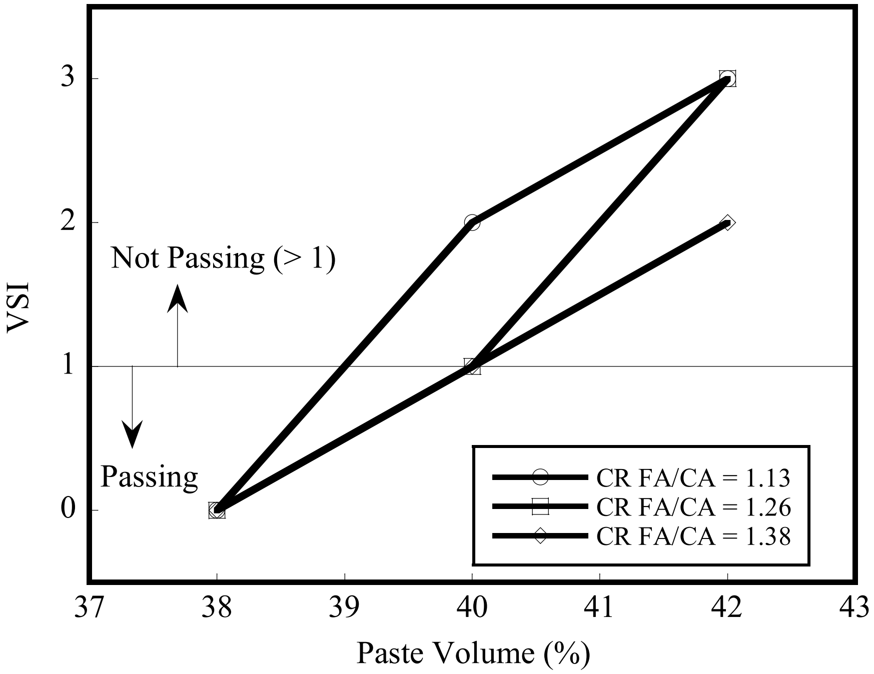

Figure 4.21. VSI versus Percent Paste Volume for CR Mixtures

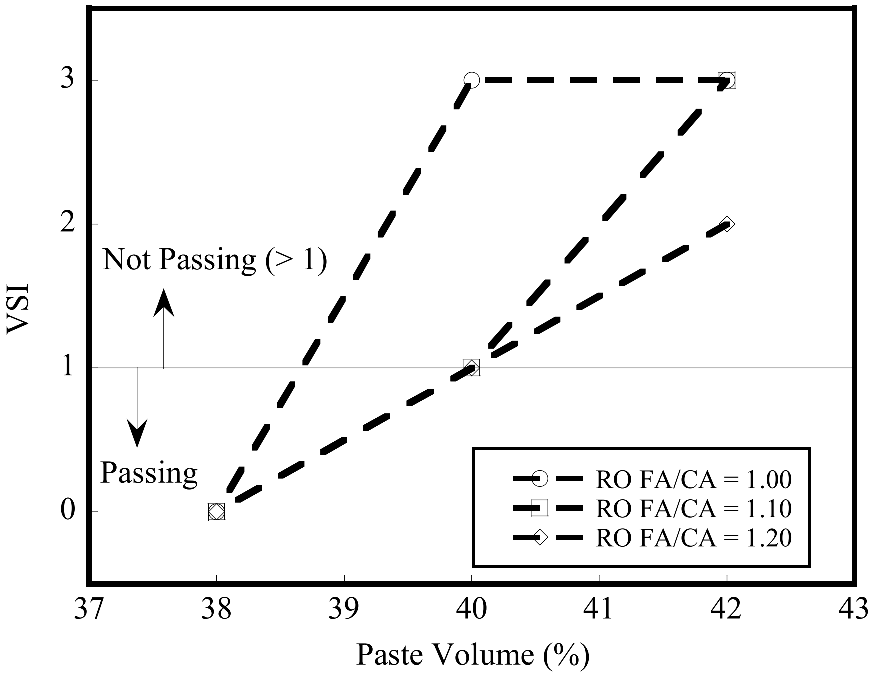

Figure 4.22. VSI versus Percent Paste Volume for RO Mixtures

The influence of FA/CA on VSI is also assessed here. The VSI versus FA/CA is shown for the CR and RO mixtures in Figures 4.23 and 4.24, respectively. The FA/CA has a slight influence on VSI for both concrete mixture types. Generally, as the FA/CA increases the VSI decreases (stability increases) for both concrete mixtures types. The results indicate that both paste volume and FA/CA have an influence on stability.

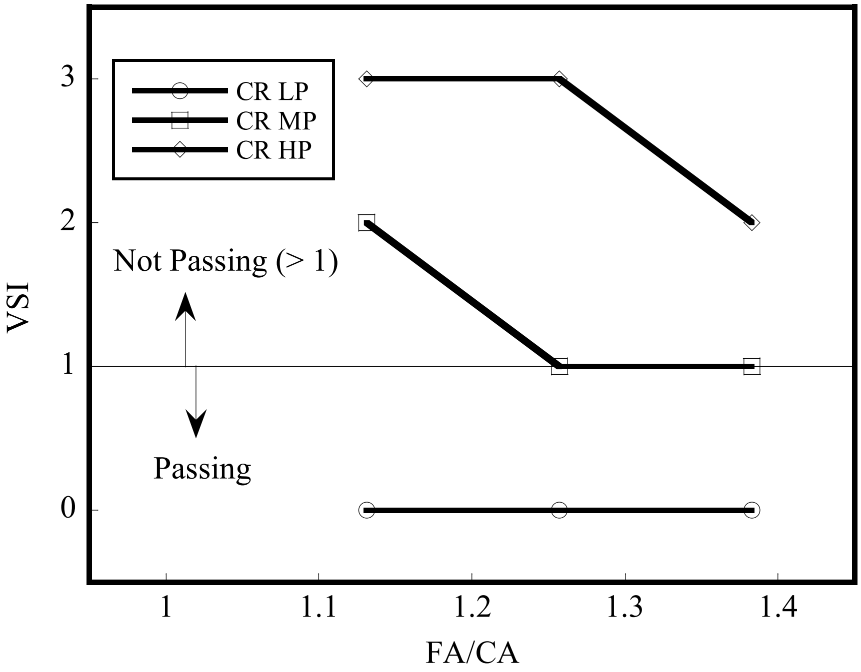

Figure 4.23. VSI versus FA/CA for CR Mixtures

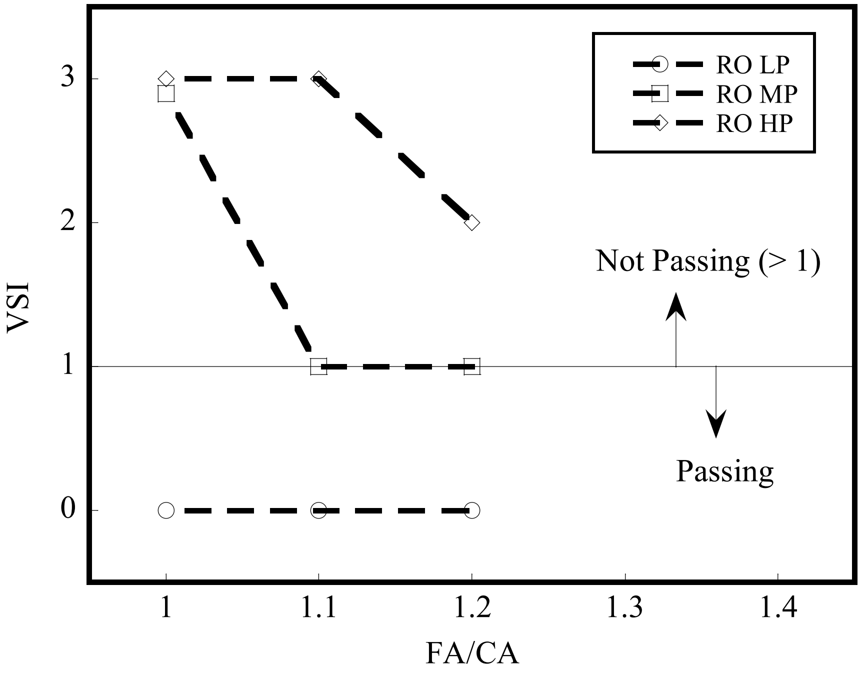

Figure 4.24. VSI versus FA/CA for RO Mixtures

The VSI as a function of the AV content is shown in Figure 4.25 for both the CR and RO mixtures. Generally, the CR mixtures increase in stability as the AV content decreases. However, the stability of RO mixtures generally increases as the AV content increases. Note that these FA/CA values were selected in the preliminary investigation of workability. The trend in the stability curves are not similar because for CR mixtures, the combined void content decreases as FA/CA increases and for RO mixtures, the combined void content increases as the FA/CA increases. This indicates that the FA/CA is the significant factor that influences VSI (concrete stability).

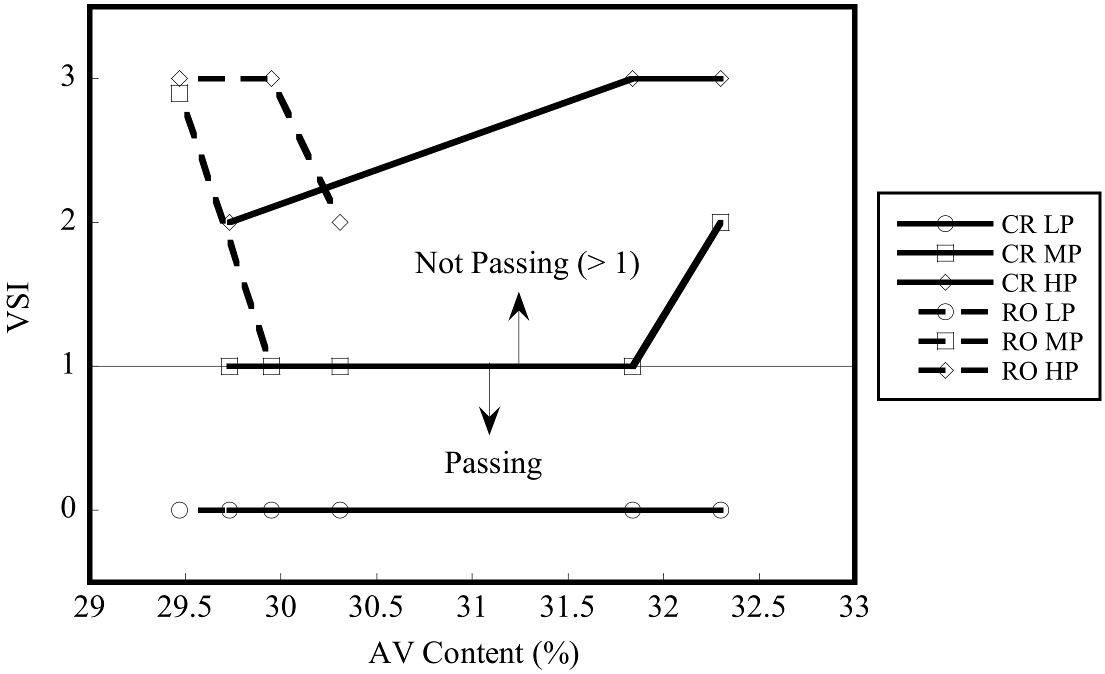

Figure 4.25. VSI versus AV Content for CR and RO Mixtures

The influence of PV/AV on VSI is shown in Figures 4.26 and 4.27 for the CR and RO mixtures, respectively. The VSI results indicate that a change in PV/AV has a significant influence on the stability of the mixtures. Therefore, results indicate that both the FA/CA and PV/AV can significantly influence stability. This would be expected as FA/CA influences the surface area of the aggregate which influences stability. Based on these stability results a maximum PV/AV limit can be estimated for each aggregate type and FA/CA aggregate mixture to achieve adequate stability. For the CR mixtures the maximum PV/AV values to achieve passable VSI results (stability) are approximately 1.21, 1.25, and 1.35 for mixtures containing 1.13, 1.26, and 1.38 FA/CA contents. For RO mixtures the maximum PV/AV values are approximately 1.31, 1.34, and 1.32 for mixtures containing 1.00, 1.10, and 1.20 FA/CA contents.

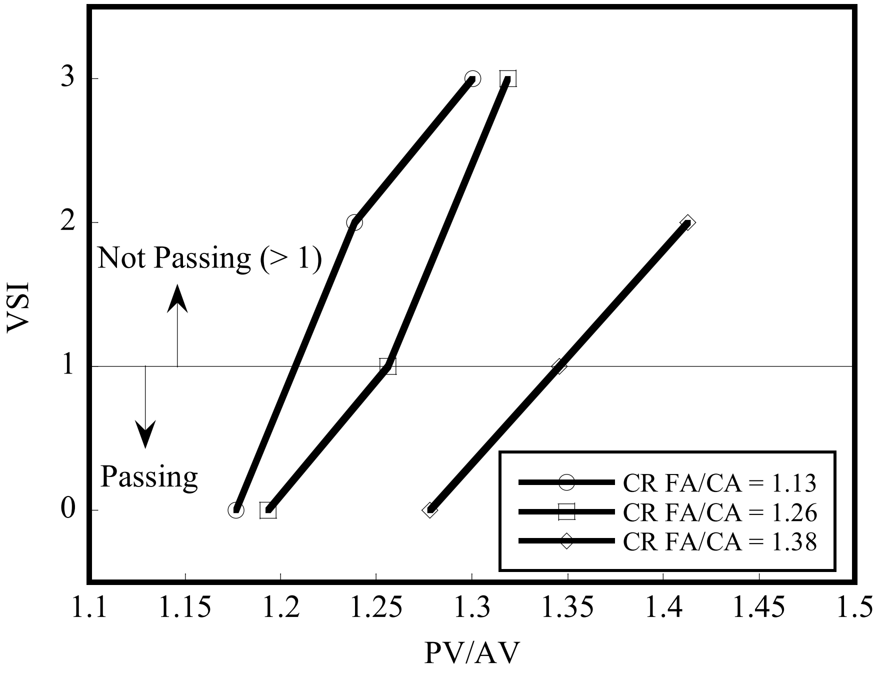

Figure 4.26. VSI versus PV/AV for CR Mixtures

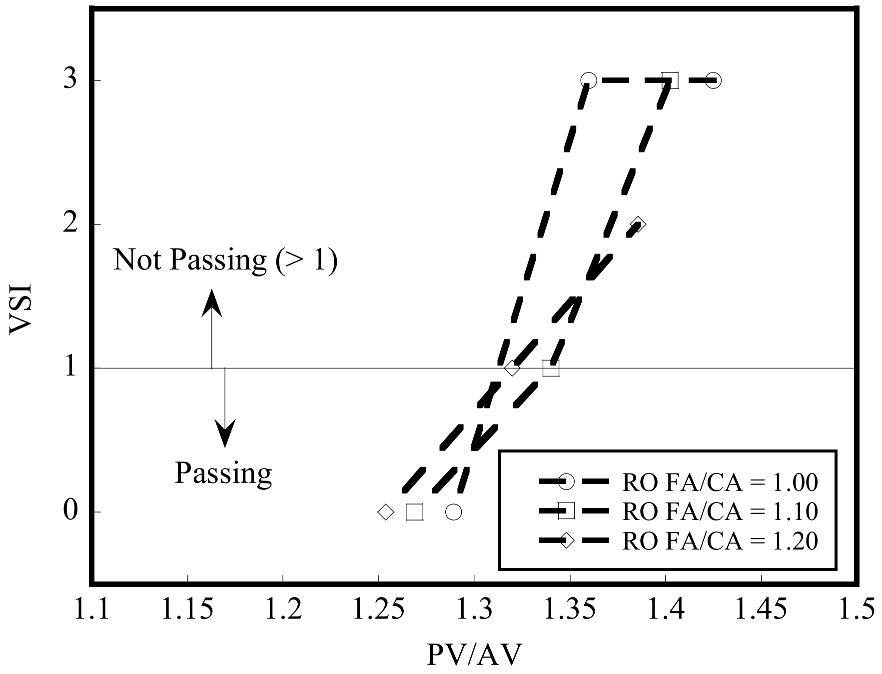

Figure 4.27. VSI versus PV/AV for RO Mixtures

The VSI testing assessed stability for HW concrete mixtures. However, the VBI_J test may be used to qualitatively assess the stability and passing ability of HW concrete mixtures. Because the VBI_J test assesses both stability and passing ability, the mixtures that fail this test could be a result of either characteristic. This makes the assessment of relating failure to a specific characteristic more challenging. As with the VSI assessment the VBI_J will also be plotted versus paste volume, FA/CA, AV content, and PV/AV. The influence of paste volume on VBI_J for the CR and RO mixtures are shown in Figures 4.28 and 4.29, respectively. A VBI_J of 1 or less is considered passing. These figures show that increasing the paste volume can increase the VBI_J (decrease stability). Also mixtures with low paste volumes can have a high VBI_J (low passing ability).

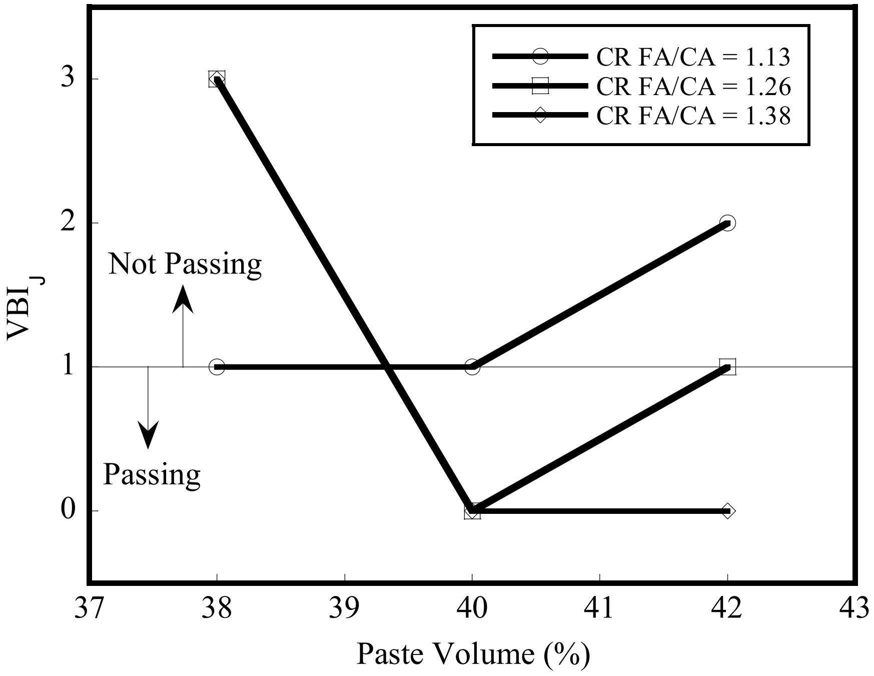

Figure 4.28. VBI$_J$ versus Percent Paste Volume for CR Mixtures

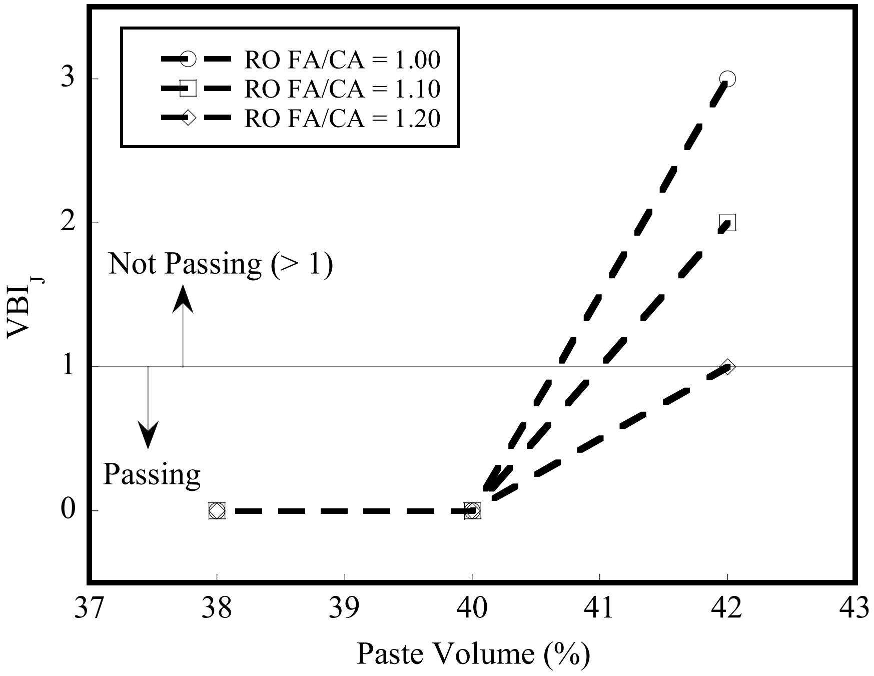

Figure 4.29. VBI$_J$ versus Percent Paste Volume for RO Mixtures

The VBI_J results for the CR and RO mixtures are plotted against FA/CA in Figures 4.30 and 4.31, respectively. Figure 4.30 shows that for CR mixtures the FA/CA can either increase or decrease in VBI_J and this depends on the paste volume of the mixture. The CR mixtures with low paste volumes have high VBI_J values at higher FA/CA values due low passing ability (blocking). The CR mixtures with high paste volumes exhibit a decrease in VBI_J (increased stability) at increased FA/CA values.

Figure 4.31 shows that for the RO mixtures, most of the mixtures pass the VBI_J test. The RO mixture with the 1.00 FA/CA and low paste volume did not pass due to a low passing ability. More RO mixtures with low paste volumes pass the VBI_J test than the CR mixtures with low paste volumes. Paste volume seems to be a more significant factor influencing VBI_J when compared with FA/CA values.

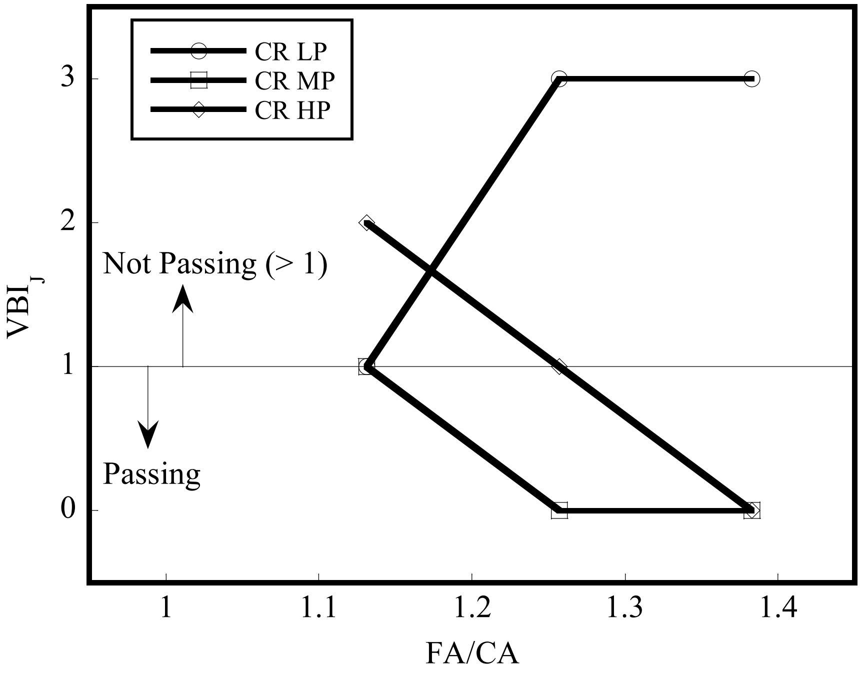

Figure 4.30. VBI_J versus FA/CA for CR Mixtures

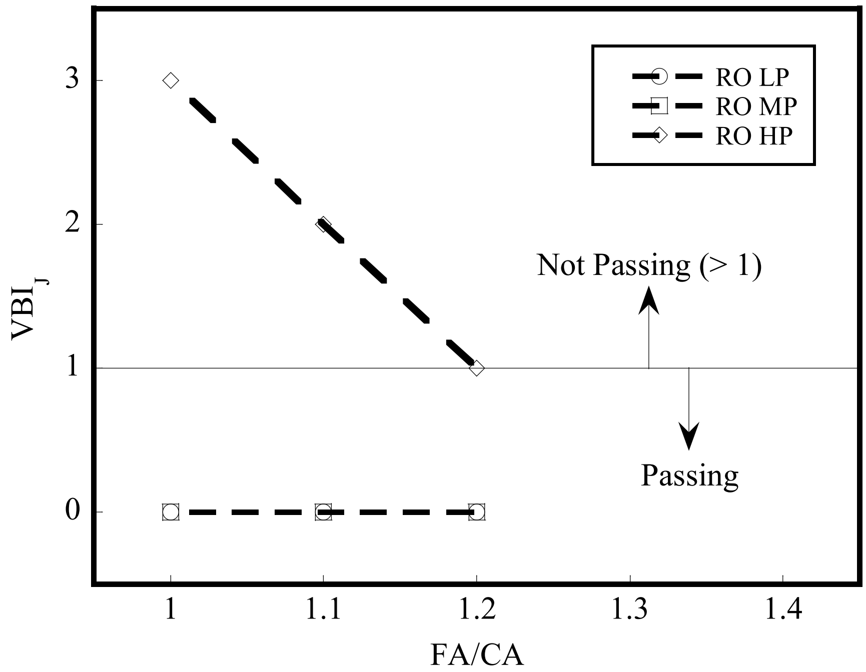

Figure 4.31. VBI_J versus FA/CA for RO Mixtures

The VBI_J results are plotted against AV content for the CR and RO mixtures in Figure 4.32. The influence of AV content on VBI_J results are similar to the VSI results plotted versus AV content. The AV content decreases as the FA/CA increases for the CR mixtures and the AV content increases as the FA/CA increases for the RO mixtures. Therefore, the CR mixtures exhibit different trends than the RO mixtures when plotted versus the AV content. This was also observed for the VSI values. Therefore, significant factors influencing VBI_J include the FA/CA and paste volume.

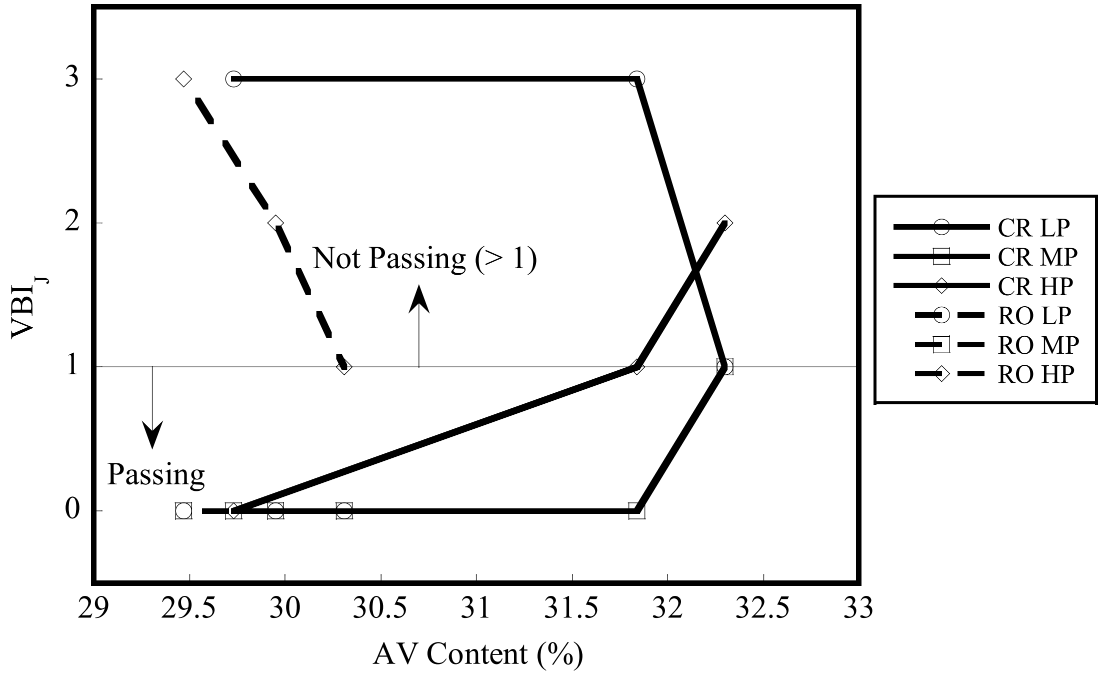

Figure 4.32. VBI_J versus AV for CR and RO Mixtures

The VBI_J results are plotted versus PV/AV for CR and RO mixtures as shown in Figures 4.33 and 4.34, respectively. These figures show that the PV/AV has a significant influence on VBI_J. Therefore, the significant influencing factors on VBI_J are the PV/AV and FA/CA values.

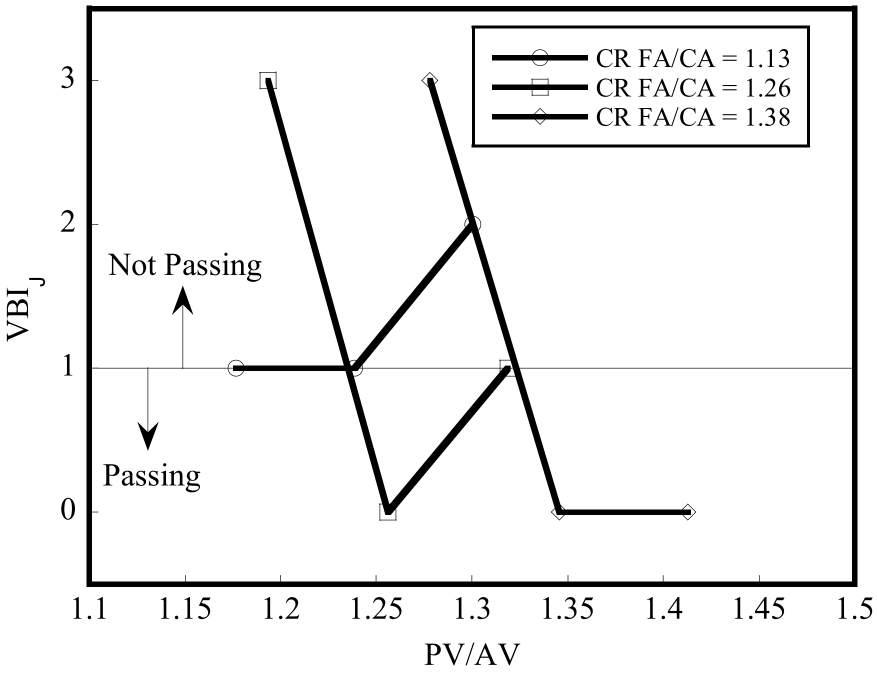

Figure 4.33. VBI$_J$ versus PV/AV for CR Mixtures

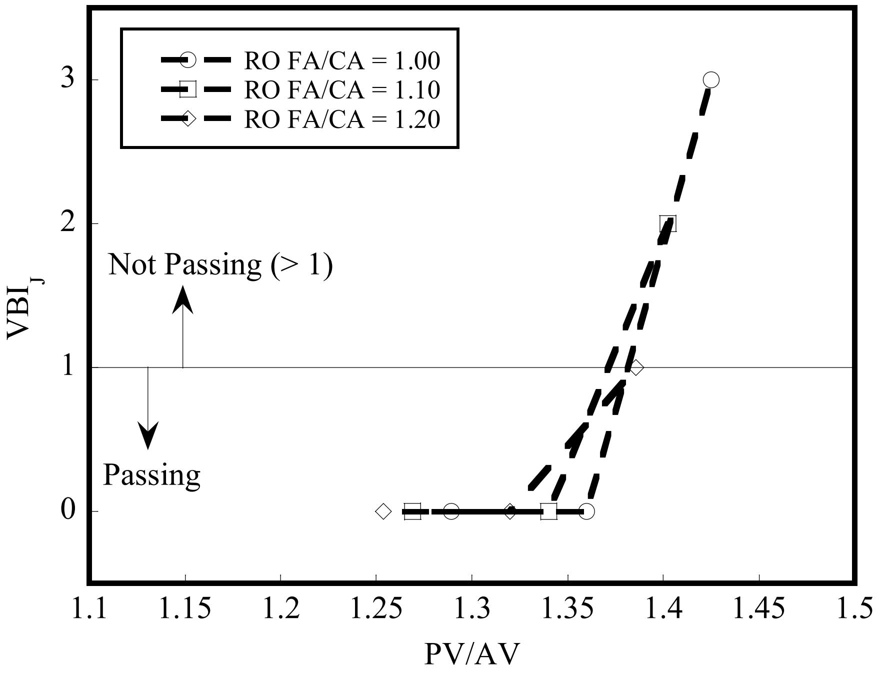

Figure 4.34. VBI$_J$ versus PV/AV for RO Mixtures

Another VBI test assessed in this study is the VBI_C test. As with the other test assessments, the influence of paste volume, FA/CA, AV content, and PV/AV on VBI_C is assessed. The VBI_C results for the CR and RO mixtures are shown in Figures 4.35 and 4.36, respectively. These figures show that there are instances where concrete mixtures with low paste volume increase the VBI_C due to poor passing ability (blocking). However, there are mixtures with high paste volumes that do not pass the VBI_C due to low stability. Note that this test assesses both stability and passing ability which can result in a mixture to failing by either characteristic.

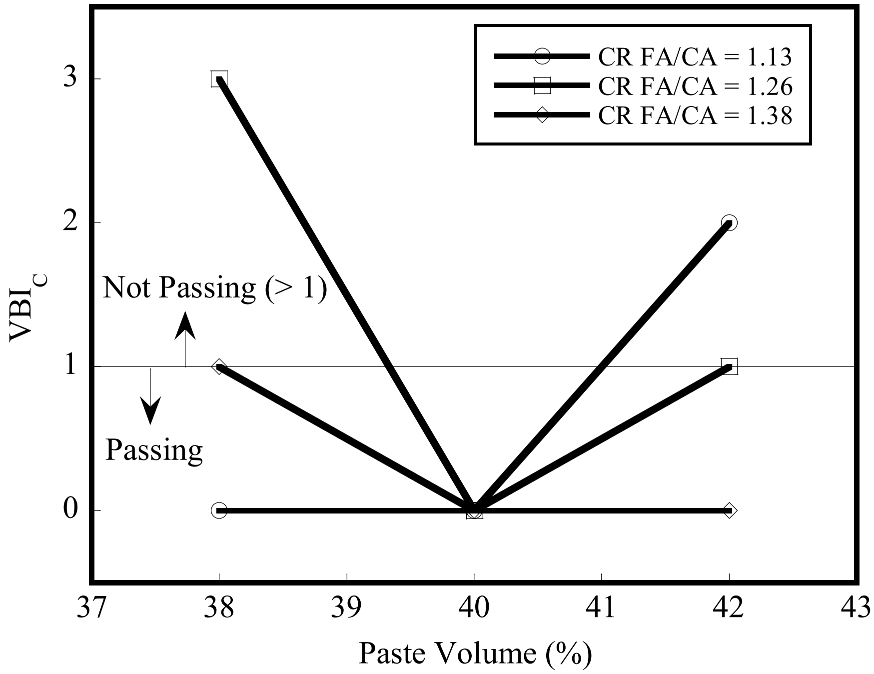

Figure 4.35. VBI_C versus Percent Paste Volume for CR Mixtures

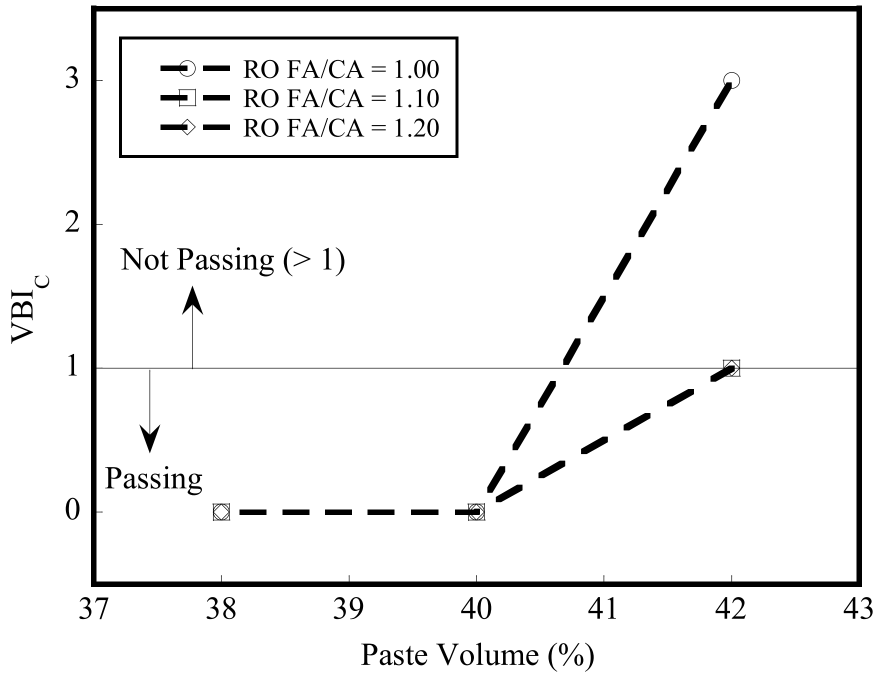

Figure 4.36. VBI$_C$ versus Percent Paste Volume for RO Mixtures

The VBI$_C$ results for the CR and RO mixtures, shown in Figures 4.37 and 4.38, respectively, show that mixtures with high paste volumes generally have a decreased VBI$_C$ with increased FA/CA. This is due to a slight increase in stability with an increase in FA/CA. The concrete mixtures containing low paste volumes that do not pass the VBI$_C$ test have poor passing ability. Paste volume is a more significant influencing factor on VBI$_C$ compared to the FA/CA value.

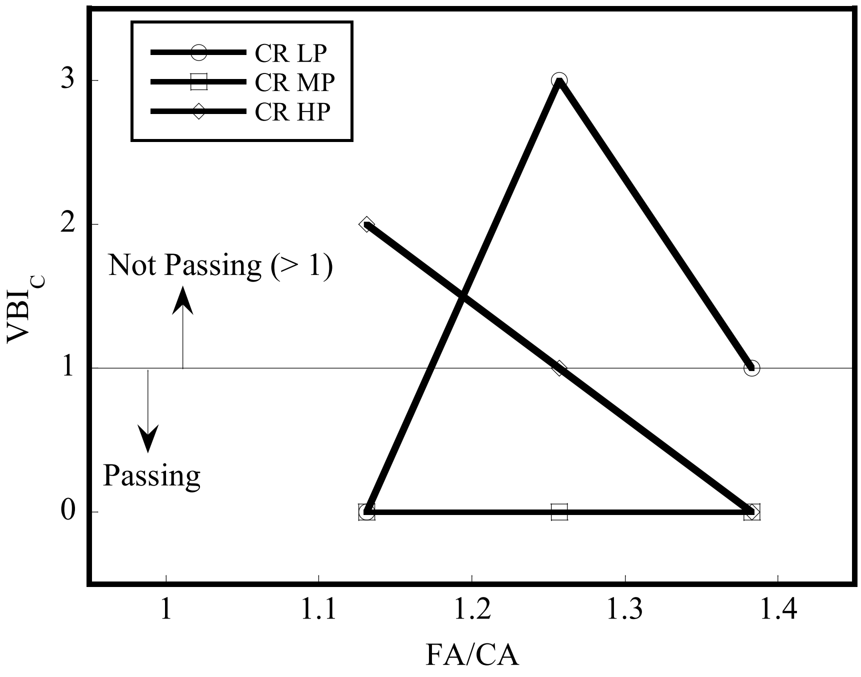

Figure 4.37. VBI$_C$ versus FA/CA for CR Mixtures

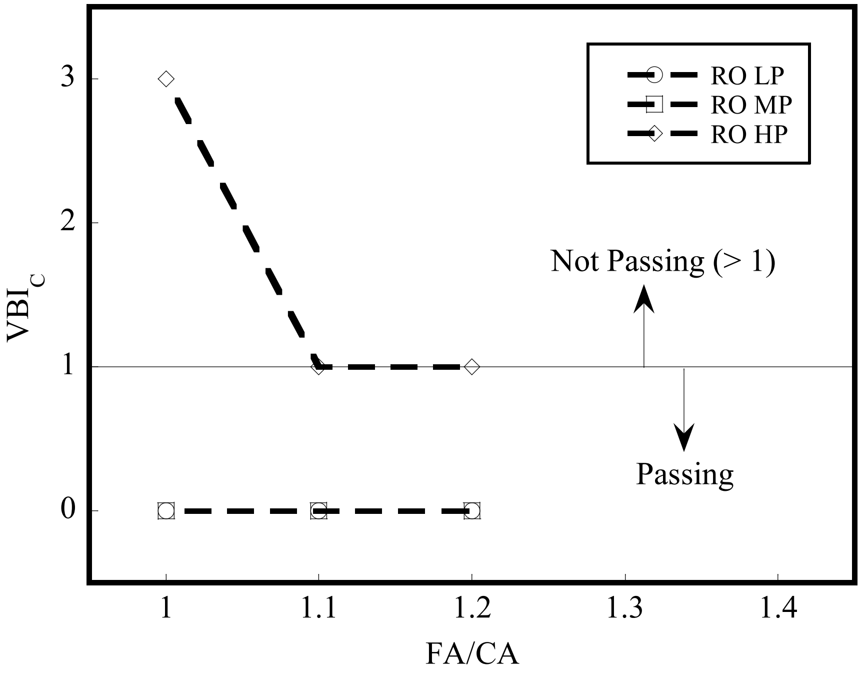

Figure 4.38. VBI$_C$ versus FA/CA for RO Mixtures

The influence of AV Content on VBI$_C$ is also assessed. The VBI$_C$ results as a function of AV content for the CR and RO mixtures are shown in Figure 3.39. Similar results are observed for VBI$_C$ as the results for the VBI$_J$.

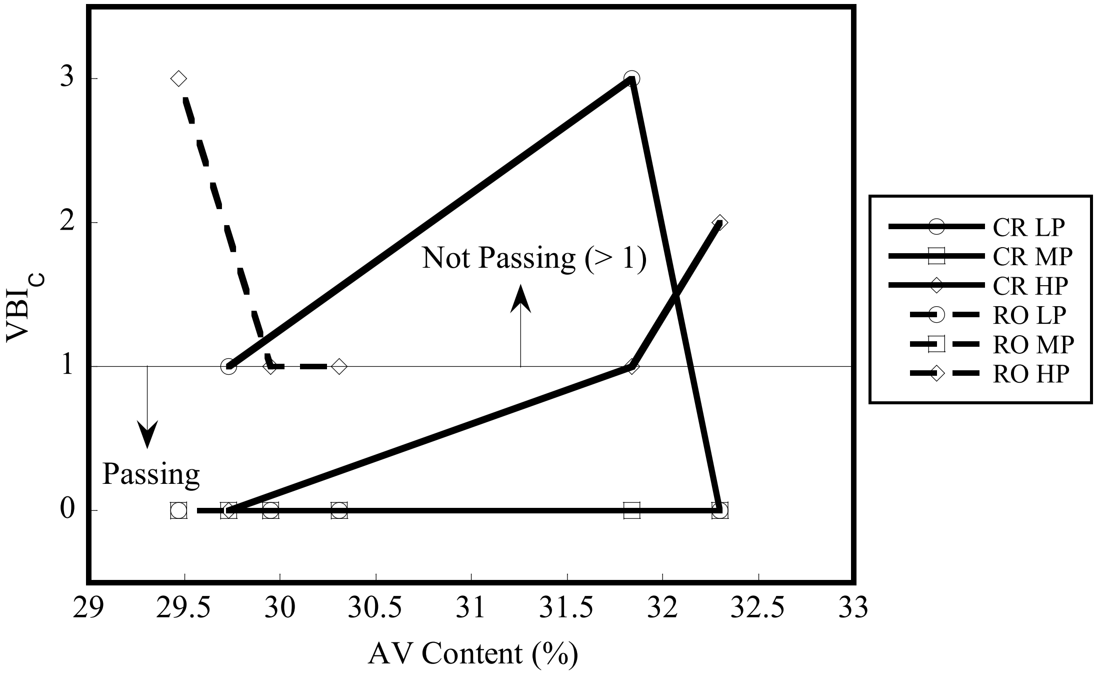

Figure 4.39. VBI$_C$ versus AV Content for CR and RO Mixtures

Figures 4.40 and 4.41 show the VBI$_C$ values as a function of the PV/AV for the CR and RO mixtures, respectively. These figures show that PV/AV significantly influences the VBI$_C$ values. This indicates that both the PV/AV and FA/CA values are the significant factors influencing the VBI$_C$ values.

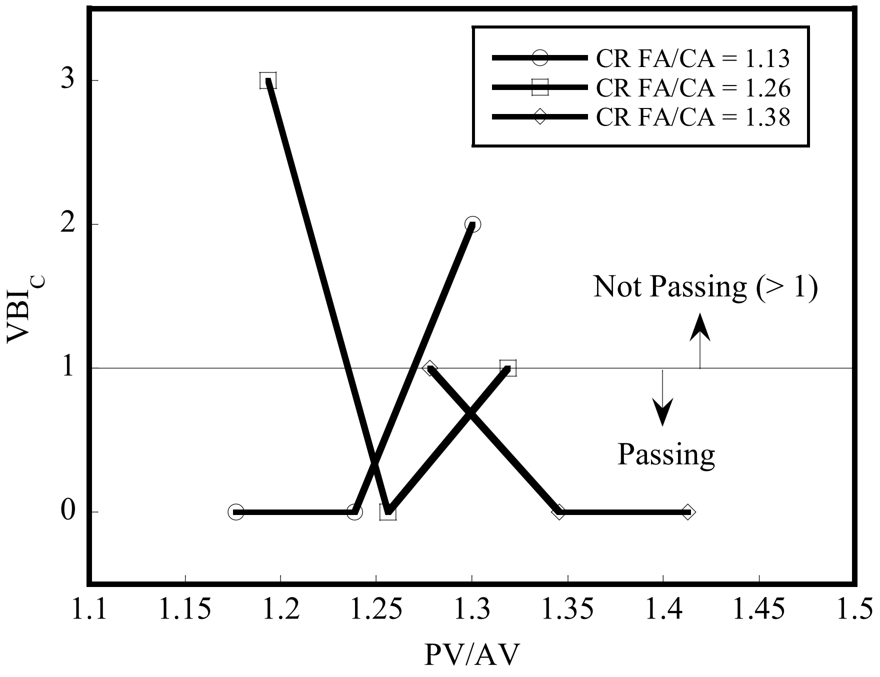

Figure 4.40. VBI_C versus PV/AV for CR Mixtures

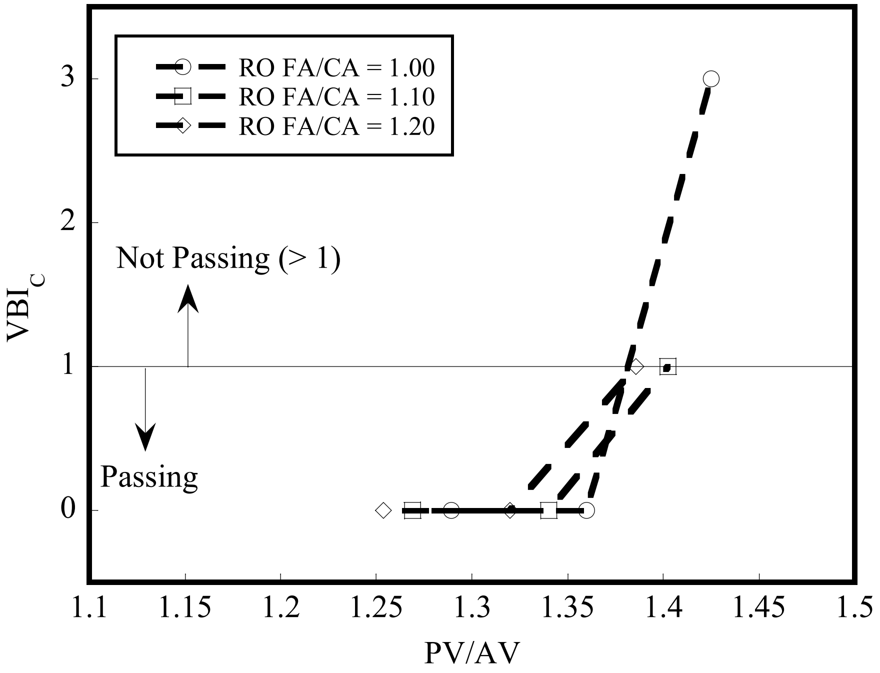

Figure 4.41. VBI_C versus PV/AV for RO Mixtures

4.2.3.1. Summary

Stability of a mixture is critical for proper placement. The VSI test is a simple test that could be used to qualitatively assess the stability of HW concrete mixtures. The influence of paste volume, FA/CA, AV content, and PV/AV on VSI was assessed. The results indicated that PV/AV and FA/CA are influencing factors on VSI (stability). However, the influence of PV/AV seems to be dependent on the FA/CA. Different limits on PV/AV can be placed on concrete mixture proportion depending on the FA/CA. Mixtures generally increased in stability as the FA/CA increased because the surface area of the aggregate increased as the FA/CA increased.

Based on VBI test results (VBI_J and VBI_C) a clear threshold or limit for mixture proportions based on stability is challenging to define when using this test. This is because the VBI tests assess both passing ability and stability. Mixtures could fail as a result of inadequate passing ability or stability and therefore no clear trend of the influence of mixture proportions on VBI, specifically stability, is observed. However, the lack of a clear trend does not mean the VBI test is not useful to assess passing ability.

4.2.4. Influence of Aggregate Type and Mixture Proportions on Passing Ability

ASTM 1621-09 reports that J-ring passability is the measure of the difference between slump flow and J-ring flow. For this research the estimated time variant slump flow (SF_{etv}) values are used for determining the J-ring passability. A concrete mixture with a J-ring passability measurement that is equal to or less than 2 inches (50 mm) is considered to have adequate passing ability (ASTM 1621-09). Note that lower J-ring results indicate that the concrete mixture exhibits higher passing ability.

As with the other results presented in this report, the J-ring passability results are plotted versus paste volume, FA/CA, AV content, and PV/AV. The J-ring passability is plotted as a function of paste volume for the CR and RO mixtures, as shown in Figures 4.42 and 4.43, respectively. Note that negative values are shown in these figures and this may be due to variation in the SF_{etv} and actual slump flow or due to variations in mixtures. For the CR mixtures containing the 1.13 FA/CA the J-ring passability values increase (passing ability decreases) as the paste volume increases. However, for the CR mixtures containing the 1.26 FA/CA the J-ring passability values increase (passing ability decreases) as the paste volume increases. The reason for this increase is unknown as more paste volume should increase passing ability. Even so, all mixtures passed except for the mixture containing a low paste volume and 1.26 FA/CA content. For the CR mixtures containing the 1.38 FA/CA the J-ring passability values show little change as the paste volume increases.

The RO mixtures in Figure 4.43 show various trends depending on the FA/CA value. For RO mixtures containing the 1.00 FA/CA the J-ring passability values increase (passing ability decreases) as paste volume increases. For RO mixtures containing the 1.10 FA/CA the J-ring passability values decrease and increase as the paste volume increases. For RO mixtures containing the 1.20 FA/CA the J-ring passability values decrease as paste volume increases. There appears to be no general trend and the influence of paste volume on J-ring passing ability is unclear for both the CR and RO mixtures.

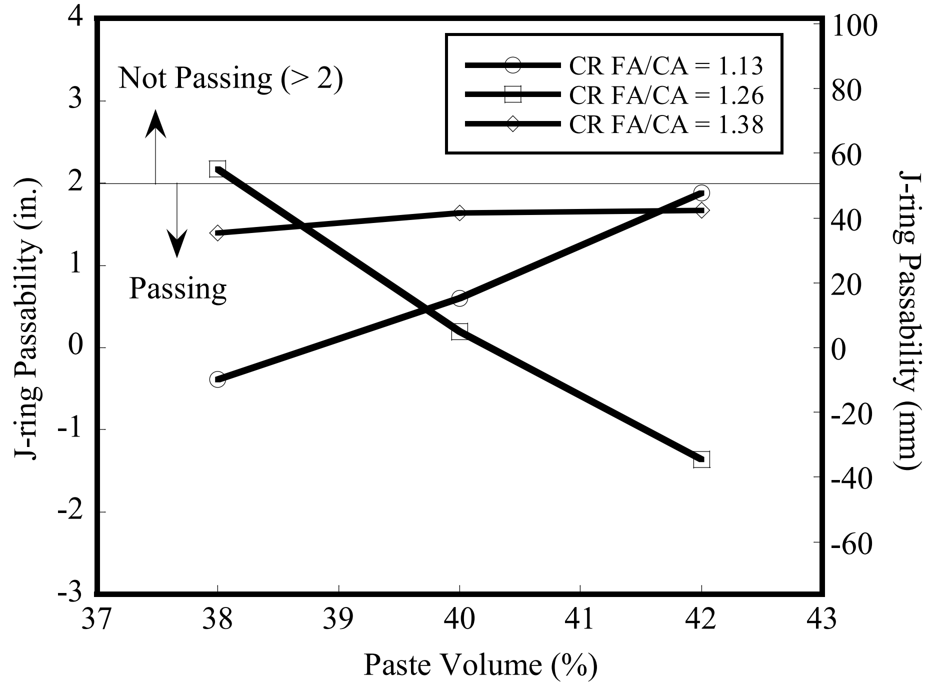

Figure 4.42. J-ring Passability versus Percent Paste Volume for CR Mixtures

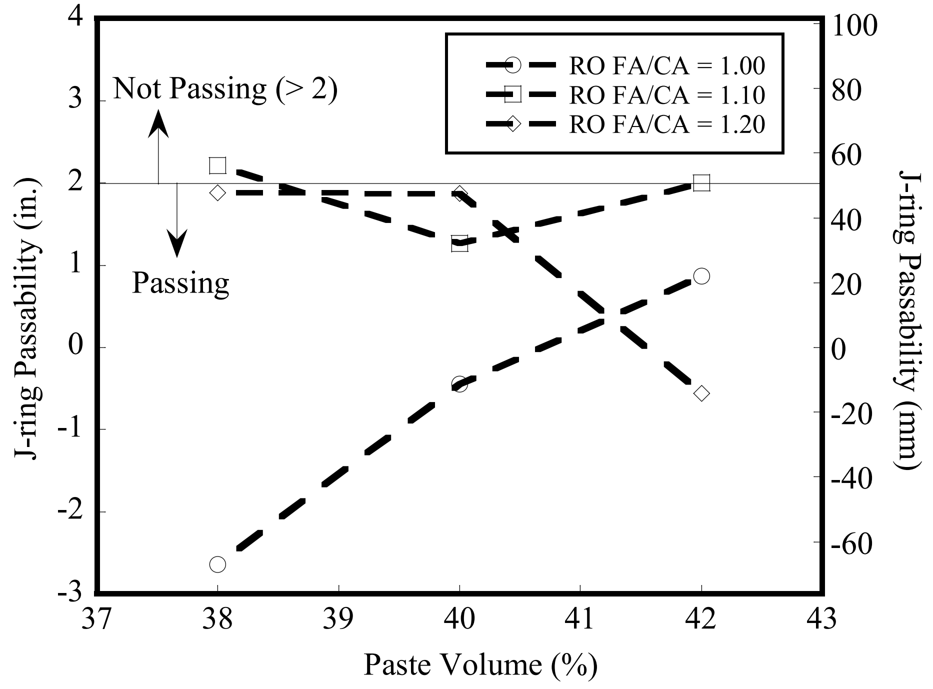

Figure 4.43. J-ring Passability versus Percent Paste Volume for RO Mixtures

The J-ring passability ratio is plotted against the FA/CA for the CR and RO mixtures in Figures 4.44 and 4.45, respectively. No clear trend between J-ring passability and PV/AV is observed.

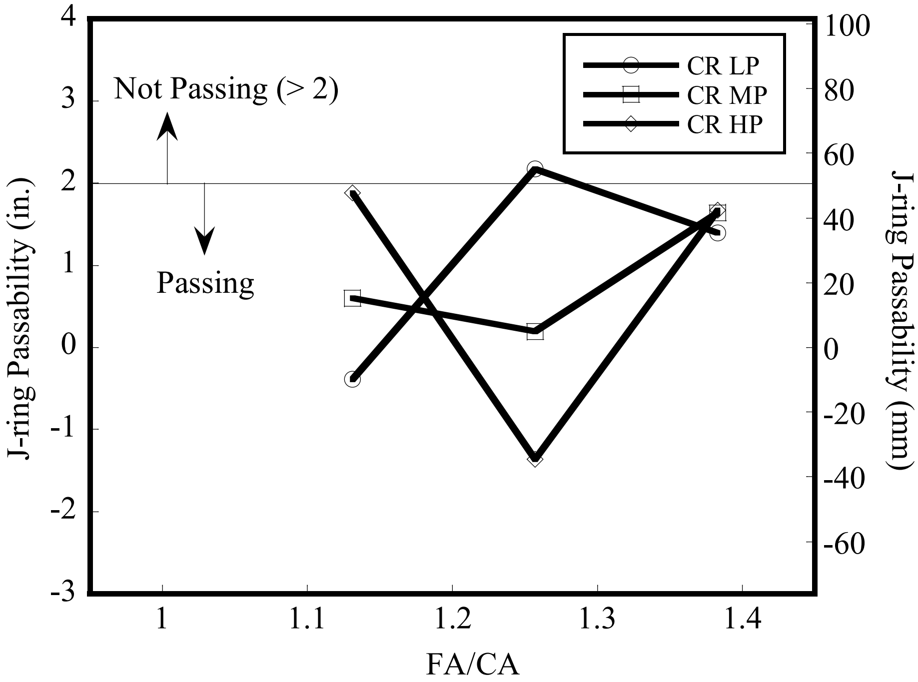

Figure 4.44. J-ring Passability versus FA/CA for CR Mixtures

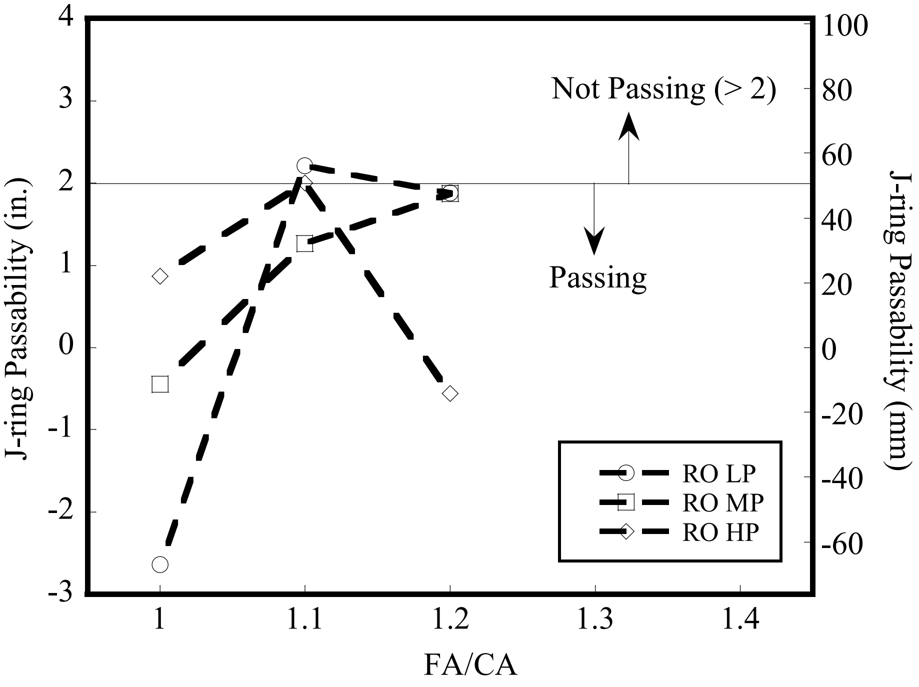

Figure 4.45. J-ring Passability versus FA/CA for RO Mixtures

Figure 4.46 shows the J-ring passability values plotted versus the AV content for CR and RO mixtures. These results again indicate no clear relation between J-ring passability and AV content. Figure 4.46 shows results similar to those shown in Figures 4.44 and 4.45.

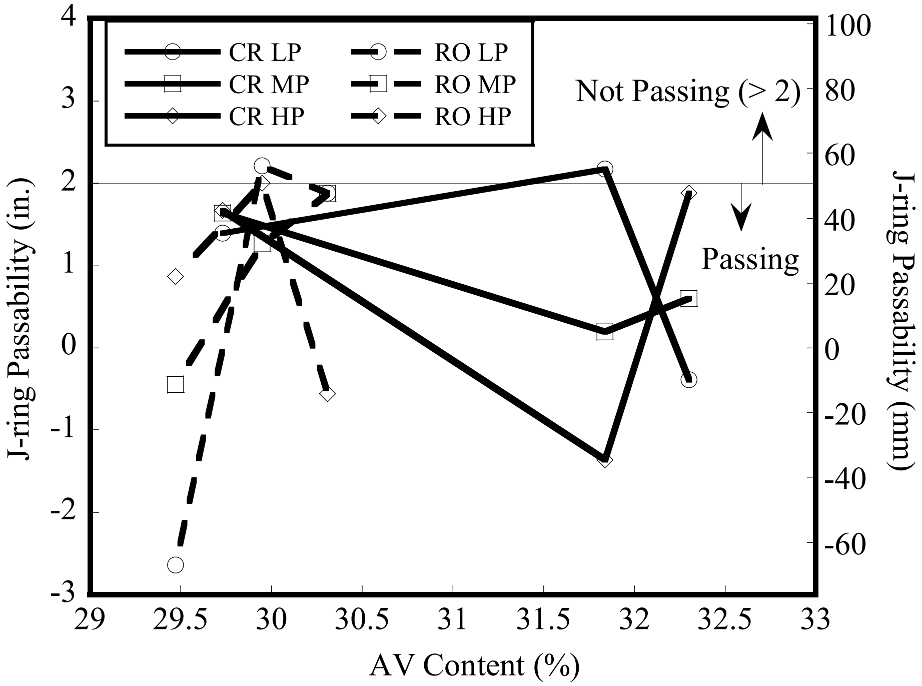

Figure 4.46. J-ring Passability versus AV Content for CR and RO Mixtures

The J-ring passability values are plotted versus the PV/AV in Figures 4.47 and 4.48 for the CR and RO mixtures, respectively. These figures show no general trend between J-ring passability and PV/AV. These results are consistent with the previous results. The J-ring test showed no general trend or sensitivity to the influence of mixture proportions.

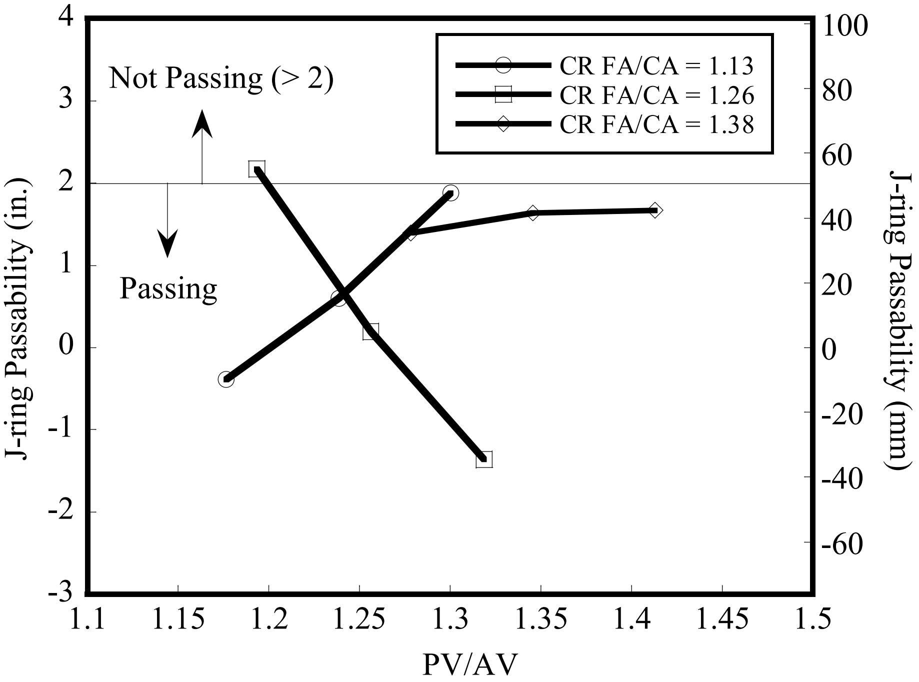

Figure 4.47. J-ring Passability versus PV/AV for CR Mixtures

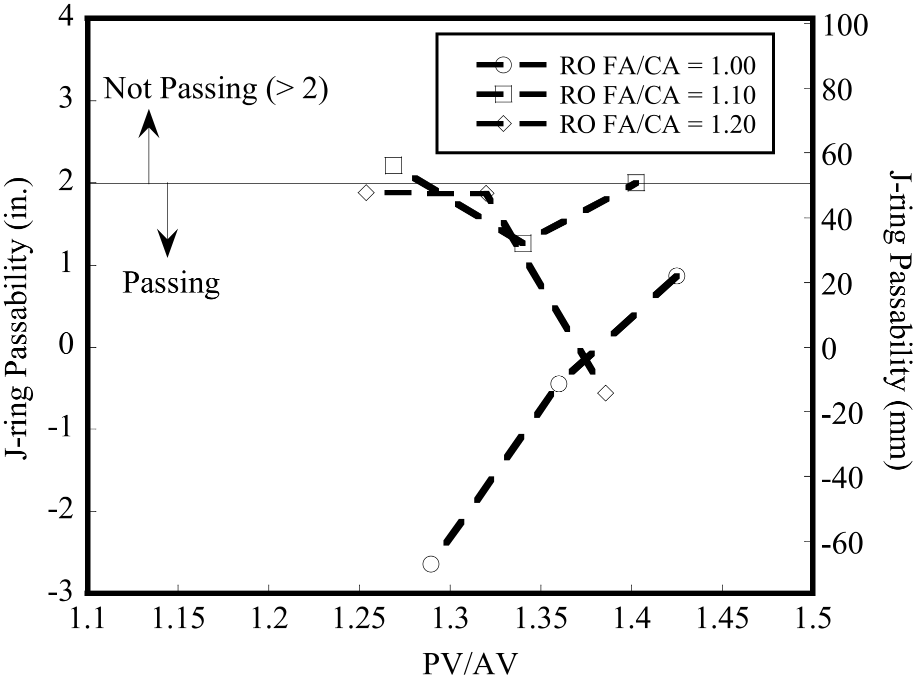

Figure 4.48. J-ring Passability versus PV/AV for RO Mixtures

The C-bar passability ratio is a ratio of the horizontal flow outside the C-bar ring in the parallel and perpendicular directions to the PVC pipes. As with the other assessment the C-bar passability ratio results are plotted versus paste volume, FA/CA, AV content, and PV/AV. The C-bar passability ratio measurements are plotted against the paste volume for the CR and RO mixtures in Figures 4.49 and 4.50, respectively. Note that lower C-bar passability ratio values indicate higher passing ability. These figures show that the C-bar passability ratio is not sensitive to paste volumes. All mixtures presented in these figures have adequate C-bar passability ratios. This may be due to the mixtures containing a 3/8-inch (9.5 mm) MSA, but further research may be necessary to assess the C-bar requirements.

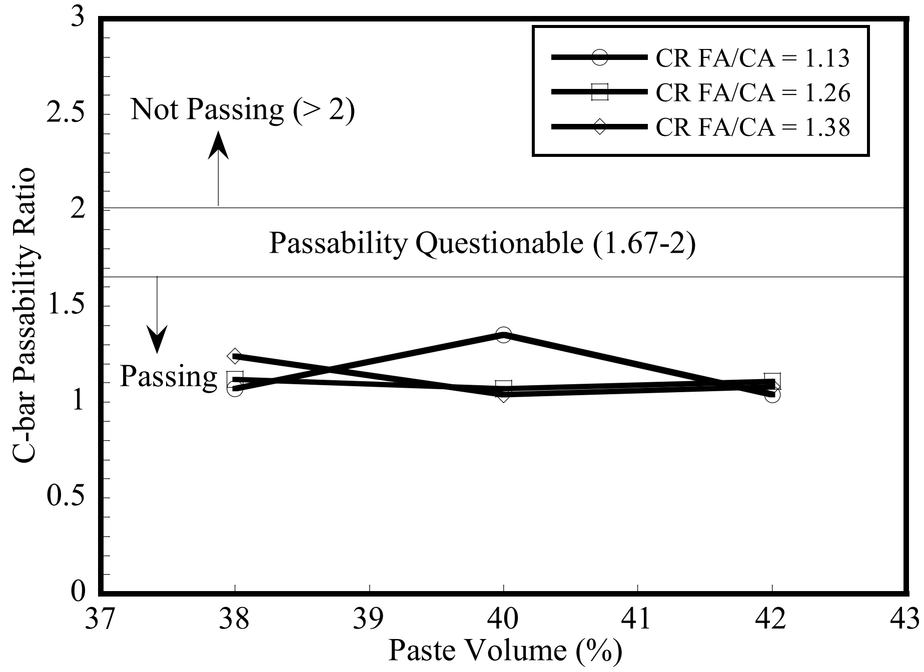

Figure 4.49. C-Bar Passability versus Percent Paste Volume for CR Mixtures

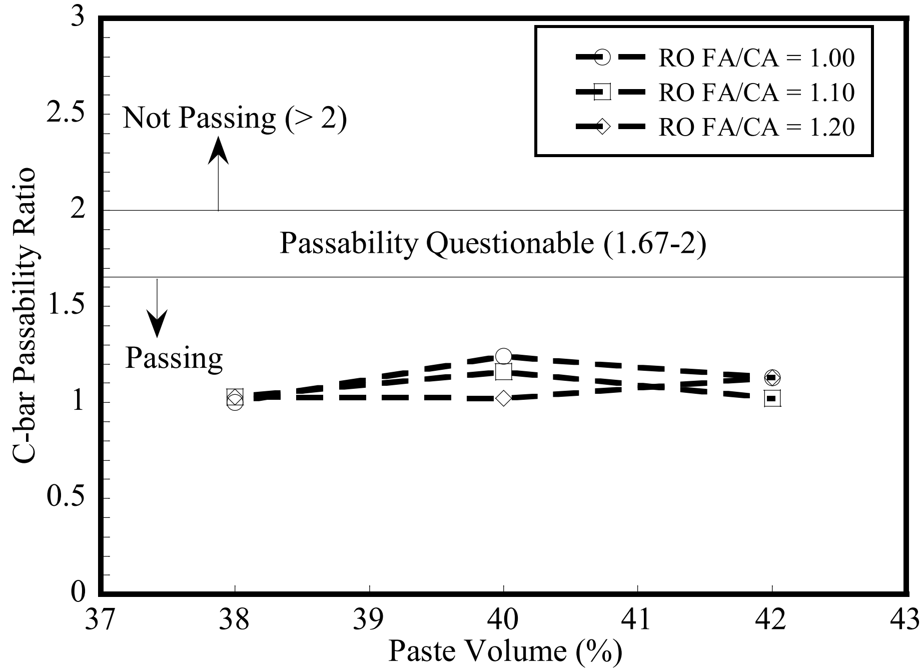

Figure 4.50. C-bar Passability versus Percent Paste Volume for RO Mixtures

The influence of FA/CA on the C-bar passability ratio is also assessed in this research. The C-bar passability ratio measurements are plotted versus FA/CA for the CR and RO mixture as shown in Figures 4.51 and 4.52, respectively. The figures show that the C-bar passability ratio is not sensitive to FA/CA.

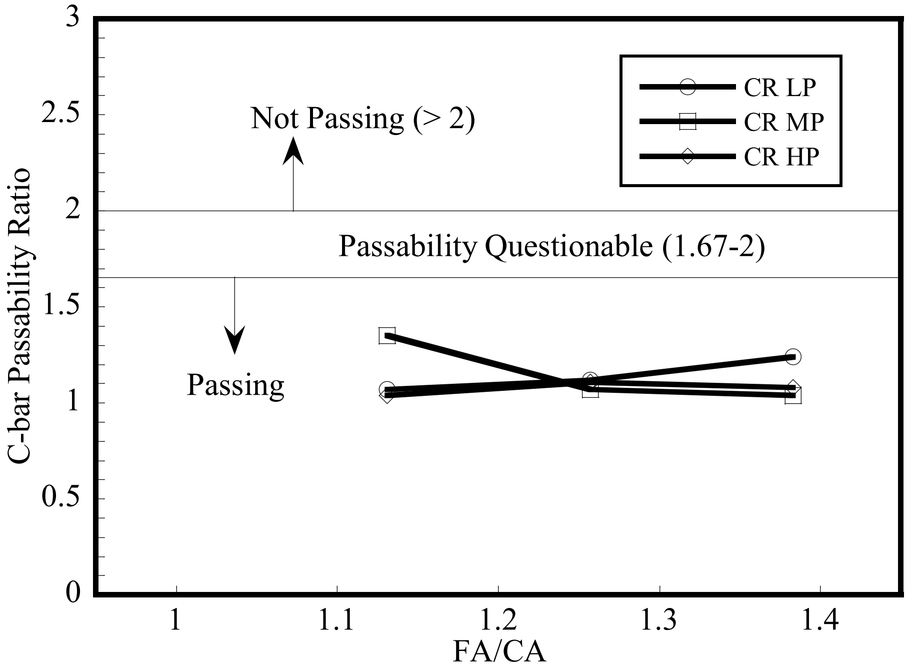

Figure 4.51. C-bar Passability versus FA/CA for CR Mixtures

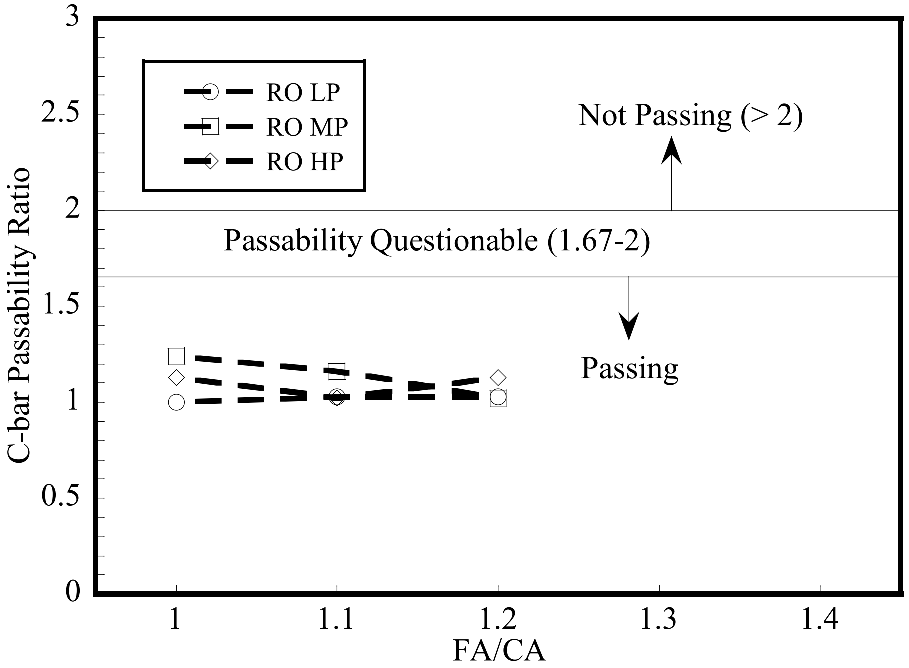

Figure 4.52. C-bar Passability versus FA/CA for RO Mixtures

The C-bar passability ratio values are plotted as a function of the AV content for CR and RO mixtures in Figure 4.53. This figure shows that the C-bar ratio for the different mixture types is not sensitive to AV content.

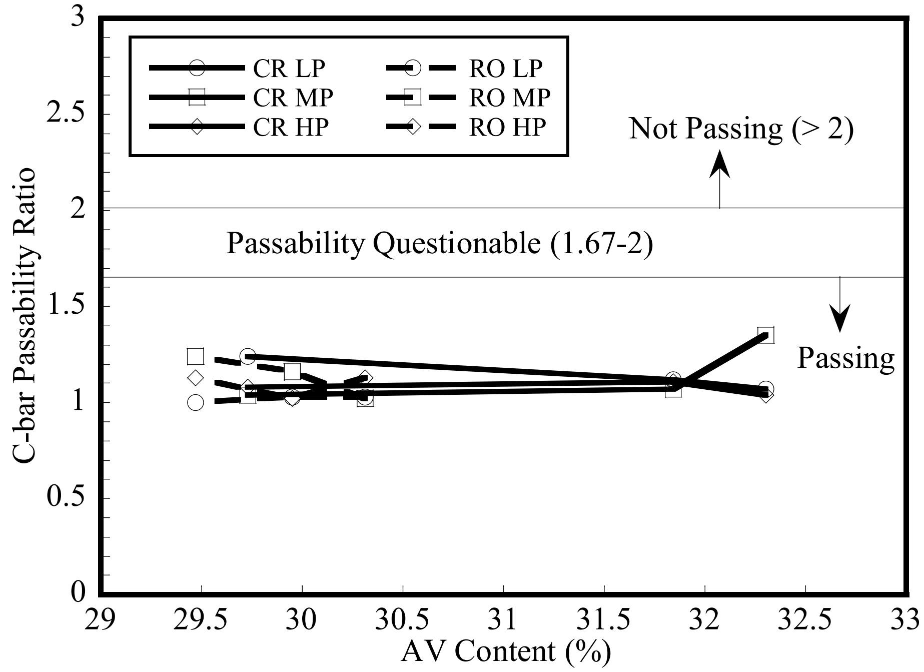

Figure 4.53. C-bar Passability versus AV Content for CR and RO Mixtures

The C-bar passability ratios are plotted as a function of the PV/AV for the CR and RO mixtures in Figures 4.54 and 5.55, respectively. As with the other results, the C-bar passability ratio (with the standard configuration) is not sensitive to PV/AV. The C-bar results in this section show no clear trend when plotted versus paste volume, FA/CA, AV content, or PV/AV. These results, however, are shown for the standard C-bar setup and this setup may not be ideal to assess passing ability. The L-box is also assessed in this report and presented next.

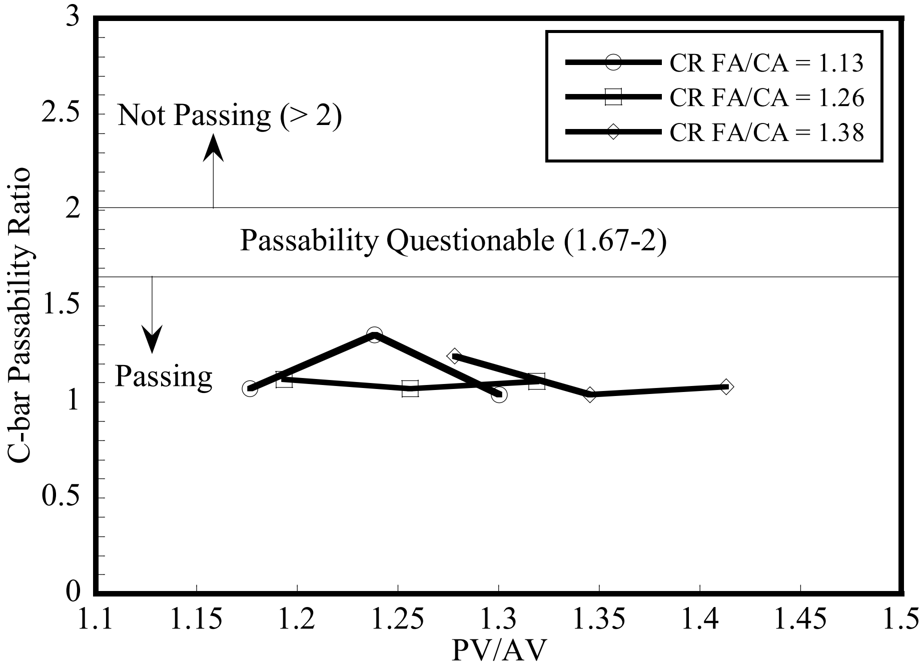

Figure 4.54. C-bar Passability Ratio versus PV/AV for CR Mixtures

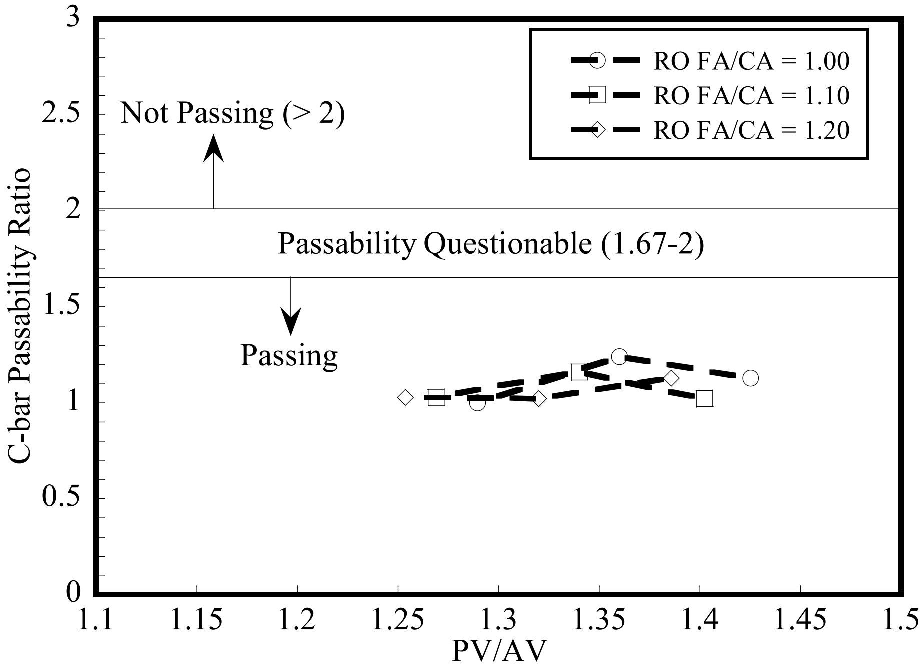

Figure 4.55. C-bar Passability Ratio versus PV/AV for RO Mixtures

The L-box is commonly used to assess concrete passing ability and the test only requires a measurement of passing ability. However, Koehler and Fowler (2008) reported that the L-box test measures a combination of flowability and passing ability. Therefore, mixtures must exhibit adequate passing ability and flowability to pass the L-box test requirements.

A concrete mixture having an L-box passability ratio of 0.8 or greater is considered to have adequate passing ability. As with the other test results assessments the influence of paste volume, FA/CA, AV content, and PV/AV on the L-box passability ratio is assessed. The L-box passability ratio is shown as a function of the paste volume for CR and RO mixtures in Figures 4.56 and 4.57, respectively. These figures show a general increase in the L-box passability ratio with an increase in paste volume for both CR and RO mixtures. The highest L-box passability ratio for the CR mixtures was 0.88 and the highest L-box passability ratio for the RO mixtures was 0.94. Because higher paste volumes are required to achieve adequate L-box passability, the 0.8 passability ratio may not be an adequate test requirement. Further research to assess the passability ratio requirements is needed.

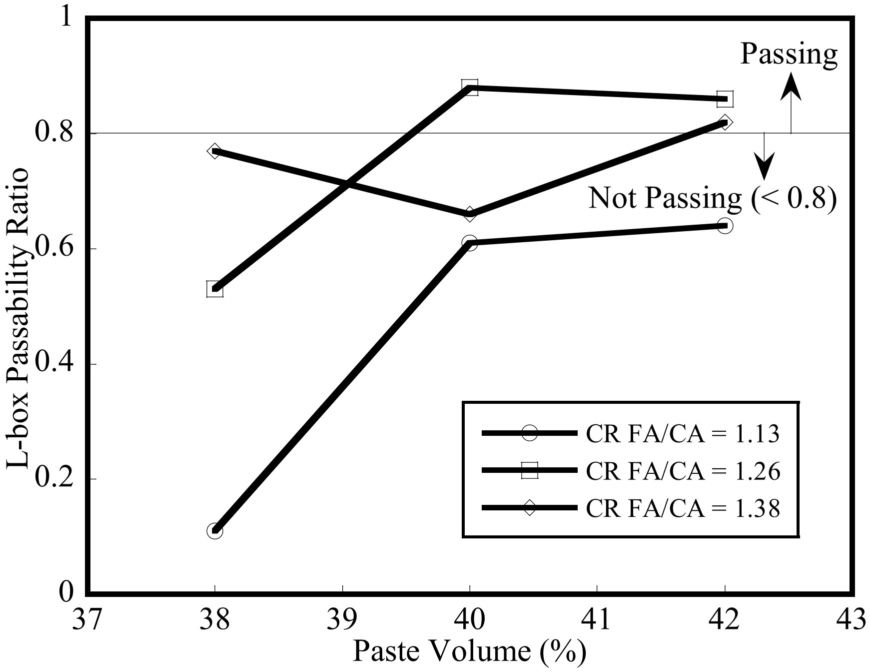

Figure 4.56. L-box Passability Ratio versus Percent Paste Volume for CR Mixtures

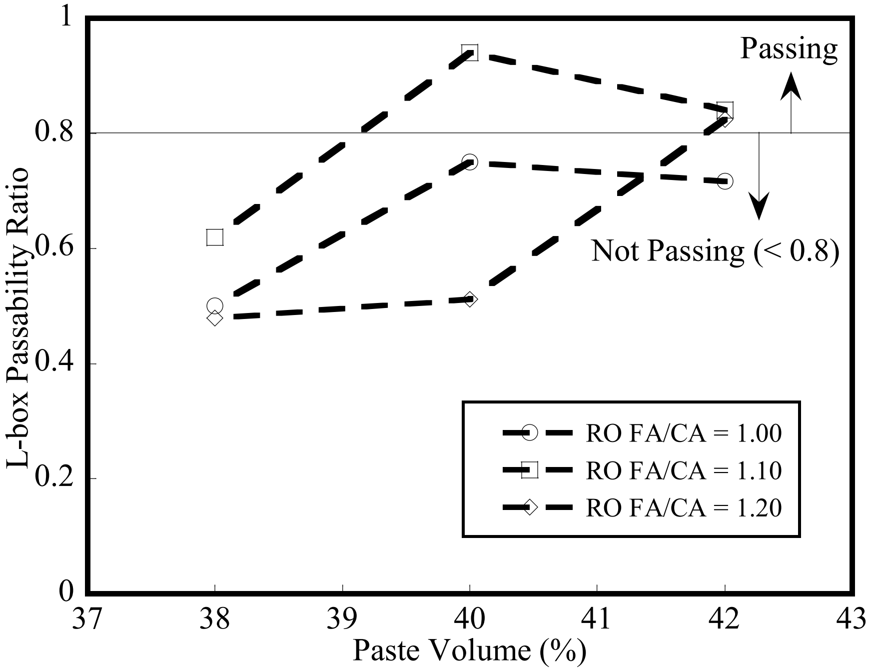

Figure 4.57. L-box Passability versus Percent Paste Volume for RO Mixtures

The L-box passability ratio measurements for CR and RO mixtures are plotted with respect to the FA/CA in Figures 4.58 and 4.59, respectively. These figures show no clear relationship between the FA/CA and L-box passability ratio. The CR mixtures containing low paste volumes exhibit increases in the L-box passability ratio as the FA/CA increases. However, the CR mixtures containing medium and high paste contents exhibit increases and decreases in the L-box passability ratio as the FA/CA increases. The RO mixtures exhibit increases and decreases in the L-box passability ratio as the FA/CA increases.

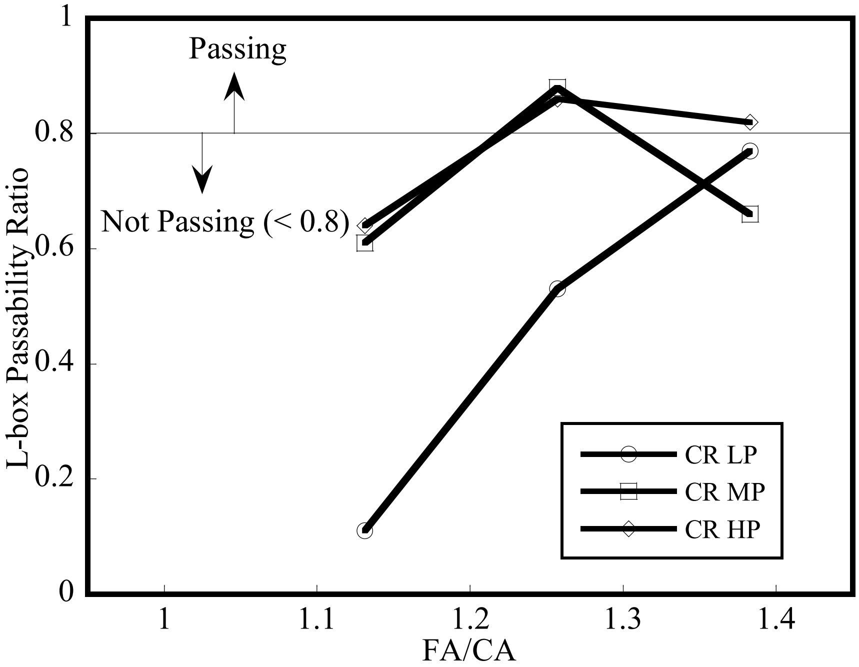

Figure 4.58. L-box Passability versus FA/CA for CR Mixtures

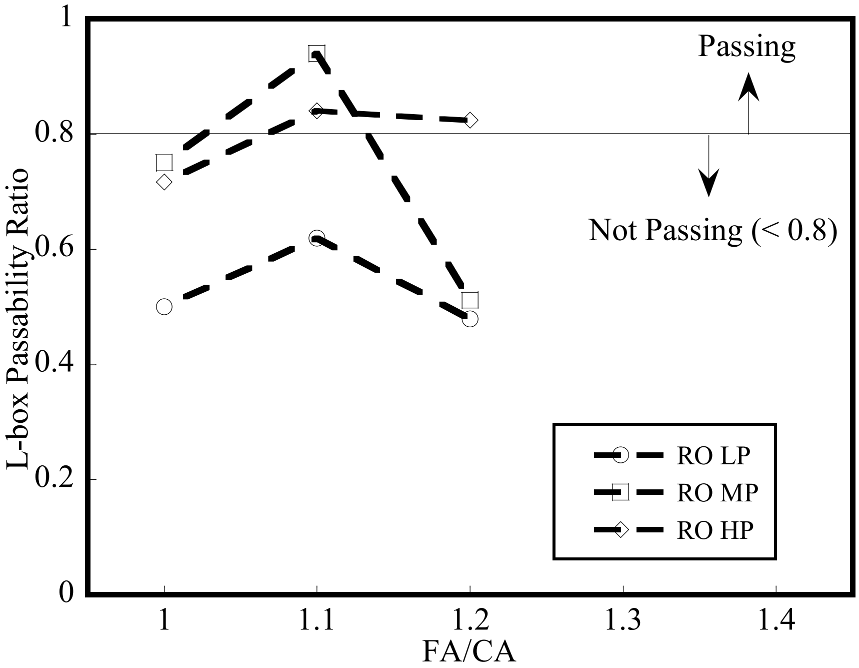

Figure 4.59. L-box Passability versus FA/CA for RO Mixtures

Figure 4.60 shows the L-box passability ratio results plotted as a function of the AV content for CR and RO mixtures. No general trend is observed when the AV content is plotted versus the L-box passability ratio. This is similar to the FA/CA results.

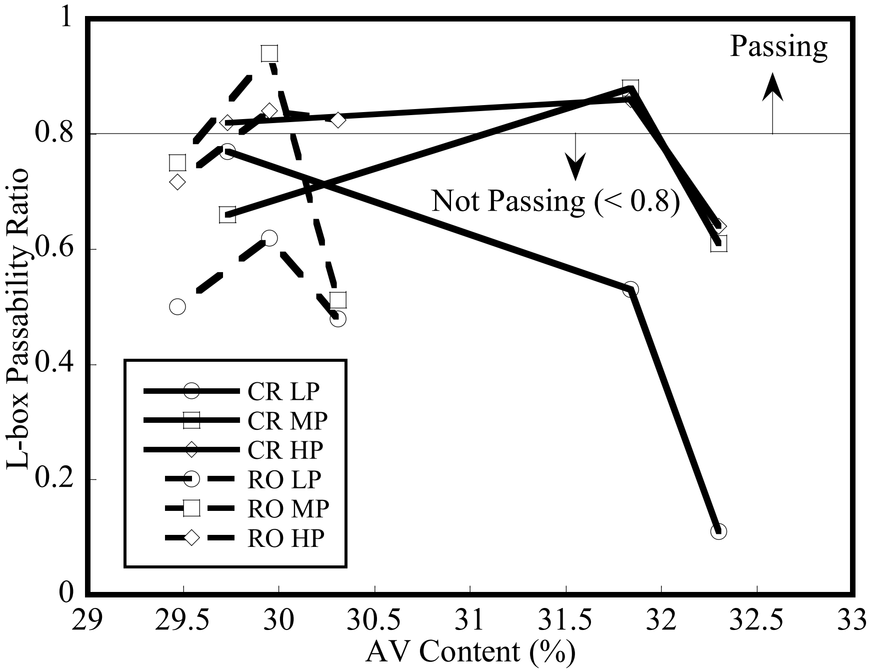

Figure 4.60. L-box Passability versus AV Content for CR and RO Mixtures

The L-box passability ratio values are plotted versus the PV/AV for CR and RO mixtures in Figures 4.61 and 4.62, respectively. The L-box passability ratio generally increases as the PV/AV increases. The PV/AV is likely a significant influencing factor because the L-box passability ratio trend is similar to the trend observed with increases in paste volume. Therefore, PV/AV and paste volume are significant influencing factors. The influences of FA/CA and AV content on the L-box passability results showed no clear trends and are not identified as significant factors.

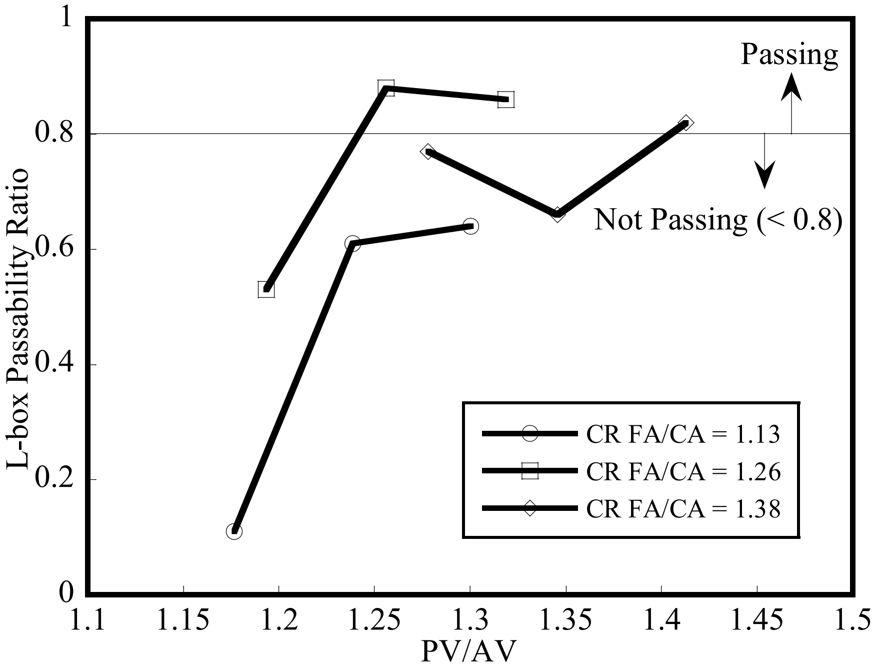

Figure 4.61. L-box Passability Ratio versus PV/AV for CR Mixtures

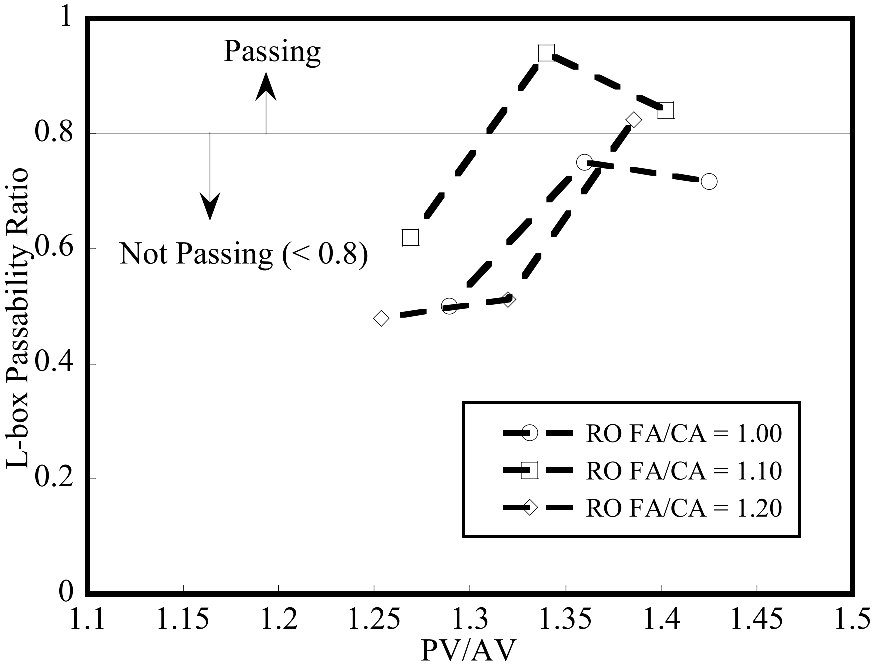

Figure 4.62. L-box Passability Ratio versus PV/AV for CR Mixtures

4.2.4.1. Summary

To assess the passing ability of HW concrete mixtures this study assessed the standard J-ring, C-bar, and L-box tests. The influence of paste volume and FA/CA on the J-ring and C-bar tests shows unclear results. Because the J-ring test results are unclear this may indicate that J-ring passability should be assessed using a different method. Koehler and Fowler (2008) reported that J-ring passability could be measured as the average difference in the height of concrete directly inside and outside the J-ring circumference in four equally spaced locations. However, because these data were not collected here, no recommendation is made on this J-ring method.

No recommendation is provided for changing the C-bar passability test method at this time. However, modifications to the test configurations are assessed in the next section. Future research may be necessary to assess the C-bar passability requirements.

The L-box test results were influenced by changes in paste volume and PV/AV. Although the L-box is intended to assess passing ability, Koehler and Fowler (2008) reported that the L-box also assesses flowability. Therefore, flowability and passing ability must be adequate for a concrete mixture to pass the L-box test. This may indicate that the mixtures in this study having adequate flowability also have adequate passing ability. If this is the case, then HW mixtures containing the aggregate in this study may only need to be assessed for flowability and stability and not passing ability. However, further research is needed. Also further research is needed to assess the L-box passability ratio requirements. The 0.8 passability ratio could potentially be reduced.

4.3. INFLUENCE OF THE TEST CONFIGURATION ON SENSITIVITY OF RESULTS

The influence of aggregate type and mixture proportions on passing ability results for standard J-ring and C-bar tests have been shown in the previous section. However, the standard J-ring and C-bar tests may or may not be suitable to assess concrete passing ability for HW concrete mixtures. These tests are assessed in this section with different test configurations (see Tables 3-4 and 3-5). This section will assess if test configuration is a critical factor influencing the passing ability of HW concrete mixtures.

The J-ring and C-bar test configurations are modified by changing the number of reinforcing bars in the test set-up. This change results in variations in clear spacing between the reinforcing bars. With a decrease in clear spacing between the reinforcement bars it could be expected that passing ability will decrease. A general trend of increased passing ability may also be expected as the paste volume increases because this decreases the amount of aggregate to pass through the reinforcement bars. Potential general trends for the different J-ring and C-bar configurations are shown in Figure 4.63. Note that lower J-ring and C-bar passability values indicate increased passing ability.

Because field testing was not a part of this research, no correlation between field performance (i.e., voids in CIDH piles) and test configuration could be assessed. However, using a test configuration with a clear spacing less than the clear spacing found in the field could be a conservative assessment of the concrete passing ability. This could help to achieve adequate field performance.

The trends shown in Figure 4.63 may not be observed because changes in paste volume can influence both flowability and stability as noted in the previous sections. Both flowability and stability can influence passing ability. If flowability is not adequate (20-inch slump flow) then a mixture may not flow through the J-ring or C-bar. In addition, a mixture with inadequate stability (VSI, VBI_J, or VBI_C greater than 1) may not flow through the J-ring or C-bar in a homogeneous manner. The homogeneity of a HW concrete mixture is critical to passing ability because the aggregate and paste must flow together through the reinforcing bars to achieve adequate passing ability. It is for this reason that the VBI_J and VBI_C should also be assessed. If a mixture exhibits adequate flowability and stability but does not pass the J-ring or C-bar test requirements, then passing ability may be considered as the critical workability characteristic.

Another reason that the trends shown in Figure 4.63 may not be observe is because this research was limited to 3/8-inch (9.5 mm) MSA coarse aggregate. The ACI Committee 318 (ACI 318-11) reported that the MSA must be three-quarters of the clear spacing between the reinforcing bars. Therefore, the 3/8-inch (9.5 mm) MSA coarse aggregates used for this research requires a minimum of 1/2-inch (12.7 mm) clear spacing. The smallest tested clear spacing is 1.47 inches (37 mm). This indicates that all mixtures with adequate flowability and stability should pass the J-ring test requirements. This is also the case for the C-bar test.

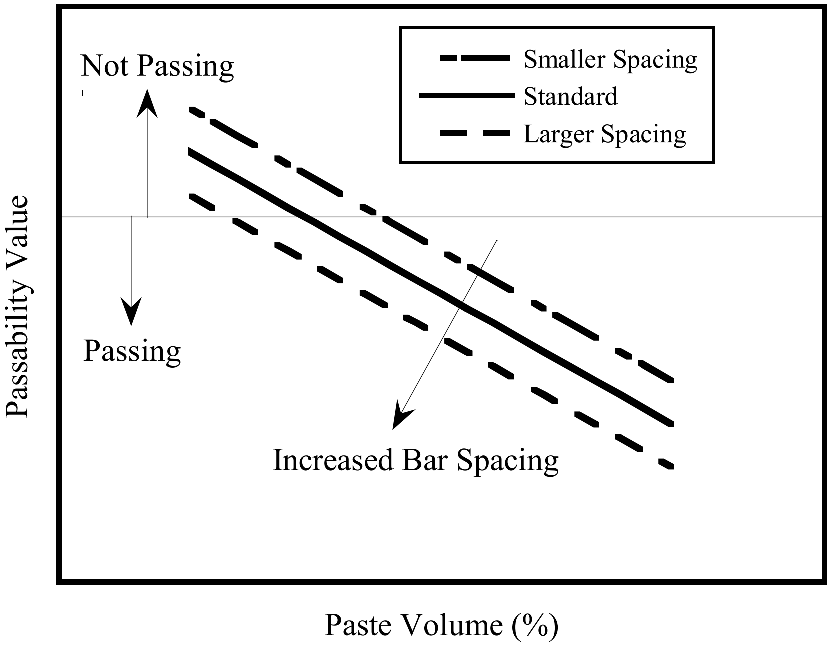

Figure 4.63. Possible General Trends for Different Passability Test Configurations

An assessment of the different J-ring configurations is presented here for each FA/CA for both aggregate types. The J-ring passability values are plotted versus paste volume in Figures 4.64, 4.65, and 4.66 for the CR mixtures. These mixtures contain 1.13, 1.26, and 1.38 FA/CA contents. It should be noted that the reinforcing bar clear spacing is listed in the legend and that the 1.73-inch (44 mm) clear spacing is the standard J-ring test configuration. These figures show that the CR mixtures containing the 1.26 FA/CA content exhibit similar trends as a function of paste volume. However, this trend is only observed for the CR mixtures containing the 1.26 FA/CA content. The other figures also do not show a clear trend as a function of paste volume. This indicates that if an adequate FA/CA is not identified, the mixture becomes more sensitive to paste volume. The results also indicate no trend as a function of reinforcement clear spacing.

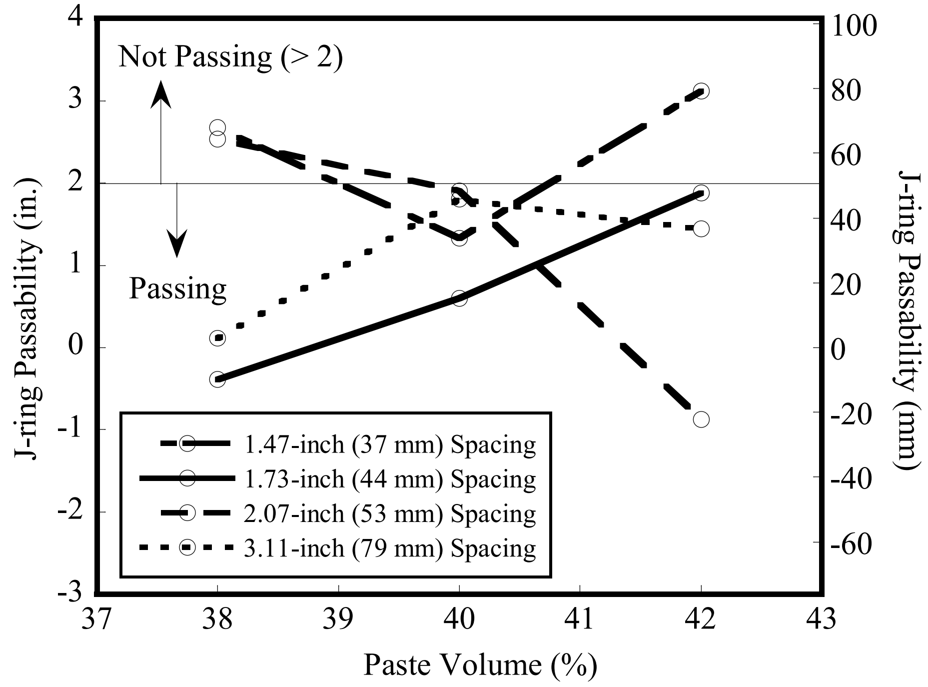

Figure 4.64. J-ring Passability versus Paste Volume for CR Mixtures Containing the 1.13 FA/CA

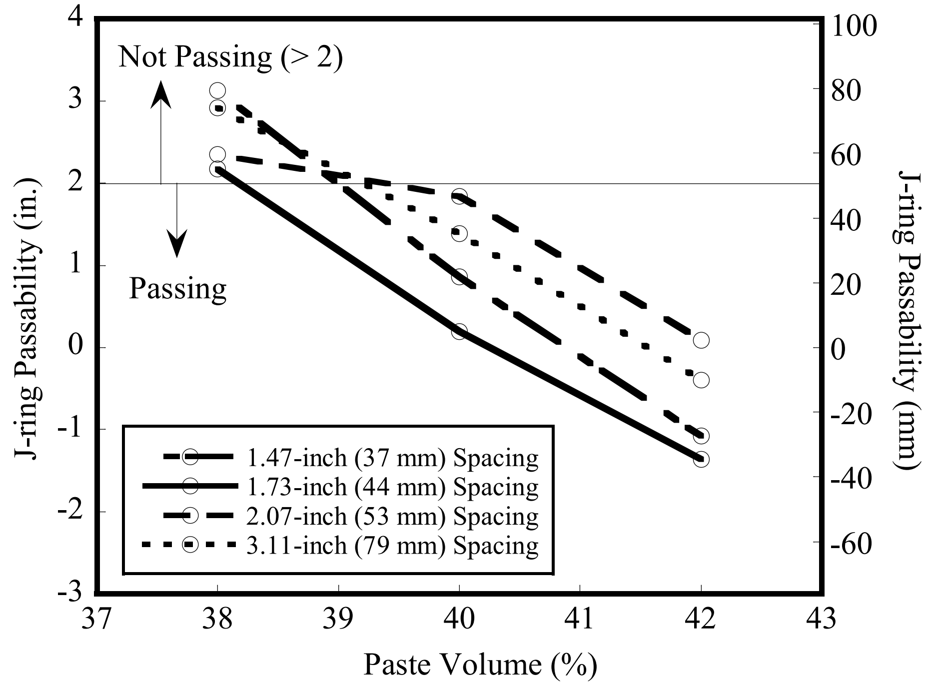

Figure 4.65. J-ring Passability versus Paste Volume for CR Mixtures Containing the 1.26 FA/CA

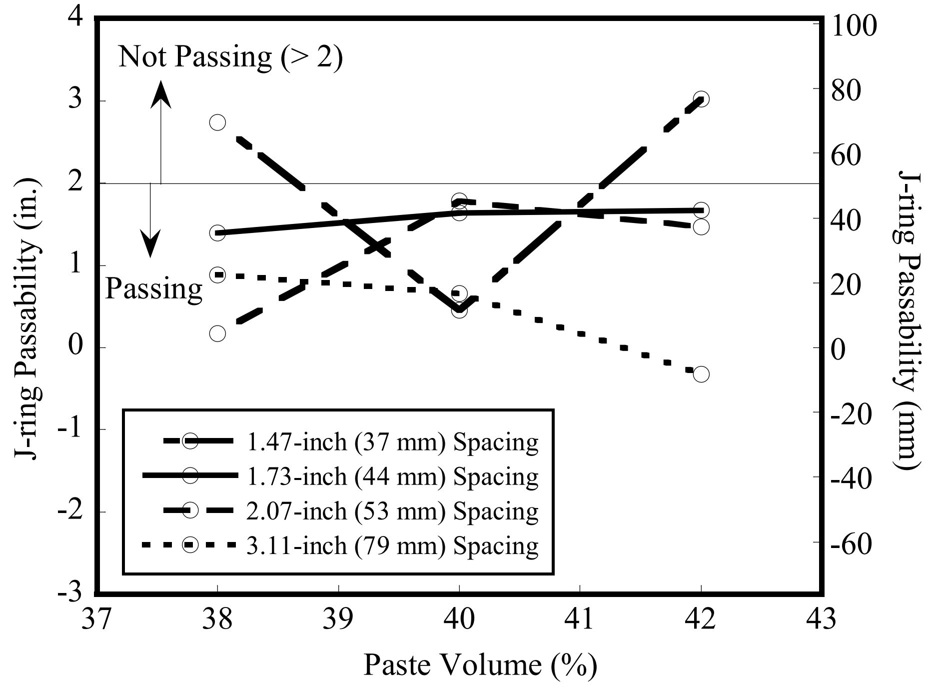

Figure 4.66. J-ring Passability versus Paste Volume for CR Mixtures Containing the 1.38 FA/CA

The J-ring passability results indicate that the J-ring test could be used to effectively assess some mixtures but a clear trend or threshold was not observed for all mixtures. The lack of observed trends or thresholds is possibly due to the 3/8-inch (9.5 mm) MSA being too small to affect passing ability. In addition, the lack of observed trends could be the results of mixtures not passing the J-ring test requirements due to inadequate flowability or stability. Because of this, Tables 4-4, 4-5, 4-6, and 4-7 were developed to identify the mixtures that failed the J-ring test due to inadequate passing ability only. Note that mixtures that do not pass the VBI_J are due to lack of stability for these tables and passing ability is only assessed with the J-ring test requirements.

There are three CR mixtures that have adequate stability and flowability but do not pass the J-ring test due to inadequate passing ability. The CR mixture containing LP volume and a 1.13 FA/CA in Table 4-4 failed due to inadequate passing ability. This is possibly due to the mixture having a higher coarse aggregate content and low paste volume. Also the J-ring tested in Table 4-4 having the smallest clear spacing could have contributed to the mixture not passing. The reason the other CR mixture in Table 4-4 failed was due to paste and sand flowing outside the J-ring and leaving coarse aggregate behind even though stability appeared adequate. The reason the CR mixture in Table 4-7 failed is possibly due to low paste volume. However, this mixture did not appear to exhibit poor passing ability and this J-ring configuration has the highest clear spacing of the four different J-ring set-ups. Therefore, the J-ring test configuration in Table 4-7 may not provide a good assessment of HW concrete mixtures that exhibit poor passing ability.

Table 4-4. Passing or Failing the J-ring Test Based on Workability Characteristics for CR Mixtures (1.47-inch (37 mm) spacing)

		1.47-inch (37 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	N	Y	Y
	MP	Y	Y	Y
	HP	N	N	Y
1.26	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	N	Y
1.38	LP	N	Y	N
	MP	Y	Y	Y
	HP	N	Y	Y

Table 4-5. Passing or Failing the J-ring Test Based on Workability Characteristics for CR Mixtures (1.73-inch (44 mm) spacing)

		1.73-inch (44 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.26	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-6. Passing or Failing the J-ring Test Based on Workability Characteristics for CR Mixtures (2.07-inch (53 mm) spacing)

		2.07-inch (53 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	N	Y
1.26	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-7. Passing or Failing the J-ring Test Based on Workability Characteristics for CR Mixtures (3.11-inch (79 mm) spacing)

		3.11-inch (79 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.26	LP	N	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

The J-ring passability values are plotted versus paste volume for the RO mixtures containing 1.00, 1.10, and 1.20 FA/CA contents in Figures 4.67, 4.68, and 4.69. The RO mixtures containing the 1.00 FA/CA content generally exhibit an increase in J-ring passability (passing ability decreases) as the paste volume increases, although all mixtures are considered to pass the J-ring test requirement for passability. This may be a result of decreased stability at higher paste volumes. For the other RO mixtures, no general trend is observed. Also, the figures show no clear trend as the reinforcement clear spacing changes. Therefore, a distinction between the mixtures that pass or fail the flowability, stability, and J-ring test requirements may provide an indication of inadequate passing ability.

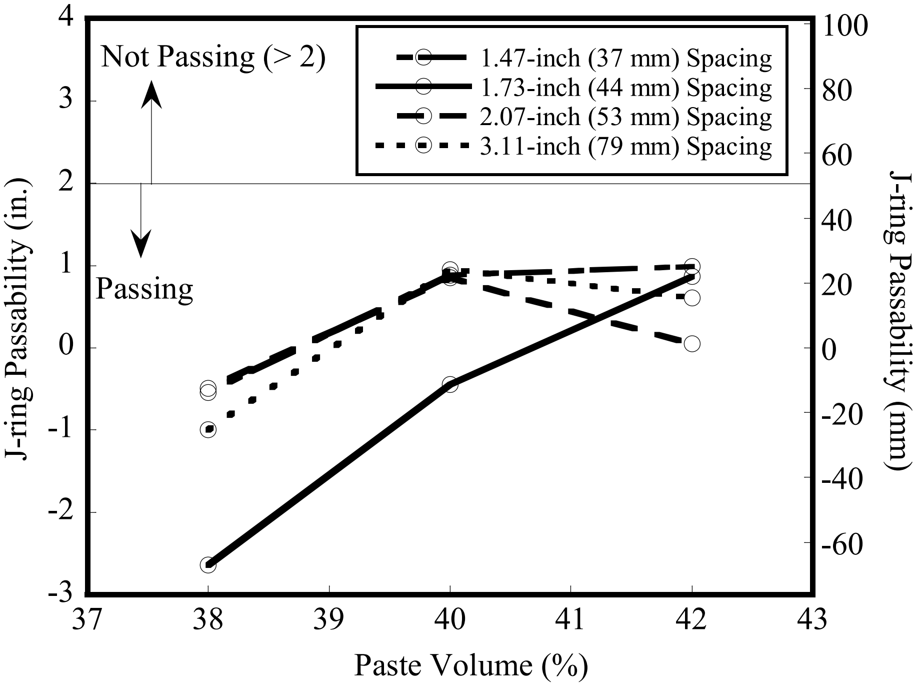

Figure 4.67. J-ring Passability versus Paste Volume for RO Mixtures Containing the 1.00 FA/CA

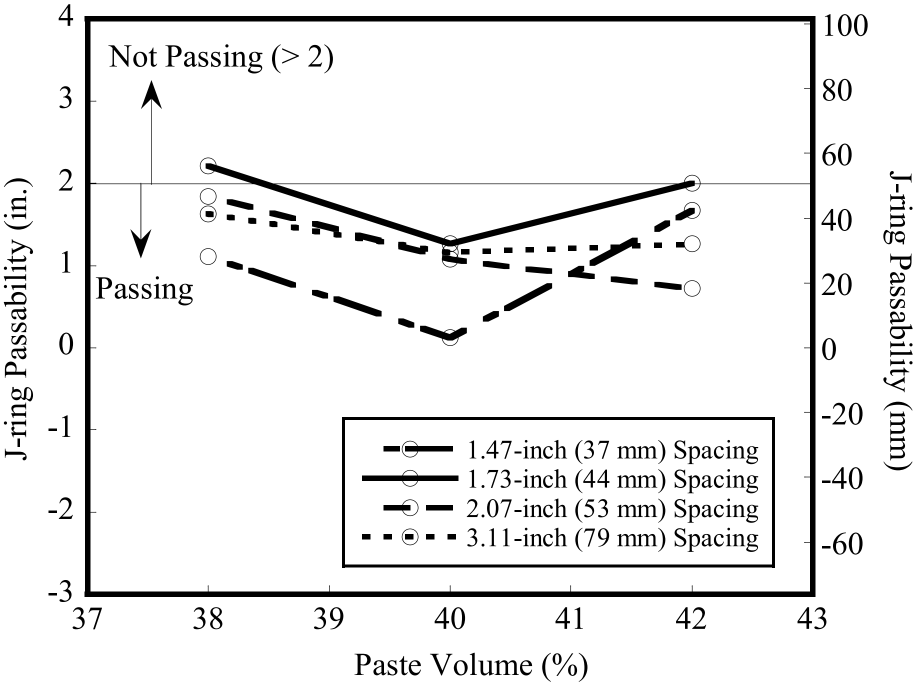

Figure 4.68. J-ring Passability versus Paste Volume for RO Mixtures Containing the 1.10 FA/CA

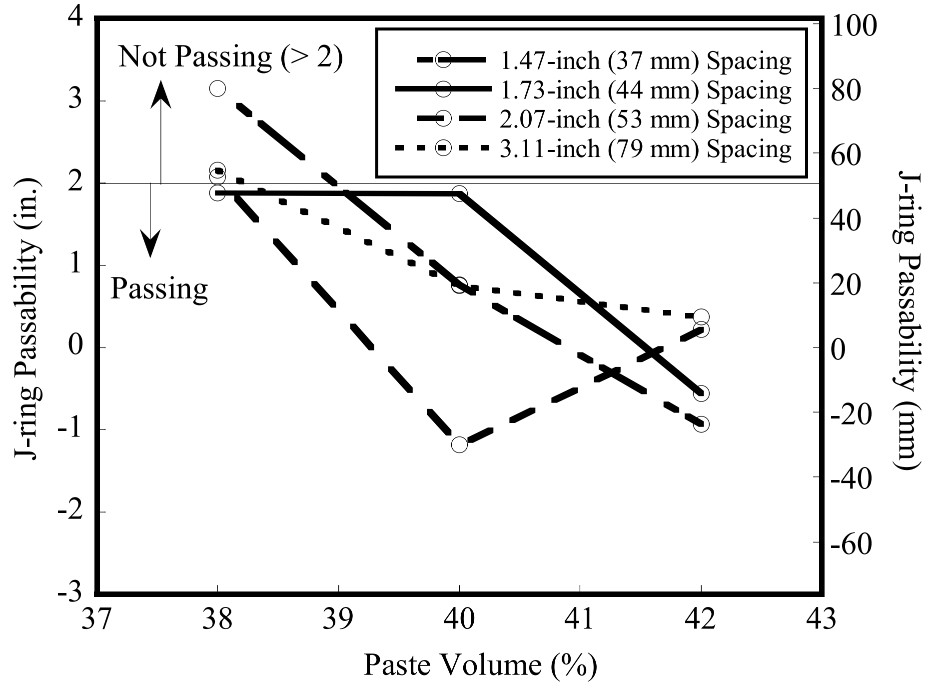

Figure 4.69. J-ring Passability versus Paste Volume for RO Mixtures Containing the 1.20 FA/CA

Tables 4-8, 4-9, 4-10, and 4-11 show the RO mixtures that failed the J-ring test requirements due to inadequate flowability, stability and/or J-ring passability. The J-ring configurations with a reinforcing bar clear spacing of 1.47, 1.73, 2.07, and 3.11 inches (37, 44, 53, and 79 mm) are shown in these tables. From these tables, the mixtures that failed due only to inadequate J-ring passabiltiy can be identified. There are three RO mixtures that do not have adequate workability due to failing the J-ring passability requirements only. The RO mixture containing a low paste volume and 1.20 FA/CA content in Table 4-8 possibly failed the J-ring passability requirement due to low paste volume, although the mixture exhibited adequate flowability and stability. The RO mixture in Table 4-9 containing a low paste volume and 1.00 FA/CA failed the J-ring passability requirements possibly due to a low paste volume and high coarse aggregate content. The RO mixture in Table 4-9 containing a low paste volume and 1.20 FA/CA value failed the J-ring passability requirements possibly due to a low paste volume.

Table 4-8. Passing or Failing the J-ring Test Based on Workability Characteristics for RO Mixtures (1.47-inch (37 mm) spacing)

		1.47-inch (37 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.20	LP	N	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-9. Passing or Failing the J-ring Test Based on Workability Characteristics for RO Mixtures (1.73-inch (44 mm) spacing)

		1.73-inch (44 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	N	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.10	LP	N	Y	Y
	MP	Y	Y	Y
	HP	N	N	Y
1.20	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-10. Passing or Failing the J-ring Test Based on Workability Characteristics for RO Mixtures (2.07-inch (53 mm) spacing)

		2.07-inch (53 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.20	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-11. Passing or Failing the J-ring Test Based on Workability Characteristics for RO Mixtures (3.11-inch (79 mm) spacing)

		3.11-inch (79 mm) J-ring Clear Spacing		
FA/CA	Paste Volume	Pass J-Ring Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.20	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

As with the J-ring configuration assessment, modifications to the C-bar test are also assessed. These are plotted versus paste volume for different C-bar configurations. These plots are shown in Figures 4.70, 4.71, and 4.72 for CR mixtures containing 1.13, 1.26, and 1.38 FA/CA contents. Note that the C-bar configurations consisting of 6 reinforcing bars is the standard configuration. Figure 4.72 shows that one mixture did not pass the C-bar test. This C-bar configuration consisted of 8 reinforcing bars. However, this mixture exhibited lower flowability and this also contributed to the mixtures lack passing ability. Other than this mixture, all other mixtures containing the CR aggregate passed the C-bar test. These results may be due to the smaller MSA aggregate used in this research. This indicates that the C-bar test may be sufficiently sensitive to assess passing ability of HW concrete mixtures.

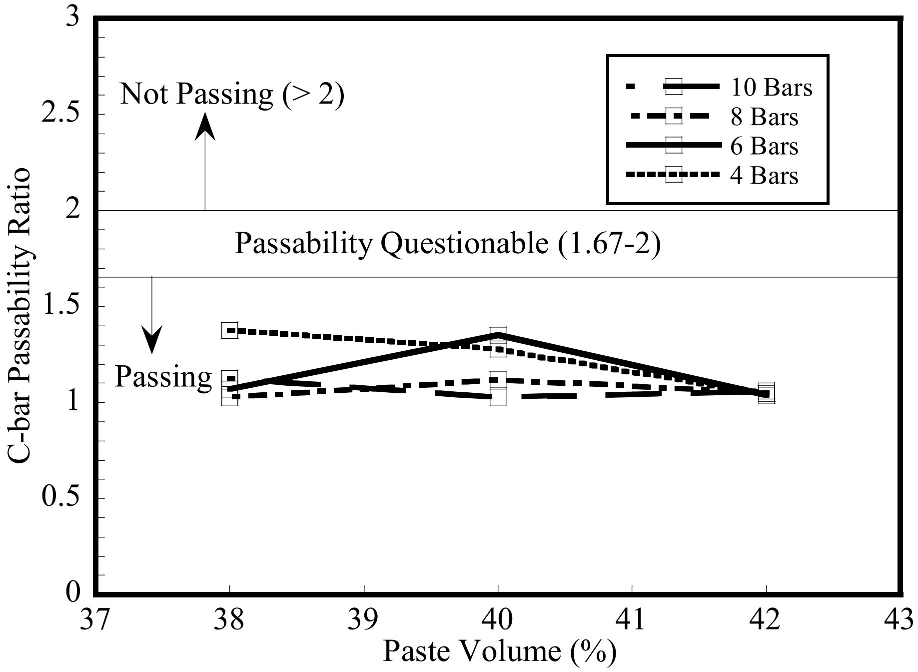

Figure 4.70. C-bar Passability Ratio versus Paste Volume for CR Mixtures Containing the 1.13 FA/CA

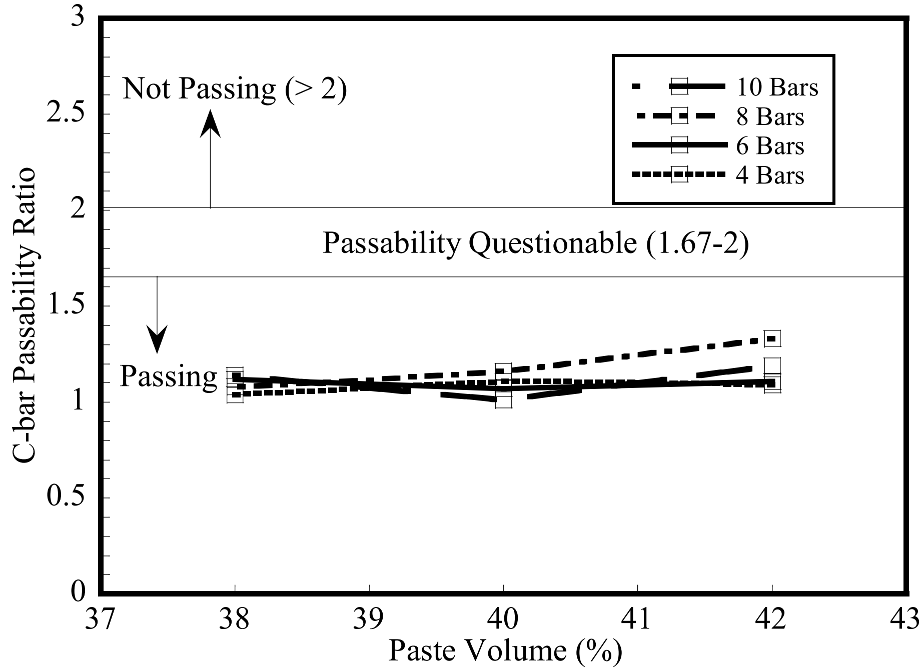

Figure 4.71. C-bar Passability Ratio versus Paste Volume for CR Mixtures Containing the 1.26 FA/CA

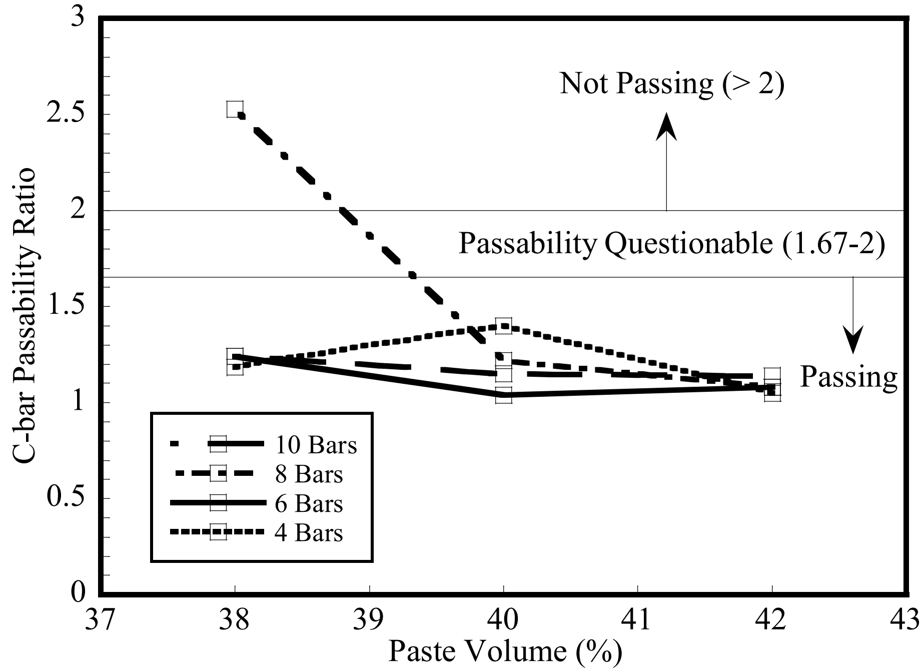

Figure 4.72. C-bar Passability Ratio versus Paste Volume for CR Mixtures Containing the 1.38 FA/CA

All CR mixtures passed the C-bar test requirements except the one mixture shown in Figure 4.72. However, not all of the CR mixtures that exhibited adequate C-bar passability also exhibited adequate flowability and stability. Therefore, the results for the CR mixtures that passed or failed the flowability, stability, and C-bar test requirements are shown in Tables 4-12, 4-13, 4-14, and 4-15. The results for the CR mixture containing the low paste volume and 1.38 FA/CA in Table 4-13 indicate that this mixture failed the C-bar passability requirements because it exhibited inadequate flowability. Results also indicate mixture exhibiting adequate flowability and stability did not fail the C-bar test due to inadequate passing ability. Unlike the results observed for the J-ring test, no mixture failed the C-bar passability requirements due to inadequate stability. These observed results may be due to the use of 3/8-inch (9.5 mm) having no effect on passing ability for this research.

Table 4-12. Passing or Failing the C-bar Test Based on Workability Characteristics for CR Mixtures (10 Bars)

		C-Bar with 10 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.26	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-13. Passing or Failing the C-bar Test Based on Workability Characteristics for CR Mixtures (8 Bars)

		C-Bar with 8 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	N	Y
1.26	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	N	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-14. Passing or Failing the C-bar Test Based on Workability Characteristics for CR Mixtures (6 Bars)

		C-Bar with 6 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	Y
	MP	Y	Y	N
	HP	Y	N	Y
1.26	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-15. Passing or Failing the C-bar Test Based on Workability Characteristics for CR Mixtures (4 Bars)

		C-Bar with 4 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.13	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	N	Y
1.26	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.38	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

The C-bar passability ratios for the RO mixtures are also plotted versus the paste volume for the different C-bar configurations in Figures 4.73, 4.74, and 4.75. These figures show that paste volume has little influence on C-bar passabiliy results for the mixtures tested in this research and that C-bar configuration has limited influence on test results.

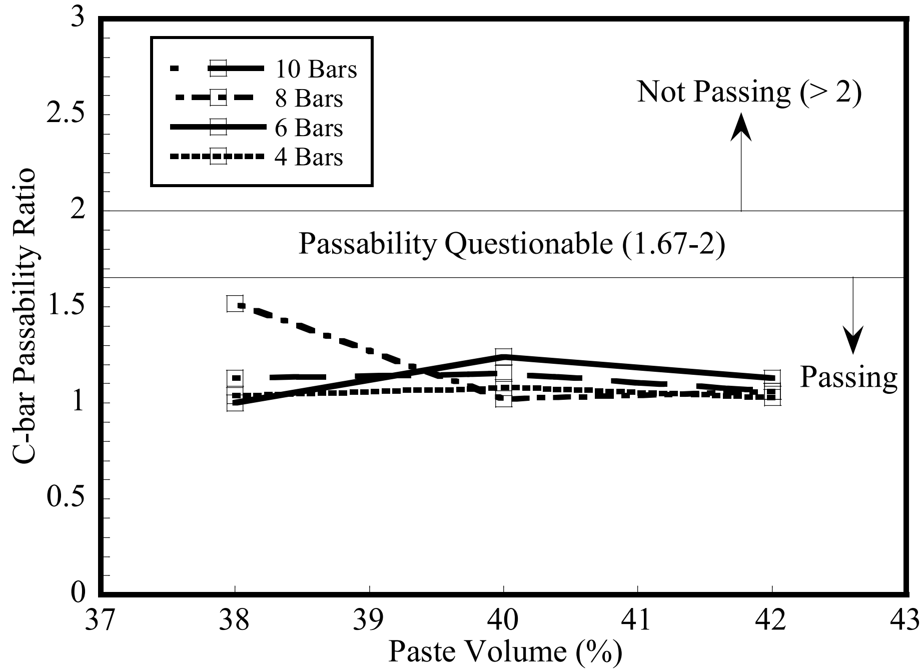

Figure 4.73. C-bar Passability Ratio versus Paste Volume for RO Mixtures Containing the 1.00 FA/CA

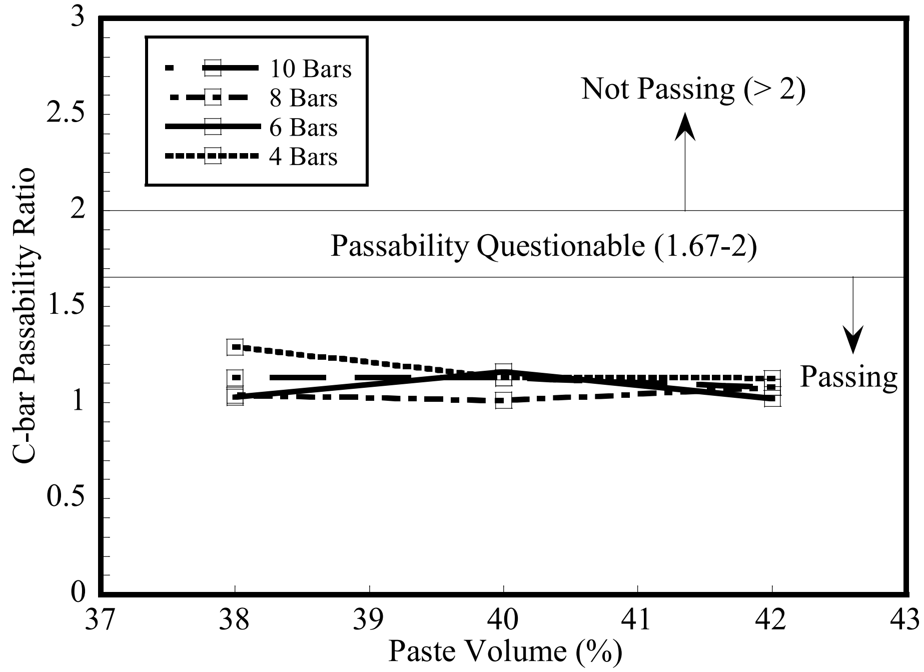

Figure 4.74. C-bar Passability Ratio versus Paste Volume for RO Mixtures Containing the 1.10 FA/CA

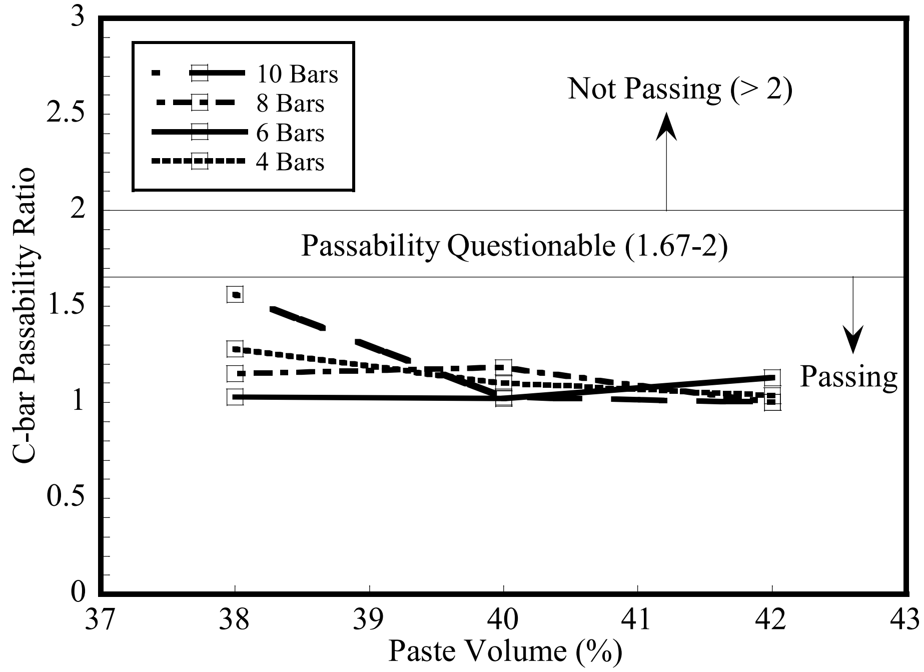

Figure 4.75. C-bar Passability Ratio versus Paste Volume for RO Mixtures Containing the 1.20 FA/CA

The results for the RO mixtures that passed or failed the flowability, stability, and C-bar test requirements are shown in Tables 4-16, 4-17, 4-18, and 4-19. Results in these tables indicate that no RO mixtures failed the C-bar passability requirements. Also, unlike the observed J-ring results, no RO mixture failed the C-bar test due to inadequate flowability and/or stability.

Table 4-16. Passing or Failing the C-bar Test Based on Workability Characteristics for RO Mixtures (10 Bars)

		C-Bar with 10 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	N	Y
	MP	Y	N	Y
	HP	Y	N	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.20	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-17. Passing or Failing the C-bar Test Based on Workability Characteristics for RO Mixtures (8 Bars)

		C-Bar with 8 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	N	Y
1.10	LP	Y	Y	Y
	MP	Y	N	Y
	HP	Y	N	Y
1.20	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-18. Passing or Failing the C-bar Test Based on Workability Characteristics for RO Mixtures (6 Bars)

		C-Bar with 6 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	Y	Y
1.20	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

Table 4-19. Passing or Failing the C-bar Test Based on Workability Characteristics for RO Mixtures (4 Bars)

		C-Bar with 4 Reinforcing Bars		
FA/CA	Paste Volume	Pass C-Bar Requirements	Pass Stability (VBI_J)	Pass Flowability
1.00	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.10	LP	Y	Y	Y
	MP	Y	Y	Y
	HP	Y	N	Y
1.20	LP	Y	Y	N
	MP	Y	Y	Y
	HP	Y	Y	Y

4.3.1. Summary

Results from testing the HW concrete mixtures assessed in this research indicate that the test configuration has some, although limited influence on the test outcome. This could be a result of the smaller MSA used in this research. Results indicate that a general trend for the J-ring test may exist for mixtures with specific proportions, but results tend to vary significantly for many mixtures. The observed J-ring results are influenced by flowability and stability of the concrete mixture. While the C-bar test results are also influenced by these workability characteristics, the influence does not seem to be as sensitive as the J-ring.

Results indicate that the C-bar test may provide an indication of lack of passing ability. Results for this research also indicate that the C-bar test with 8 reinforcing bars (shown in Table 3-5) may be an appropriate test set-up. However, more testing is required. For field testing, the clear spacing for the J-ring or C-bar test configuration used to assess passing ability may be less than the spacing for the structures reinforcing bars so that a conservative assessment of passing ability can be performed. The C-bar test configuration more representative of the CIDH pile configuration and could provide a more accurate simulation of how the concrete will perform in the field.

5. MIXTURE PROPORTIONING OF HW CONCRETE MIXTURES

Based on the results from this research, a method for mixture proportioning of HW concrete mixtures is developed. This mixture proportioning method is intended to assist concrete producers to produce HW concrete mixtures with adequate flowability, stability and passing ability as defined by this research. Based on the results of this research the paste volume, AV content, aggregate IAPST, and PV/AV content can significantly influence flowability. Results also indicate that paste volume, FA/CA, and PV/AV can significantly influence stability. Paste volume and PV/AV, based on L-box results, influence passing ability. Results for the J-ring and C-bar tests indicate that these tests may provide an adequate measure of passing ability. Each passing ability test performed in this research has the potential to assess passing ability but, further testing is required.

The proposed method of proportioning HW concrete mixtures for this research considers the influence of mixture proportions on workability to achieve adequate flowability, stability, and passing ability. Note that testing was performed for mixtures containing a limited number of constituent materials and that all materials may not exhibit the same or similar results. Using the mixture proportioning method presented here, may result in a combined fine and coarse aggregate gradation that does not meet Caltrans specifications. It is recommended that the method for proportioning of the fine and coarse aggregate presented in this research be used. Also, the nominal slump may be well above the minimum of 7 inches (178 mm). It is recommended that a minimum slump flow value be taken into consideration by Caltrans specifications. Minimizing cost and producing favorable hardened properties are also considered here.

All mixture proportioning equations are based on English units and conversions to SI units are performed after mixture proportions are determined. The following steps can be used to estimate the mixture proportions for a required workability for HW concrete mixtures for CIDH pile applications:

Step 1. Perform an ASTM D3398-00 IAPST test for the chosen coarse aggregate. Report this IAPST value.

Step 2. Perform a modified ASTM C29-09 test for select combined fine and coarse aggregates. It is recommended that if the aggregate is rounded (low IAPST) that the initial FA/CA be 1.1 and decrease by 0.1 FA/CA for this test. If the aggregate is crushed (higher IAPST) then the initial FA/CA be 1.1 and increase by 0.1 FA/CA for this test. Increase or decrease the FA/CA for this test until the minimum AV content for the combined aggregates is observed. An example of the AV content resulting from different FA/CA values and different aggregates are shown in Figure 5.1. The minimum AV content is marked on this figure. Report the FA/CA value and the minimum associated AV content produced.

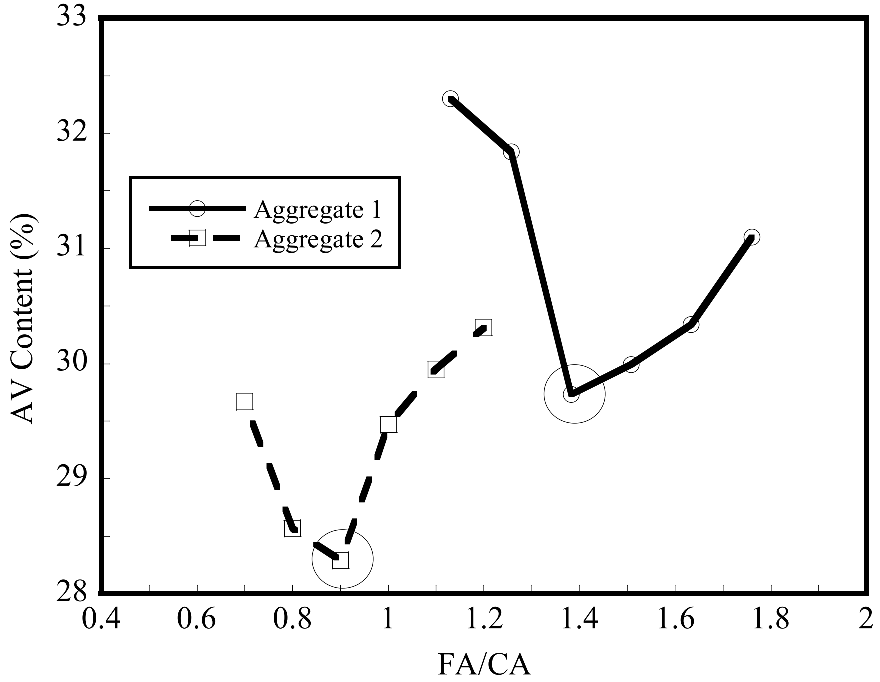

Figure 5.1. Example of Relating the FA/CA to the Minimum AV Content

Step 3. Determine the appropriate FA/CA. Results indicate the minimum FA/CA is likely not the optimal value for stability. An optimal FA/CA should be identified. Using Figure 5.2 and the IAPST value form Step 1, determine the potential optimum FA/CA. The optimum FA/CA can change from the FA/CA associated with the minimum AV content. The FA/CA may increase for coarse aggregates with a low IAPST so that stability increases for concrete mixtures that are deficient in fine aggregate. This effect is less for coarse aggregates with higher IAPST values. For example, an aggregate having an IAPST of 5.0 will require 1.11 of the FA/CA associated with the minimum AV content. Note that these results are based on 3/8-inch (9.5 mm) MSA aggregate and that a low IAPST is different for different MSA's.

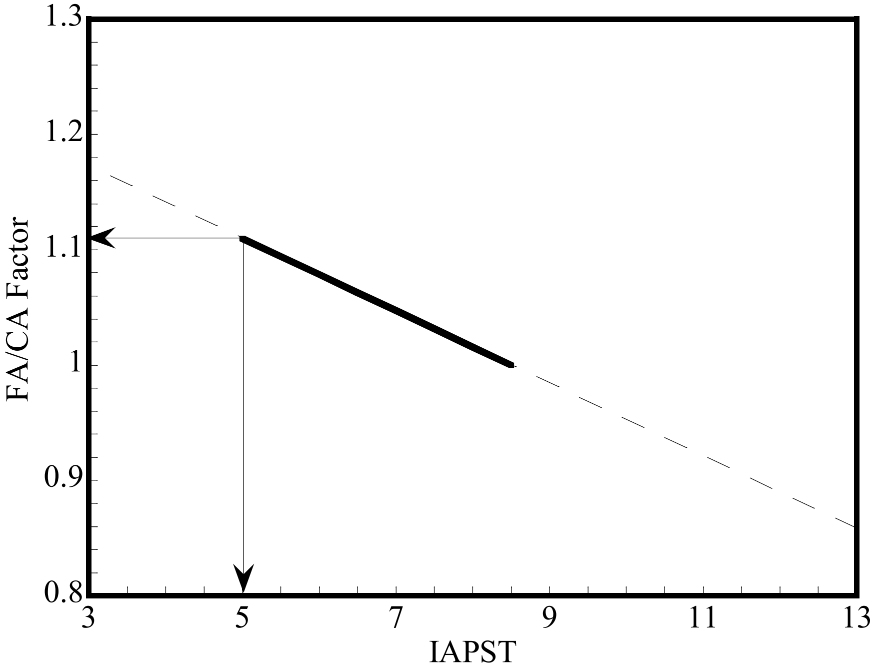

Figure 5.2. Percent FA/CA Increase over the FA/CA That Result in Minimum Voids Depending on the IAPST

From Figure 5.2, equation 5.1 can be used to determine the potential optimal FA/CA value for 3/8-inch (9.5 mm) coarse aggregates with different IAPST values as follows:

$$FA/CA_{Factor} = 1.267 - 0.031 \times (IAPST) \tag{5.1}$$

where the FA/CA$_{\text{Factor}}$ is the factor of FA/CA change from the minimum AV content and the IAPST has been defined previously. The optimal FA/CA is determined by multiplying the FA/CA$_{\text{Factor}}$ by the FA/CA determined in Step 2. Report this value.

Step 4. Identify the AV content for the optimum FA/CA determined in Step 3 and report this value as AV$_{\text{opt}}$.

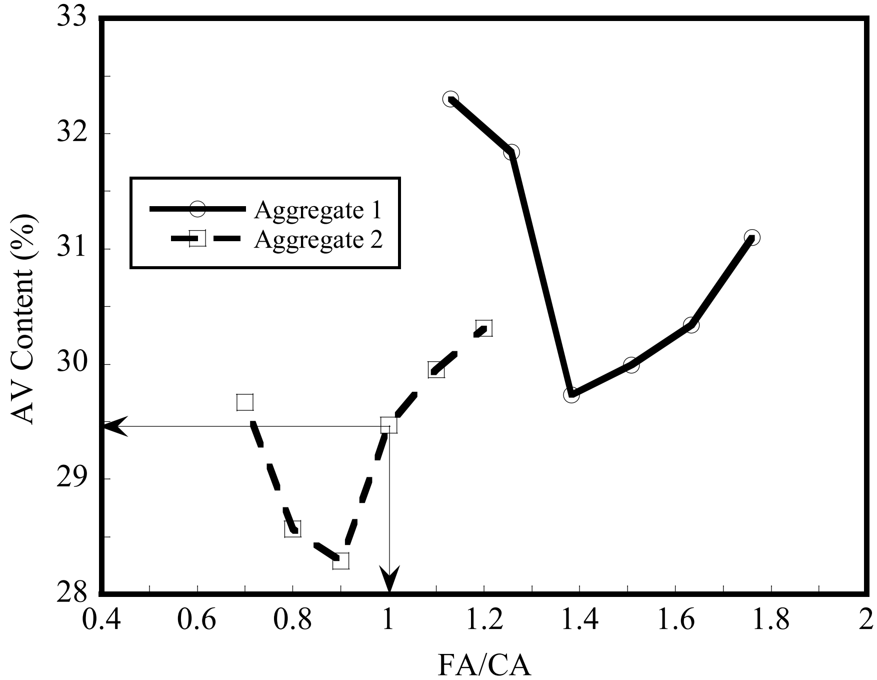

Figure 5.3. Example of Relating the AV Content to the Determined FA/CA

Step 5. With the optimum FA/CA and AV_{opt} content values determined, develop three trial mixtures with the percent paste volumes at 1.10, 1.25, and 1.40 times the AV_{opt} content. Assuming a unit volume of concrete (1 $yd^3 = 27\ ft^3$), determine paste volumes.

Step 6. To determine mixture proportions for the trial mixtures, select a target *w/cm* based on strength requirements; using this *w/cm*, the cement and water weights for the mixture proportions can be estimated using the following equations:

$$Wt_{Water} = \frac{\left(\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrained}}{100})\right)\times\left(62.4\right)}{1+\frac{1}{\left(w/cm\right)\times\left(SG_{Cement}\right)}} \qquad (5.3)$$

$$Wt_{Cement} = \frac{\left(\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrained}}{100})\right)\times\left(62.4\right)\times(SG_{Cement})}{1+\left(w/cm\right)\times(SG_{Cement})} \qquad (5.4)$$

Report these proportions for the different trial mixtures. Note that only the water or the cement weight needs to be determined using equation 5.3 or 5.4 (not both). If the water weight is determined, use the *w/cm* to determine the cement weight. Alternatively, if the cement weight is determined, use the *w/cm* to determine the water weight.

Step 7. The aggregate volume for these mixtures will fill the remaining unit volume of the concrete mixture; using the FA/CA identified in Step 3, the fine and coarse aggregate weights for the mixture proportions can be estimated using the following equations:

$$Wt_{CA} = \frac{\left(1-\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrianed}}{100})\right)\times\left(62.4\right)\times(SG_{CA})}{1+\left(\frac{SG_{CA}}{SG_{FA}}\right)\times\left(\frac{FA}{CA}\right)} \qquad (5.5)$$

$$Wt_{FA} = \frac{\left(1-\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrained}}{100})\right)\times\left(62.4\right)\times(SG_{FA})}{1+\frac{1}{\left(\frac{SG_{CA}}{SG_{FA}}\right)\times\left(\frac{FA}{CA}\right)}} \qquad (5.6)$$

Report these proportions for the different trial mixtures. Note that only the coarse or the fine aggregate weight needs to be determined using equation 5.5 or 5.6 (not both). If the coarse or fine aggregate weight is determined, use the FA/CA to determine the other aggregate weight.

These weight proportions should be used for trial mixtures. Note that the paste volume is assumed to have no SCMs. The SCMs can be incorporated based on the producer's preference and changes to the cement weight can be made accordingly by modifying the specific gravity of the cementitious material.

5.1. MIXTURE PROPORTIONING EXAMPLE

To demonstrate the mixture proportioning of HW concrete mixtures, an example is presented here. The following is an example of mixture proportioning for one trial mixture:

Given:

The 3/8-inch (9.5 mm) MSA coarse aggregate has an IAPST value of 6 and an oven-dry specific gravity of 2.74. The fine aggregate has an oven-dry specific gravity of 2.53. The modified ASTM C29-09 results indicate that a 0.90 FA/CA value exhibits the minimum AV content that is 29.0 percent. Shown in Figure 5.4 is an example of the AV contents exhibited by the selected FA/CA values. The hardened concrete is required to have a compressive strength of 6000 psi (41 MPa) at 28 days. Therefore, the *w/cm* must be 0.41 or less. The entrained air is estimated to be approximately 2 percent.

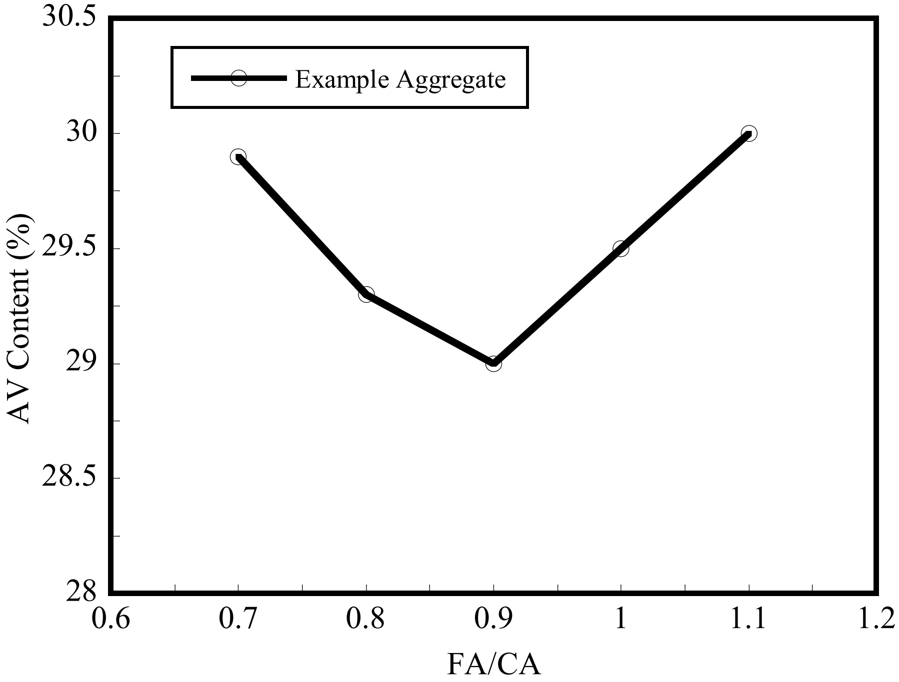

Figure 5.4. Example of Percent AV contents versus FA/CA

Mixture Proportioning Calculations:

First determine the optimum FA/CA as follows:

$$FA/CA_{Factor} = 1.267 - 0.031 \times (IAPST)$$

$$FA/CA_{Factor} = 1.267 - 0.031 \times (6)$$

$$FA/CA_{Factor} = 1.08$$

$$FA/CA = (1.08) \times (0.90)$$

$$FA/CA = 0.97$$

Next determine the AV_{opt} content exhibited by the optimum FA/CA from Figure 5.5: Based on the results in Figure 5.5 the AV_{opt} is approximately 29.3%.

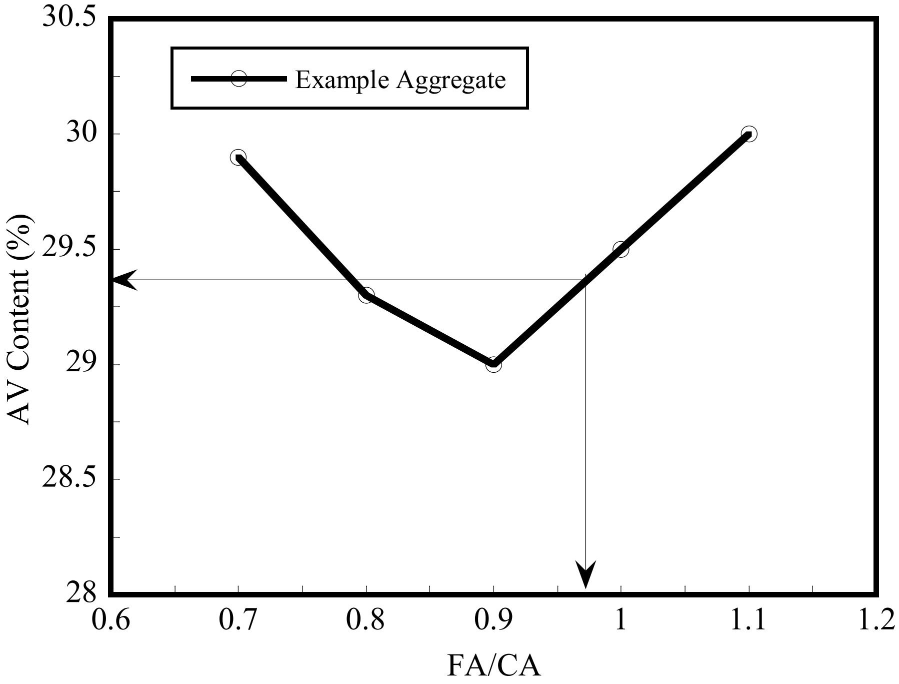

Figure 5.5. Example of determining AV Content Exhibited by Optimum FA/CA

Then determine the trial percent paste volume (for the first trial it is recommended that 1.10 times the AV_{opt} content be used):

$$\%Paste = (29.3\%) \times (1.10)$$

$$\%Paste = 32.2\%$$

Now determine the water and cement weights as follows:

$$Wt_{Water} = \frac{\left(\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrained}}{100})\right)\times\left(62.4\right)}{1+\frac{1}{\left(w/cm\right)\times\left(SG_{Cement}\right)}}$$

$$Wt_{Water} = \frac{\left(\frac{32.2\%}{100}\right)\times\left((27)\times(1-\frac{2\%}{100})\right)\times\left(62.4\right)}{1+\frac{1}{\left(0.41\right)\times\left(3.15\right)}}$$

$Wt_{Water} =$ 299.6 lbs/yd^3 (177.8 kg/m^3)

$$Wt_{Cement} = \frac{299.6 \text{ lbs/yd}^3}{0.41}$$

$Wt_{Cement} =$ 730.8 lbs/yd^3 (433.6 kg/m^3)

Determine the coarse and fine aggregate weights as follows:

$$Wt_{CA} = \frac{\left(1-\frac{\%Paste}{100}\right)\times\left((27)\times(1-\frac{\%Air_{entrianed}}{100})\right)\times\left(62.4\right)\times(SG_{CA})}{1+\left(\frac{SG_{CA}}{SG_{FA}}\right)\times\left(\frac{FA}{CA}\right)}$$

$$Wt_{CA} = \frac{\left(1-\frac{32.2\%}{100}\right)\times\left((27)\times(1-\frac{2\%}{100})\right)\times\left(62.4\right)\times(2.74)}{1+\left(\frac{2.74}{2.53}\right)\times\left(0.97\right)}$$

$Wt_{CA} =$ 1495.9 lbs/yd^3 (887.5 kg/m^3)

$$Wt_{FA} = (1495.9 \text{ lbs/yd}^3) \times (0.97)$$

$$Wt_{FA} = 1451.0 \text{ lbs/yd}^3 \ (860.8 \text{ kg/m}^3)$$

Check Volumes:

$$V_{Air} = (\frac{2\%}{100}) \times 27$$

$$V_{Air} = 0.54 \text{ ft}^3$$

$$V_{Water} = \frac{299.6 \text{ lbs/yd}^3}{(62.4)}$$

$$V_{Water} = 4.80 \text{ ft}^3$$

$$V_{Cement} = \frac{730.8 \text{ lbs/yd}^3}{(3.15) \times (62.4)}$$

$$V_{Cement} = 3.72 \text{ ft}^3$$

$$V_{CA} = \frac{1495.9 \text{ lbs/yd}^3}{(2.74) \times (62.4)}$$

$$V_{CA} = 8.75 \text{ ft}^3$$

$$V_{FA} = \frac{1451.0 \text{ lbs/yd}^3}{(2.53) \times (62.4)}$$

$$V_{FA} = 9.19 \text{ ft}^3$$

$$V_{Total} = 0.54\ \text{ft}^3 + 4.80\ \text{ft}^3 + 3.72\ \text{ft}^3 + 8.75\ \text{ft}^3 + 9.19\ \text{ft}^3 = 27\ \text{ft}^3\ (0.76\ \text{m}^3)$$

The other trial mixture proportions should be determined following the previous example. The trial mixtures should be mixed and assessed for slump flow and VSI. The PV/AV has been shown to influence slump flow and VSI. Therefore, it is a useful tool to plot slump flow versus PV/AV. From the trial mixtures a relationship between slump flow and PV/AV can be developed as shown in Figure 5.6. This figure also shows an estimate of the PV/AV values that exhibit a VSI greater than 1 (upper limit) and a slump flow of 20 inches (510 mm) (lower limit). However, additional trial mixtures should be mixed and tested to identify a range of mixtures with adequate slump flow and VSI.

Figure 5.7 shows an example of the actual upper and lower limit that can be determined from additional trial mixtures. Now that the actual range of mixtures that exhibit adequate flowability and stability have been identified, these limits may change based on adequate passing ability. Mixtures within the shaded area in Figure 5.7 should also be assessed for passing ability. The possible limit change due to mixtures exhibiting adequate passing ability is shown in Figure 5.8. This figure shows that the lower limit could possibly increase which would increase the minimum slump flow to 22 inches (560 mm) and PV/AV to 1.25. Results indicate that increasing the PV/AV can increase passing ability so this is a possible change to the lower PV/AV limit. However, selecting a mixture at the lower PV/AV limit can decrease the high cost and unfavorable hardened properties associated with higher paste volumes.

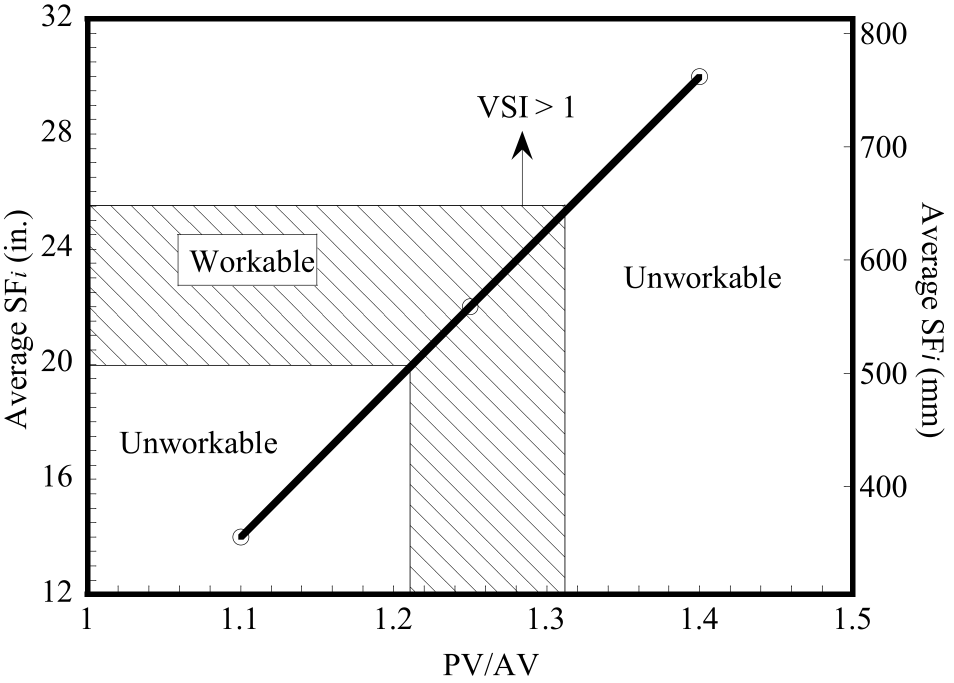

Figure 5.6. Example of Possible Slump Flow and PV/AV Relationship Based on Trial Mixtures Showing Estimated Upper and Lower Limits

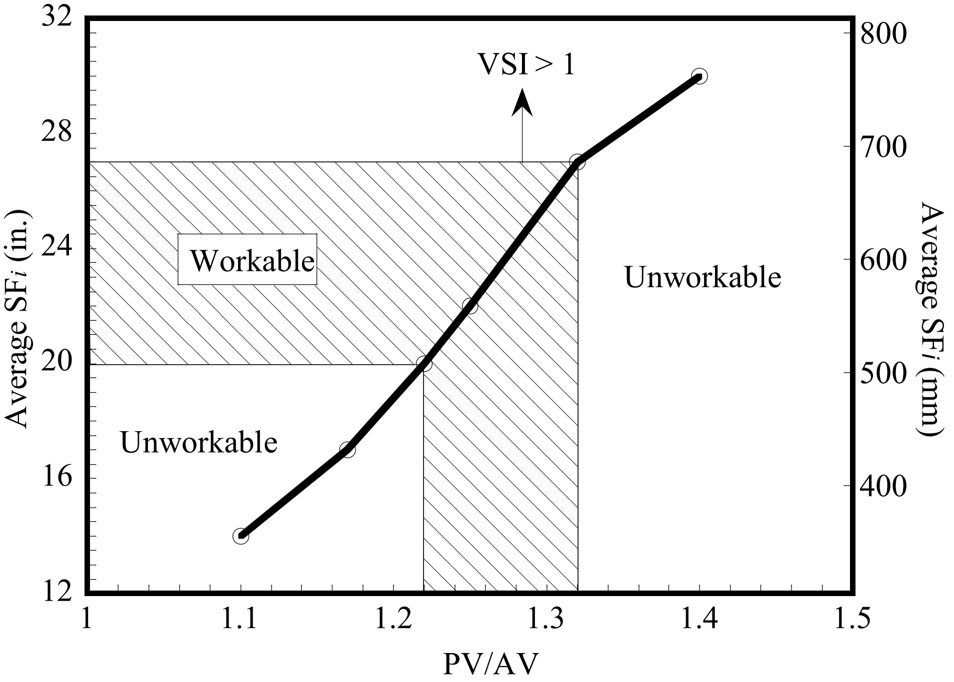

Figure 5.7. Example of Possible Slump Flow versus PV/AV Relationship Based on Additional Trial mixtures Showing Actual Upper and Lower Limits

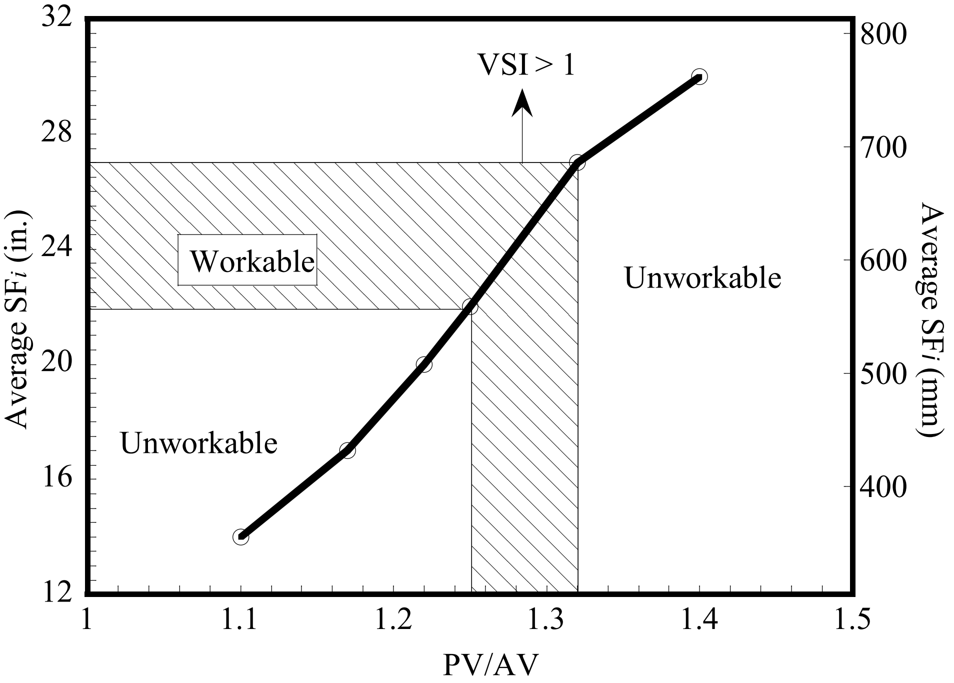

Figure 5.8. Possible Limit Change Based on Passing Ability Requirements

6. SUMMARY AND RECOMMENDATIONS

The following summary and recommendations are based on the results of this study. Included in this section are a summary of the results from the preliminary investigation of the influence of *w/cm* on flowability and stability, the influence of aggregate type and mixture proportions on workability, and the influence of test configuration on the sensitivity of results. Recommendations are presented base on the results of these sections.

6.1. PRELIMINARY INVESTIGATION: INFLUENCE OF W/CM ON FLOWABILITY AND STABILITY

1. Slump flow is dependent on the *w/cm*.
2. Increasing the paste volume and *w/cm* can increase slump flow.
3. Increasing the *w/cm* and paste volume can decrease concrete stability.
4. Results indicate that a minimum paste volume limit should be identified for a minimum flowability limit and maximum paste volume limit should be identified for stability at the desired *w/cm*.

6.2. INFLUENCE OF AGGREGATE TYPE AND MIXTURE PROPORTIONS ON WORKABILTIY

The research investigated the influence of aggregate type and mixture proportions on flowability, stability, and passing ability.

6.2.1. Influence of Aggregate Type and Mixture Proportions on Flowability

1. Paste volume, PV/AV, AV content, and coarse aggregate type (IAPST) influence slump flow. FA/CA indirectly influences slump flow because FA/CA influences the AV content.

2. Increasing the paste volume and PV/AV can increase slump flow.
3. Concrete mixtures containing a lower AV content can exhibit higher slump flow values than other mixtures containing the same paste volume.
4. Coarse aggregates that exhibit lower IAPST values tend to exhibit lower AV contents at lower FA/CA values than coarse aggregates with higher IAPST values. Therefore, aggregate with a lower IAPST can be used to decrease the paste volume and FA/CA requirements to achieve a given slump flow. However, a coarse aggregate with a high IAPST can also be used for HW concrete mixtures.

6.2.2. Influence of Aggregate Type and Mixture Proportions on Stability

1. The paste volume, PV/AV, and FA/CA significantly influence stability.
2. Increasing the paste volume and PV/AV generally decreases the stability of concrete mixtures.
3. Increasing the FA/CA value can increase stability.
4. The results indicate that the coarse aggregate IAPST and AV content do not significantly influence stability for the mixtures assessed in this research.

6.2.3. Influence of Aggregate Type and Mixture Proportions on Passing Ability

1. The L-box results indicate that paste volume and PV/AV are influencing factors on passing ability.
2. The L-box results indicate that increasing the paste volume and PV/AV generally increase passing ability.
3. The L-box results also indicate no clear influence or trend on the influence of FA/CA, AV content, and coarse aggregate IAPST on passing ability.
4. The observed influence of coarse aggregate IAPST and mixture proportions on J-ring and C-bar passing ability results is unclear. This could be a result of the smaller MSA used in the research. Even so, both methods are reasonable approaches to assessing passability. However, further testing is needed.

6.3. INFLUENCE OF TEST CONFIGURATION ON THE SENSITIVITY OF RESULTS

1. The J-ring test results indicate that a general trend may exist for mixtures with specific mixture proportions, but results varied significantly for many mixtures. No recommendations for changing the J-ring configuration is presented here as further research is needed to assess these test variables.

2. Test results indicate that the C-bar test may provide a measure of passing ability. In general, mixtures that exhibited adequate flow and stability exhibited adequate passing ability. One mixture that exhibited low flow failed the C-bar test which indicates the test may add value. However, more testing is required, especially with lager MSA coarse aggregates, to make recommendations on the C-bar configuration.

3. Because the J-ring and C-bar test results for different configurations are not correlated to field performance of concrete placement, there is no recommendation for the reinforcing bar clear spacing for these tests in this report. However, the reinforcing bar clear spacing used for these tests may be less than the clear spacing found in the field for a conservative assessment of passing ability.

4. The C-bar test configuration likely provides an indication of how the concrete will perform in the field because the C-bar test configuration more closely represents the CIDH pile configuration. However, more research is required.

6.4. RECOMMENDATIONS

The J-ring, C-bar, and L-box tests can possibly be used to assess concrete passing ability but a correlation between field performance and test results needs to be established for a test method to be recommended. It is recommended that the results for different reinforcing clear spacing of the J-ring and C-bar test configuration be correlated to field performance. The C-bar test configuration represents the situation found in CIDH piles and therefore, may provide a more accurate assessment of how the concrete will perform when placed in CIDH piles. The 8 bar C-bar configuration shown in the appendix is the recommended configuration to provide a conservative passing ability assessment. It is also recommended that research be performed to assess the passability requirements for the different C-bar tests using different sizes and gradations of coarse aggregates. It is also recommended that research be performed to assess J-ring passability. The difference in height in four equally spaced locations directly inside and outside the circumference of the J-ring should be assessed. The L-box passability ratio requirements may be reduced but further research is needed to assess the passing ability requirements for field applications.

If the C-bar test is used to assess passing ability then a minimum slump flow of 20 inches (508 mm) is required to achieve adequate flowability to perform the test. It is recommended that Caltrans change the specified minimum slump of 7 inches (178 mm) to a minimum slump flow of 20 inches if the C-bar test is going to be implemented. It is recommended that the assessment of the workability be performed more frequently than the one instance specified in Section 49-3.02A(4)(c) of Caltrans Specification (2010). It is recommended that assessing workability includes the assessment of flowability, stability, and passing ability. Also, if the mixture proportioning method described here is going to be implemented then, Caltrans may consider revising the combine aggregate gradation to allow a higher percent passing for the No.4 sieve. This is because several aggregate mixtures in this study were slightly outside this requirement but exhibited adequate flowability, stability, and passing ability.

It is recommended that further research be performed to assess the passing ability of concrete mixtures with larger coarse aggregate MSA's than 3/8-inch (9.5 mm). It is recommended that further research be performed for mixture proportioning of aggregates with different MSA's and IAPST values than the ones presented in this research. However, it is recommended that the mixture proportioning method presented in this research be used to create HW concrete mixtures for CIDH pile applications. This method can be used to create HW concrete mixtures with adequate flowability, stability, and passing ability.

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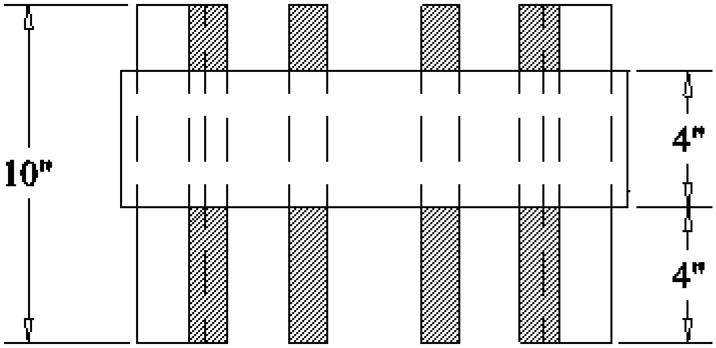
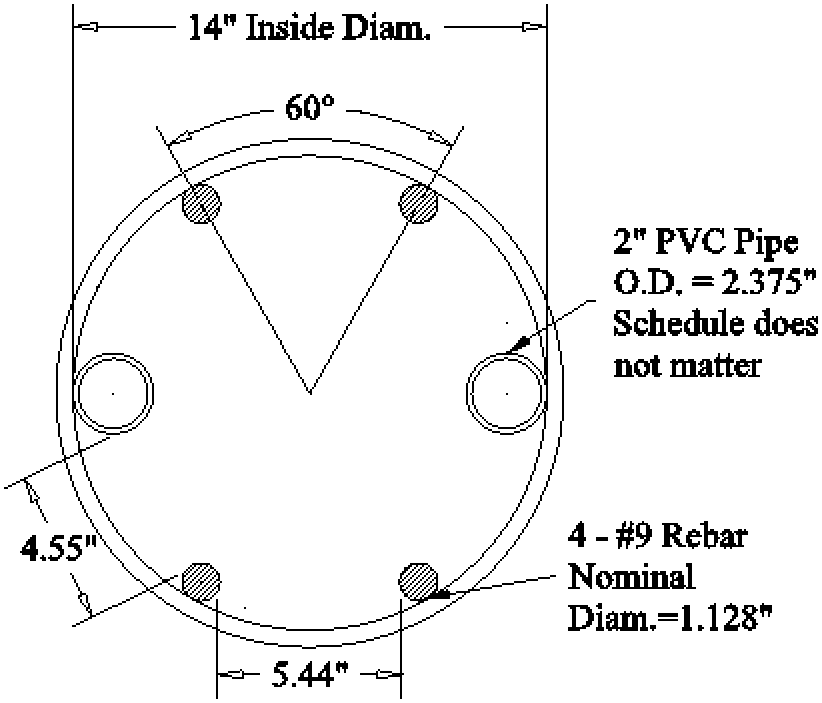
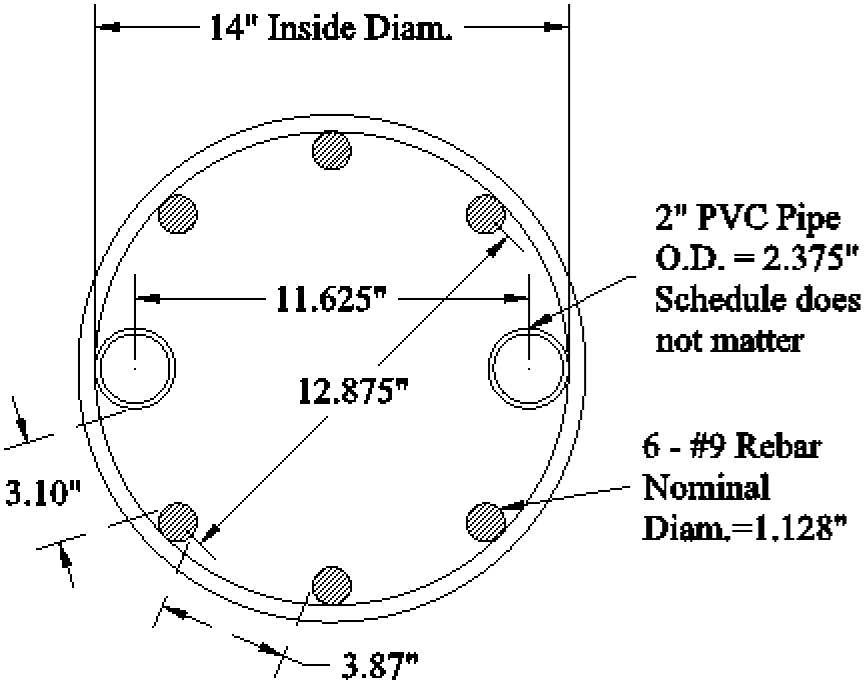
7. APPENDIX



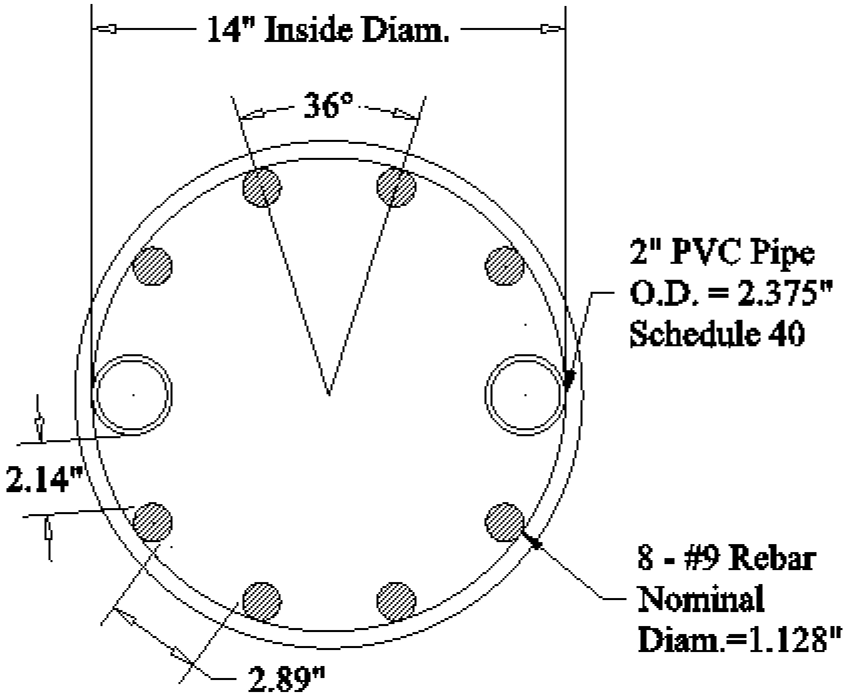
Elevation View of the C-bar Test



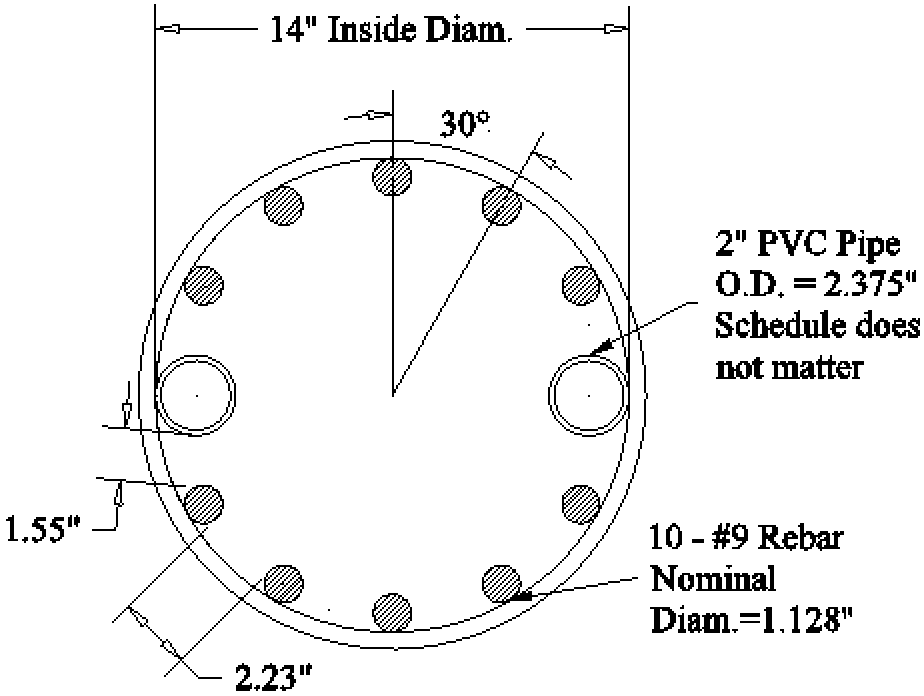
Plan View of the 4 bar C-Bar Test Setup



Plan View of the 6 bar C-Bar Test Setup



Plan View of the 8 bar C-Bar Test Setup (Recommended Test Setup)



Plan View of the 10 bar C-bar Test Setup