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Qualification of Concrete Workability by Means of the Vibrating Slop Apparatus

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16. Abstract:

A new device, the Vibrating Slope Apparatus (VSA), developed for qualifying concrete workability under vibration, was borrowed by the International Center for Aggregates Research (ICAR) Project 105 researchers for evaluation. Initial evaluation consisted of testing 24 different concretes that possessed a wide range of workability. The results indicate that the VSA is capable of differentiating between mixtures of similar workability and characterizing established trends. However, testing identified three problems inherent of the proposed test method. An excessive amount of time required to obtain results, the possibility of shear failure of a sample that skews results, and the possibility of an inverse relationship, if the minimum of two chute angles are tested. To solve these problems, the VSA was fitted with an accelerometer to monitor vibration displacement and frequency during testing. A new wedged-shape chute gate was also constructed. The data from the accelerometer were consolidated into one variable, energy, which was used to replace the chute angle from the initial test procedure. The new equipment and procedure were evaluated in a similar manner as before and promising results were obtained. The new procedure solved all three problems identified with the original procedure. A linear correlation between VSA and slump cone measurements for less then 3 inches was defined. This new method was able to characterize expected patterns and differentiate between mixtures of similar workability in an acceptable time, whereas a single-point test, the slump cone, was not. However, the size and complexity of the VSA limit implementation within the field.

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QUALIFICATION OF CONCRETE WORKABILITY BY MEANS OF THE VIBRATING SLOPE APPARATUS

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ABSTRACT

A new device, the Vibrating Slope Apparatus (VSA), developed for qualifying concrete workability under vibration, was borrowed by the International Center for Aggregates Research (ICAR) Project 105 researchers for evaluation. Initial evaluation consisted of testing 24 different concretes that possessed a wide range of workability. The results indicate that the VSA is capable of differentiating between mixtures of similar workability and characterizing established trends. However, testing identified three problems inherent of the proposed test method. An excessive amount of time required to obtain results, the possibility of shear failure of a sample that skews results, and the possibility of an inverse relationship, if the minimum of two chute angles are tested. To solve these problems, the VSA was fitted with an accelerometer to monitor vibration displacement and frequency during testing. A new wedged-shape chute gate was also constructed. The data from the accelerometer were consolidated into one variable, energy, which was used to replace the chute angle from the initial test procedure. The new equipment and procedure were evaluated in a similar manner as before and promising results were obtained. The new procedure solved all three problems identified with the original procedure. A linear correlation between VSA and slump cone measurements for less then 3 inches was defined. This new method was able to characterize expected patterns and differentiate between mixtures of similar workability in an acceptable time, whereas a single-point test, the slump cone, was not. However, the size and complexity of the VSA limit implementation within the field.

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CHAPTER 1. INTRODUCTION

1.1 RESEARCH BACKGROUND

The American Concrete Institute (ACI), Committee 116 – Cement and Concrete Terminology, defines concrete workability as "the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition." Similarly, The Japanese Association of Concrete Engineers defines workability as "that property of freshly mixed concrete or mortar which determines the ease with which it can be mixed, placed, and compacted due to its consistency; the homogeneity with which it can be made into concrete; and the degree with which it can resist separation of materials" (Ferraris 1999). Together these definitions illustrate that qualification of concrete workability by a single test suitable for use adjacent to construction operations is a daunting task.

Since inception of the slump cone in the 1920s, concrete mixtures have become more complex. The addition of chemical admixtures used to promote workability, modify set times, and entrain air into the matrix, and supplementary cementitious materials (SCM), used to improve characteristics of the hardened product, have complicated concrete. Applications in which these new concretes are used have also expanded made the process of producing concrete more complex. Overall, most all aspects of concrete construction have advanced with time. However, the means in which we qualify concrete in a plastic state before placement has seen minimal advancements. This point can be illustrated by a visit to a construction site, where there is a high probability that a slump cone will be in use to determine the concrete's workability. The lack of a better means of qualification suitable for use in the field is not because of a lack of effort to develop such a device. In fact many devices have been developed since the slump cone was standardized by many individuals with many backgrounds. However, only a few of these devices have progressed to common use in the field.

In general, the purpose of developing a device suitable for use by engineers, technicians, and tradesmen to qualify the workability of concrete in the field adequately has consumed extensive amounts of research effort. These efforts have produced significant insight; however, the objective of qualifying workability has not been met.

1.2 RESEARCH OBJECTIVES

The objective of this study, funded by the International Center for Aggregates Research (ICAR), was the identification or development of a device suitable for qualifying the workability of high-microfines concrete in a field environment. It has been shown that concrete produced with heightened levels of microfines often exhibits in improved hardened properties. However, conventional wisdom has held that increased levels of this material will result in poor workability of the fresh concrete as evidenced by increased efforts for placement, consolidation, and finishing. The reason for this belief is in large part due to low slump values for concrete containing high levels of microfines. Slump tests do not mimic true placement procedures in which energy is added by vibration, but instead measure the workability in a static state. Slump, therefore, inaccurately characterizes concrete that is often quite workable.

A recent device, the Vibrating Slope Apparatus (VSA), was developed by the Waterway Experiment Station (WES) of the Army Corps of Engineers for the Federal Highway Administration (FHWA) for the purpose of qualifying low slump concrete used for paving. This is done by measuring the rate at which a sample discharges from an inclined chute. The measurements, in contrast to most other tests, are taken when the sample is subjected to vibration energy.

Before the VSA was built, the developers conducted a literature review to learn what other devices were available and their advantages and disadvantages. Therefore, because of similar project purposes, it seemed prudent for ICAR to evaluate the VSA before development of a new device began. The objectives of this evaluation are:

- Conduct an analysis of the VSA apparatus to determine if in its present forms it is able to qualify the workability of concrete accurately both with and without increased levels of microfine material.

- Upon analyzing the results of the initial evaluation, determine if modification to the apparatus or procedure would improve the accuracy of workability predictions.

1.3 SCOPE

The report contains five chapters. A brief background on the topic of concrete workability and discussion of the objectives of this report are given in Chapter 1. A literature review, summarizing the complexity of concrete workability and methods of qualification is included in Chapter 2. An introduction to the VSA and details of the initial evaluation with results is contained in Chapter 3. Modifications made to the VSA and the re-evaluation procedure is discussed in Chapter 4. A summary of the key findings and suggestions for future work is presented in Chapter 5.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

With increasing technology significantly changing concrete composition, the need for advanced testing methods to qualify concrete properties while in a plastic state is clear. One property that has received considerable attention from engineers and contractors is concrete workability. Concrete workability research has been documented since the early 1900s, when literature began addressing various concerns. Since this time, great amounts of research have been conducted investigating this problem. One focus that has received large amounts of interest is the development of an empirical test that can qualify concrete workability. Recent research has also focused on developing models which simulate concrete composition and predict characteristics; therefore, the need to prepare trial batches to determine these qualities is eliminated.

2.1.1 Workability and Its Importance

The American Concrete Institute (ACI) Committee 116 defines workability as "that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition." Depending on mixture proportions and admixtures, fresh concrete can cover a wide range of workability. These mixtures include less workable concrete, which requires large pieces of construction equipment for placement and consolidation, to self-consolidating concrete that can be placed at a single point and flow to fill a form, requiring minimal labor.

2.1.1.1 Engineers

Since Duff Abrams developed the relationship between the strength of hardened concrete and water-to-cement ratio in 1918, engineers began specifying water-to-cement ratios. These limits are enforced by requiring contractors to use some kind of consistency test to monitor changes between deliveries. The most popular consistency test specified is the slump cone, standardized under the American Standards and Testing for Materials (ASTM) C143.

Along with the hardened strength of concrete, the workability of concrete can affect other properties as well. Concrete is a composition of suspended aggregate within a cement paste medium. In order for proper placement to occur, the cement paste must be capable of keeping the aggregate in suspension. Therefore, a cement paste must be stable in order to maintain the suspension of the aggregate. If excess water is added to aid in placement, segregation may begin to occur because of the increased water-to-cementitious materials ratio. On the other hand, if not enough water is available then proper placement around obstacles becomes increasingly difficult or in some cases impossible. Adequate consolidation may also be an issue when there is deficient water in the mixture.

2.1.1.2 Contractors

The concrete contractor is concerned with concrete workability for other reasons. Optimal workability, for a contractor, allows placement of the concrete into the structure that meets specifications with the least amount of labor and equipment wear. In the case of pavements, a mixture that is too fluid will not maintain shape after the slip form passes. While the contractor is attempting to minimize costs, regard must be given to make sure that the product meets specifications.

2.1.2 Properties a Workability Measurement Needs to Consider

A mixture may be highly workable when used in a pavement, but not workable enough for use in a large, reinforced column. History has shown that due to the variables present in concrete placement, the use of a single test to qualify concrete for use is impractical. Reiner (1960) suggested using four different single-point tests to qualify multiple properties of a mixture. The suggested tests included methods that would measure harshness, segregation resistance, shear strength and stickiness. Some proponents of the slump test may argue that this test is capable of achieving all these tasks alone. However, the reason that the slump test is still in use today is not that it is capable of qualifying concrete, but that it was developed early, when concrete was still simplistic relative to mixtures today, and has gained acceptance over time. In short, its use has become the norm due to its simplicity and the lack of another test in which users are as well versed.

Use of the term "workability" to describe a concrete mixture is largely user-defined. Throughout the years, a plethora of testing instruments has been developed to qualify what tradesmen have been doing qualitatively for years. Many of these devices are only suitable for measuring one aspect of concrete workability. The previously cited ACI definition includes references to mixing, placement, consolidation and finishing. Ritchie (1968) subdivided concrete rheology into three main parameters: stability, compactibility, and mobility (Figure 2.1). In summary, there are many opinions about what characteristics a workability device should measure. However, the majority agrees that more than one characteristic, for example the slump, is needed to qualify the workability of concrete.

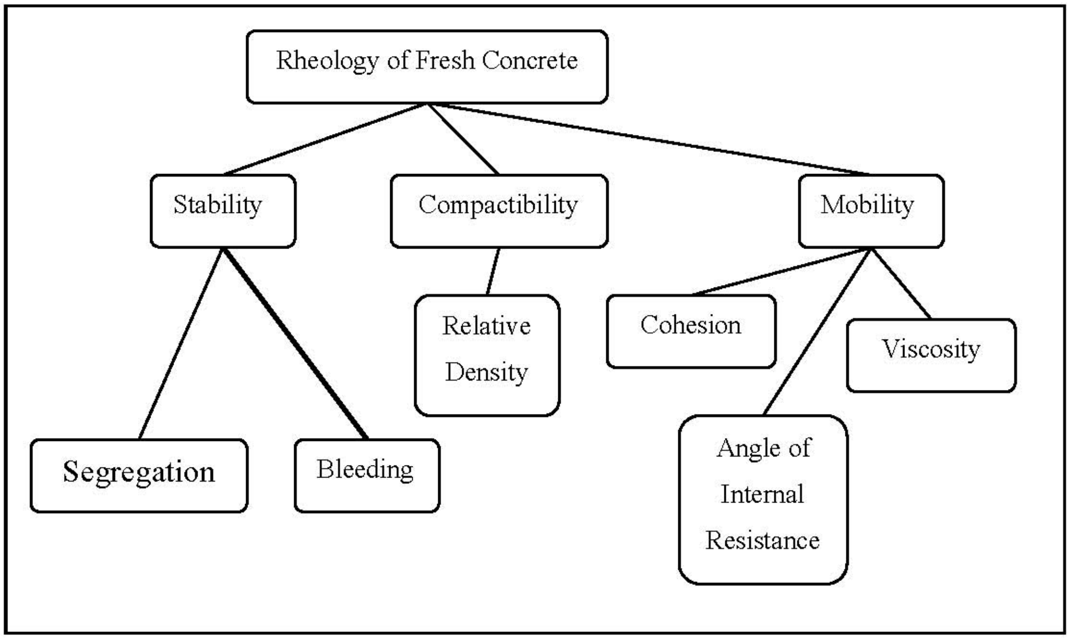


Figure 2.1 Ritchie's Parameters of the Rheology of Fresh Concrete (Ritchie, 1968)

2.2 CONTRIBUTING FACTORS

Because concrete is a composite material, the overall mixture workability is the resultant of each component's individual contribution. Concrete mixtures are prepared in degrees of precision, ranging from simple ratios of coarse aggregate, sand, and cement to complicated mixture designs that include tertiary blends of SCMs and also chemical admixtures. Mixture proportioning criteria usually focus on hardened strength and exposure conditions, while the workability of the mixture, a characteristic commonly thought of in hindsight, is adjusted accordingly for job-specific conditions. Therefore, components are often added that have adverse effects on workability because of their ability to increase strength or durability. The components of concrete work together to determine concrete workability in as many ways as there are to design a mixture. Therefore, the development of a test device capable of monitoring the workability of such a complex material is difficult. The following will discuss the effects that each component involved in a basic mixture has on workability. This discussion is limited to the effects that aggregate, water-to-cementitious material ratio, and placement environment have on workability.

2.2.1 Aggregate

Coarse and fine aggregates account for approximately 75-80% (by mass) of concrete. For this reason, aggregate properties need to be assessed in order to predict the workability of the concrete mixture in which the aggregate is intended for use. The following discussion, pertaining to the evaluation of aggregate characteristics that effect workability, is divided into two sections: coarse aggregate and fine aggregate.

2.2.1.1 Coarse Aggregate

With depletion of natural gravel, concrete producers have begun replacing natural river gravels with crushed stone. Because of the method by which this aggregate is produced, particles are more angular. The angularity of these particles, coupled with their close proximity to each other, produce interlocking between coarse aggregate that results in a less workable mixture than if rounded natural gravel were used. The decrease in workability when crushed stone is substituted for natural gravel is due to two properties of the natural gravel (Tattersall, 1991). Qualification methods used to assess the properties of natural gravel commonly assume that these aggregate particles can be modeled by perfect spheres. The spherical shape of the aggregate particles creates a "ball-bearing effect," which allows individual particles to move among each other relatively easily as compared to the effort required to move angular and irregularly shaped crushed particles. The second advantage of these spheres over crushed aggregates is that for a given mass a sphere has the lowest surface area. Therefore, less cement paste is needed to coat the surface of these particles and fill the voids between them (Tattersall, 1991). The reduced paste or mortar needed to coat and fill the voids between the aggregate allows more paste to be available to contribute to the overall flow of the mixture.

Research efforts have attempted to develop qualification methods for coarse aggregate and then correlate these measurements to workability measurements. These qualification methods seem quite rudimentary, using elongated sieves or special gauges resulting in tedious, labor-intensive measurements that are not commonly practiced today. Because this work seems to have little significance to workability prediction and measurement and has already been reviewed by other authors (Tattersall, 1991), further discussion is omitted. In general a concrete mixture will be more workable when spherical natural gravel is used versus a crushed stone.

2.2.1.2 Fine Aggregate

Because the fine aggregate or sand used in concrete comes from the same sources as coarse aggregate, its effects on workability follow the same patterns. In general, a finer coarse aggregate will require more cement paste to coat and lubricate individual particles due to the increased surface area. It should be noted that it is easier to conceal deleterious materials in sands than coarse aggregates due to the smaller size. Because these materials have the capability of adversely affecting concrete workability, their percentages are limited in the grading requirements set forth in ASTM C 33 - Standard Specification for Concrete Aggregates.

2.2.1.3 Aggregate Grading

For the reasons outlined above, the size of the particles and their respective qualities that make up an aggregate will have considerable influence on the workability of a mixture in which they are used (Tattersall, 1991).

It seems apparent that since the use of spherical aggregate increases workability, due to its decreased surface area and ball bearing-like effects, that use of increased amounts of coarse aggregate would result in a more workable mixture. However, by using increased amounts of coarse aggregate, there is less mortar available to coat and lubricate the increasing amount of coarse aggregate or fill the voids between particles. The lack of sufficient mortar results in a harsh mixture that does not flow well, is prone to segregation, and is difficult to finish. On the opposite end of the spectrum, use of fine grained sand will increase the cohesion of the mixture. In certain cases where segregation or bleeding is a problem this trait may be beneficial. However, this increased cohesion can also result in a less workable mixture. ASTM has established grading limits within specification ASTM C 33 for use in normal concrete mixtures. These limits (Table 2.1) specify a well-graded mixture with zero to ten percent passing a No. 100 sieve. Microfine material, defined by the ability to pass a No. 200 sieve, is limited to three to five percent when the material is suspected to be deleterious or clay-like. These limits are increased to five to seven percent when the material is non-deleterious, commonly the dust of fracture from aggregate processing.

Table 2.1 ASTM C33 Fine Aggregate Grading Limits for Use in Normal Concrete

Sieve	Percent Passing
9.5-mm (3/8-in)	100
4.75-mm (No. 4)	95 to 100
2.36-mm (No. 8)	80 to 100
1.18-mm (No. 16)	50 to 85
600-µm (No. 30)	25 to 60
300-µm (No. 50)	5 to 30
150-µm (No. 100)	0 to 10

Initially, qualification of aggregate grading consisted of a ratio between fine and coarse aggregate. However, different sands can produce quite different concretes, depending on what size sieve the majority of the particles will pass. Today, because of the size of most aggregates used in normal concrete mixtures, aggregates intended for use can be sieved into individual sizes for quantification. A chart that plots individual sieve sizes on the horizontal axis against the percentage of aggregate passing each sieve, commonly referred to as a particle size distribution, is the commonly used qualification tool for aggregate distribution.

Several attempts have been made to represent an aggregate grading curve by a single numerical value. The fineness modulus, used by ACI 211 for design of concrete mixtures, is likely the most common value used in the United States. Calculation of the fineness modulus is done by adding up the cumulative percentages by weight of the aggregate retained on the nine sieves from five millimeters to 75 micrometers and dividing by 100 (Mehta et al., 1993). Results from this test generally lie between one and three. It may be noted that the higher the fineness modulus, the coarser the aggregate.

2.2.2 Cement Paste

Cement paste is obviously the most complicated constituent of concrete, consisting of fine cement particles undergoing a chemical reaction with and within a water medium (Tattersall, 1976). A complete understanding of concrete workability, therefore, must include a thorough understanding of the cement paste that suspends the aggregate.

2.2.2.1 Water-to-Cementitious Materials Ratio

Studies have been completed that focus on rheology measurements of cement paste with varying water-to-cementitious materials ratios. Tattersall and Banfill (1983) gathered the results of these studies for comparison. What they found, in general, was that the yield value and plastic viscosity decrease with increased water-to-cementitious materials ratio. There was, however, considerable scatter between the data from different projects, yield values spanning a 20-fold range and plastic viscosities a 50-fold range. This broad band of inconsistency was attributed to differences between test devices and procedures.

2.2.2.2 Type of Cement Used

Tattersall (1991) completed a comprehensive review of the available literature pertaining to the effects that differing types of cements have on workability. The review focused on proving or disproving the commonly held belief that, other things being equal, substitution of rapid-hardening portland cement for ordinary portland cement will result in a decrease of mixture workability. The basis for this belief is that due to the finer grinding of identical clinkers and increased sulfate contents, rapid-hardening portland cement will require higher amounts of water to maintain a given workability (Tattersall, 1991). However, evidence is presented that supports both sides of this question, with no clear indication of a common trend. Overall, the conclusion reached is that the important factors affecting concrete workability in regards to cement composition is C_3A content and the quality and state of the sulphate (Tattersall, 1991). Before a specific trend can be determined more work needs to be completed in the laboratory along with further analysis of available data.

2.2.3 Environment

The impacts of weather are well known. The American Concrete Institute (ACI) Committees 305 and 306 have prepared recommendations for placing concrete in hot and cold weather respectively. The impacts that hot and cold weather have on the workability of a concrete mixture have been gleaned from these reports and are summarized below.

2.2.3.1 Impacts of Hot Weather on Concrete Workability

ACI Committee 305 recommends measuring the loss of workability, due to rising concrete temperature, in inches of slump loss. A general rule is that when working with concrete in hot weather an increase of 20 degrees in concrete temperature will result in the loss of one inch of slump. To recover the loss of workability, water is commonly added in the field. When additional water is added in the field that exceeds design limits, the result is usually decreased hardened strengths and durability. The relationship between slump loss and the respective amounts of water that must be added to recover this loss of workability is illustrated in Figure 2.2.

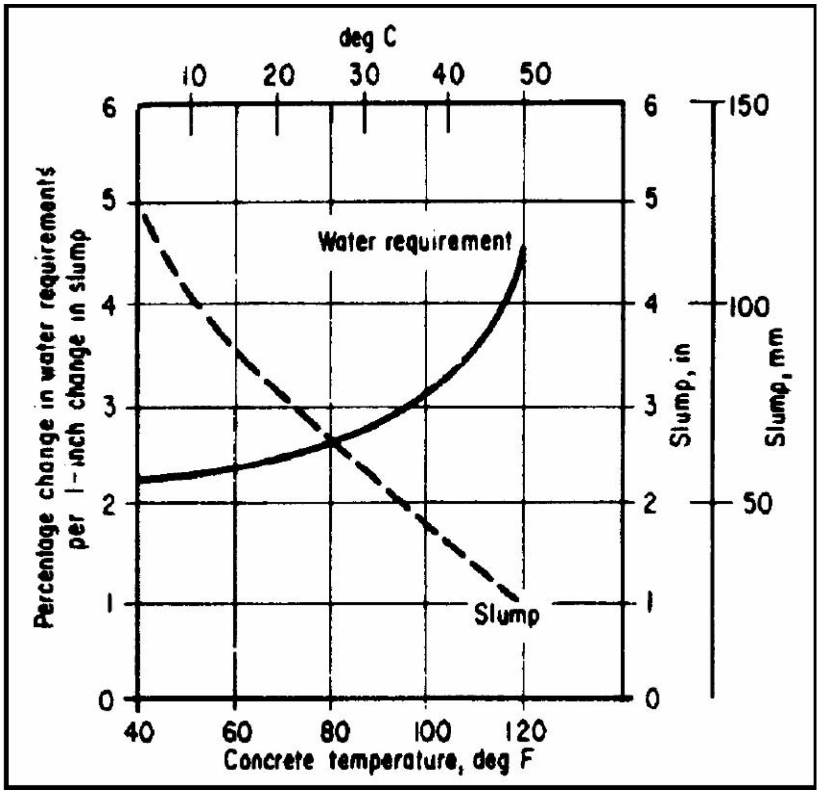


Figure 2.2 Effect of Concrete Temperature on Slump and Water Required to Change Slump (Klieger, 1958 in ACI)

A key point that should be noted for Figure 2.2 is that slump loss, due to increased concrete temperature, occurs in a relatively linear fashion, where as the amount of water needed to increase the slump by one inch increases at an increasing rate. Therefore, where it would take 2.5 percent more water to increase the slump of a mixture by one inch at 70 °F, a 4.5 percent increase in water would be needed to gain the same increase in workability for concrete at 120 °F (ACI 305, 2001). Another trend that relates to concrete workability and elevated temperatures is the rate at which workability decreases due to hydration. Because hydration of cement is a chemical process, elevated concrete temperatures will increase the rate of hydration, thereby increasing the rate of workability loss versus that of an identical mixture with a cooler temperature.

2.2.3.2 Impacts of Cold Weather on Concrete Workability

The report prepared by ACI 306 pertaining to cold weather concreting has little information about the effects of cold weather and concrete workability. Yet, just as an increase in concrete temperature results in a loss of workability, a decrease will result in a gain in workability. ACI Committee 306 also cautions users to be aware that due to the decrease in concrete temperature, presumably caused by lower ambient temperatures, the rate at which bleed water evaporates from the surface will decrease. Due to the increased time for bleed water evaporation, increased effort is required to finish the concrete surface. This decreased level of finishability is noted here because most definitions of concrete workability reference degree of finishability.

2.3 MEASURING WORKABILITY

Concrete technologists have attempted to qualify the workability of concrete since the beginning of the twentieth century. These attempts have led to the development of over sixty different concrete test methods or devices. Due to the lack of acceptance of any one method, a conclusion can be drawn that none of these devices alone is capable of properly measuring all aspects needed to properly qualify workability. The primary reason for the lack of this ability is that the majority of the developed apparatuses are only capable of taking one measurement (Tattersall, 1976). In the early 1970s Tattersall classified concrete as a material that behaves according to Bingham characteristics. This led researchers to investigate and attempt to measure rheological properties of concrete by the means of a simple, economical and portable device.

2.3.1 Science of Rheology

Rheology is defined as “the science of the deformation and flow of matter,” which is what makes qualification of concrete rheology particularly applicable to concrete workability (Whorlow, 1992). Today many materials are monitored during production using rheological techniques for quality control. Some of these products include paints and printing inks, toothpastes, and cleaning products. However, direct measurement of concrete viscosity and yield stress is difficult when compared to other materials because of the aggregate component. There are many commercially available devices used to measure rheological properties; however, none is capable of measuring a substance such as concrete with solid particles the size of typical coarse aggregate.

2.3.1.1 Newtonian Fluids

It is useful to examine the rheological principles of simple materials whose behavior can be described by simple relationships. The simplest case is where Hooke's law is obeyed and the deformation of a solid is directly proportional to the applied load by a proportionality constant, η, or, more simply stated, strain is proportional to stress (Tattersall, 1976). This relationship is illustrated as:

Equation 2.1

$$\tau = \eta\gamma$$

where: τ = shear stress

γ = shear strain

An ideal elastic material is described as a material that will recover any deformation caused from an applied force. An example of Hooke's law is seen in Figure 2.3 where a shear force is applied to a cube made from an ideally elastic material. The shear strain, γ, is a result of the applied shear stress, τ, or F/A, which will be fully recovered when the applied force, F, is removed.

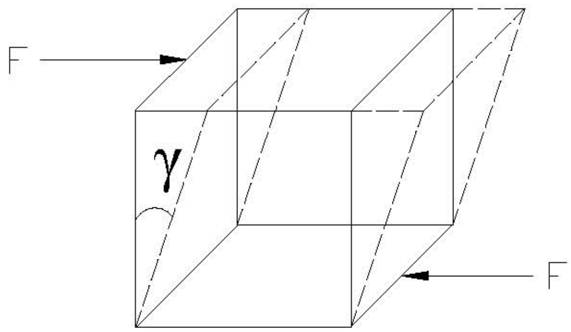


Figure 2.3 Hooke's Law for a Material in Shear: F/A = $\eta\ \gamma$ (Tattersall, 1976)

However, in applying a similar stress to a cube made from a simple liquid it is evident that the resulting strain would continue to increase as long as the shear stress was being applied. This strain would continue to increase regardless of the magnitude of the applied stress, τ. However, the rate at which the deformation would occur, measured by the time differential, is dependent on the magnitude of the applied shear stress (Tattersall, 1976). This differential relationship is illustrated by:

Equation 2.2

$$\tau = \eta(d\gamma / dt)$$

Equation 2.2 is very similar to the Hooke's equation, but the shear strain has been replaced by the shear strain rate, $d\gamma/dt$, and η the coefficient of proportionality or shear modulus, is called the coefficient of viscosity.

Since it is not possible to mold a simple fluid into the shape of a cube, scientists have instead simplified this experiment by placing the same simple fluid between two parallel plates. One of the plates is moved at a constant known velocity relative to the other so that a laminar motion of the liquid is produced. This arrangement then simulates

Newton’s law of viscous flow that states that the shear stress is proportional to the velocity, υ, and inversely proportional to the distance, y, between the planes. This relationship is expressed mathematically as:

Equation 2.3

$$\tau = \eta (d\upsilon / dy)$$

The term for shear strain rate, $d\gamma/dt$, has been replaced with, $d\upsilon/dy$, the velocity gradient; therefore Newton’s law of viscous flow may be written as:

Equation 2.4

$$\tau = \eta \cdot \dot{\gamma}$$

By using the assumption of laminar flow in each direction of a perpendicular plane to the y-direction, the velocity gradient of a liquid can be used to classify its flow characteristics. It should be noted that variable temperatures during measurements can result in significant changes in the viscosity. Measurements can also be altered by varying pressure; however, in most applications this condition can be ignored. Therefore, by determining the shear stress for a particular shear rate a point can be plotted on a shear stress versus shear rate graph. Next, a straight line is passed through this point and the origin. Then by calculating the slope of this line, $1/\eta$, fluid viscosity can be determined. This procedure is illustrated in Figure 2.4.

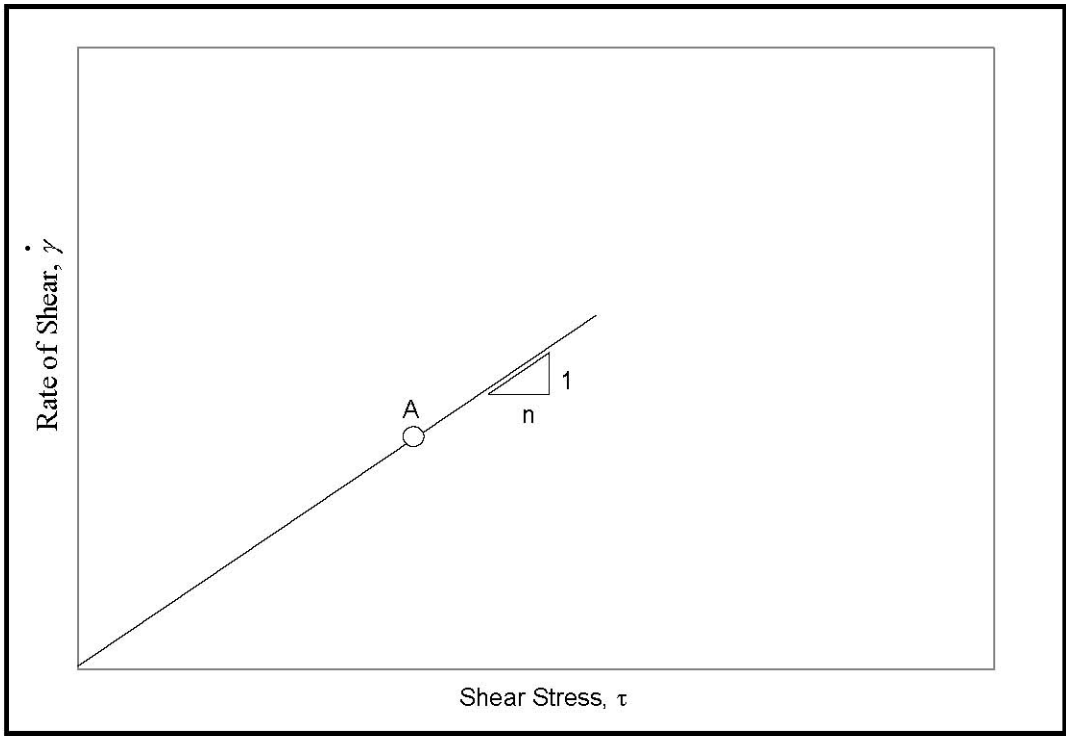


Figure 2.4 Newtonian Liquid: $\tau = \eta\dot{\gamma}$. A Single Experimental Point is Sufficient to Determine the Slope of the Line (Tattersall, 1976)

2.3.1.2 Non-Newtonian Fluids

After a review of basic fluid rheology, it might be erroneously concluded that application of these concepts to more complicated materials can be done with little effort. However, due to several unique characteristics of these materials, definition of their rheological properties is still quite difficult. Shear stress divided by the rate of shear is a constant (Equation 2.3). It was mentioned previously that external factors such as temperature and pressure may have an effect on measurements; however, with more complicated materials other factors, such as rate of shear and time of shear, may play a role. Probably the most obvious characteristic is the ability of concrete to withstand a certain degree of stress without deformation. This property is best illustrated by subjecting concrete to a standard (ASTM C143) slump test (Tattersall, 1976). The slump test shows that concrete is capable of supporting some of its own weight without deformation. It is known that a simple Newtonian fluid such as water is not capable of this behavior. The amount of stress that a material is capable of withstanding without experiencing deformation is called its yield stress, τ_0.

2.3.1.2.1 Bingham Model

The result of applying the concept of yield stress to the Newtonian model is that the line qualifying the flow characteristics of the fluid no longer passes through the origin. A result of this is that two parameters of measurement, τ_0 and μ, are needed in order to characterize the flow properties of a material. In incorporating the yield stress into Equation 2.3 η is replaced by μ, which still acts as a constant and has dimensions of viscosity but is called the plastic viscosity. The modifications that are made to the Newtonian equation, which is now called the Bingham model, are represented in Equation 2.5 (Tattersall, 1976).

Equation 2.5

$$\tau = \tau_0 + \mu\gamma$$

These modifications to the Newtonian model are shown in a plot of shear stress verses rate of shear. The incorporation of a yield stress, τ_0 and the two points of measurement, A and B, that are needed to determine the slope of the line 1/μ or plastic viscosity and yield stress τ_0 are illustrated in Figure 2.5 (Whorlow, 1992).

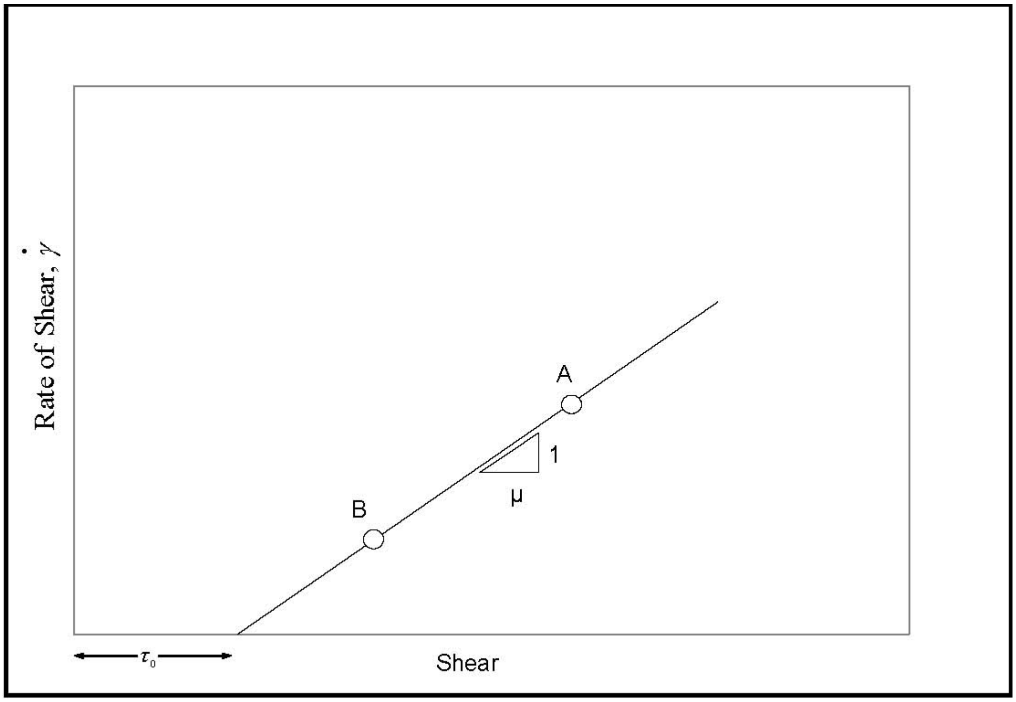


Figure 2.5 Bingham Model: $\tau = \tau_0 + \mu \cdot \dot{\gamma}$, A and B Represent the Two Experimental Points Needed to Fix the Line (Tattersall, 1976)

2.3.1.2.2 Power Model

Although the Bingham model is slightly more complicated, with its introduction of yield stress, than the Newtonian model it is still considered somewhat rudimentary when compared to more complex behavior. The Bingham model, however, remains the most popular among concrete engineers due to its ability to qualify the flow behavior of concrete in a somewhat simplistic method. Further examination of more complex materials introduces flow curves that exhibit exponential instead of linear behavior. Although, these relationships are important to be aware of due to the continuous developments in high-performance concretes, an in-depth examination is beyond the scope of this report. Therefore, the following discussion is merely meant to introduce the more complicated flow behavior that occurs in complex materials.

The power-law model (Equation 2.6) can be used to describe materials whose flow characteristics resemble those of Figure 2.6:

Equation 2.6

$$\tau = k\gamma^{n}$$

where: k = viscosity

n = material constant

Such materials are called pseudoplastic materials.

The power-law model resembles Equation 2.4, used for Newtonian fluids, in that it is used to classify the simplest form of exponential behavior. The addition of a yield stress that earlier transformed a Newtonian fluid to behave as a Bingham material is now considered. With the addition of a yield stress to Equation 2.6 the power-law model takes on a new form called the Hershel-Bulkley model (Equation 2.7).

Equation 2.7

$$\tau = \tau_0 + k\lambda^n$$

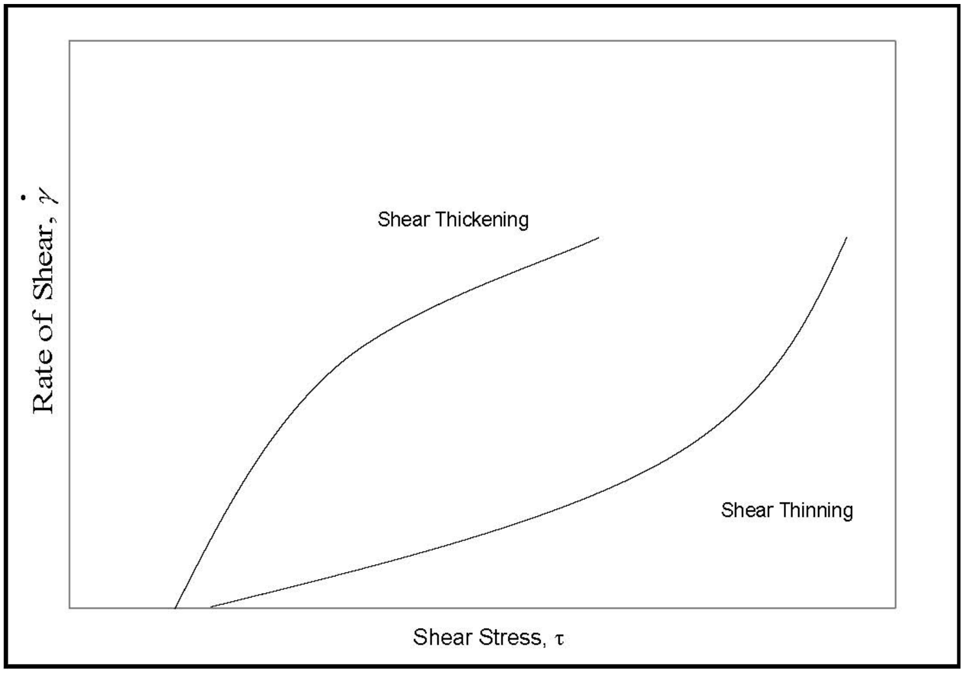


Figure 2.6 Nonlinear Flow Curves (Tattersall, 1976)

2.3.1.3 Considerations during Measurement

When testing a simple Newtonian fluid little consideration needs to be given to the way in which the material will be tested because similar results will be reached with most all methods. This however, does not hold true for more complicated fluids, such as concrete. Rheology measurements of suspensions must consider at what rate the suspension will be sheared in use and then attempt to duplicate this rate during testing in order to measure appropriate rheologic values. Careful consideration must also be given to the time in which the material will be sheared. The considerations correspond with a phenomenon called shear thinning as well as thickening and thixotropy that occur in complicated fluids.

2.3.1.3.1 Shear Thinning and Shear Thickening

As noted previously the flow curve can take on an exponential form that may or may not intersect the origin. In either case the curve may be either concave up, known as shear thinning, or concave down, known as shear thickening (Figure 2.6). A material whose flow curve is concave towards the stress axis is said to be shear thickening because the shear stress is increasing more rapidly than the shear rate, and at higher shear rates it becomes more difficult to make the material flow more quickly (Tattersall, 1976). In certain materials shear thickening behavior will be accompanied by dilatancy or the tendency of a repacking of the particles resulting in an increase in volume (Tattersall, 1976).

A material whose flow curve is concave towards the shear rate axis is said to be shear thinning because the stress is increasing less rapidly than the shear rate, and it becomes easier and easier to increase the flow rate. This behavior is likely to be seen in a material whose structure is capable of being broken down or altered by shearing.

2.3.1.3.2 Thixotropy

Thixotropy, according to an accepted definition, is a gradual decrease of fluid viscosity under shear stress followed by a gradual recovery of structure when the stress is removed (Barnes et al., 1989). A bentonite-slurry, commonly used to support excavations because of the ease in placing this material by means of pumping followed by a gain in strength, is a good example of a material that exhibits thixotropic behavior. Subjecting concrete to high levels of shear, at which the existing structure is destroyed resulting in a decrease of shear strength, is another example of causing thixotropic behavior. Not all thixotropic materials regain their initial strength once the shear rate has returned to zero; these materials are classified as pseudo-thixotropic.

2.3.1.3.3 Vibration

Before vibrators were introduced to concrete construction, compaction efforts consisted of manual tamping. However, consolidation by this means became less effective when thinner cross sections were used, due to the increased strengths gained with steel reinforcement. These thinner sections, coupled with the use of reinforcing steel, required industry to find new methods in which to consolidate concrete around these new obstacles. Because Abrams (1922) had not yet discovered the relationship between hardened strength and water-to-cement ratio, more water was added to decrease the viscosity of the mixture, allowing it to flow inside of the formwork. However, the obvious problems associated with this solution led to further investigations. Around 1930, machines were developed to impart vibration to concrete. Concrete vibrators are now used in most all concrete construction. ACI Committee 309 has written a report on the behavior of fresh concrete during vibration. In this document the authors note that although vibration is the most-used means of consolidating concrete, little work has been completed that investigate the characteristics of vibration.

The use of vibration for consolidation of concrete is achieved by setting the particles into motion, thus eliminating the internal friction (ACI 309, 2001). L'Hermite and Tournon (1948) have shown that the internal friction within common concrete when vibrated is 0.15 psi. This value is approximately five percent of the internal friction in a static state, or 3 psi. In order to achieve adequate consolidation, a minimal acceleration of 0.5 g and amplitude of 0.0015 inches must be exceeded. From here there is a linear rate of progression of the compaction effort with increased acceleration upwards to 4 g (ACI 309, 2001). Consolidation of concrete occurs in two stages. The first stage begins to occur once the vibrator and concrete come in contact, when the placed material subsides. Next, with continued vibration, entrapped air begins to leave the mixture.

The degree of compaction obtained from a pre-determined amount of vibration energy has been used in several cases as an attempt to qualify the workability of concrete. The Vebe test, classified as a remolding test, measures the remolding ability of concrete under vibration (Bartos, 1992). Other work includes measuring the electrical resistance across a concrete sample after it has been subjected to various levels of vibration (Alexander and Haskins, 1997). Olsen (1987), investigated the degree of consolidation obtained from vibration, measured by an accelerometer, and compared it to an optimal sample with no air voids, calculated from mixture proportions and components' specific gravities. Correlations between the amounts of energy imparted to the sample from vibration and the calculated relative densities are shown in charts.

2.4 CONCRETE AS A COMPOSITE MATERIAL

The combining of aggregate, both coarse and fine, with cement paste creates concrete. This combination of solid particles ranging in size from one micrometer – cement – to five centimeters – coarse aggregate – results in a concentrated suspension of solid particles in liquid medium. Qualification of the mobility of this suspension is significantly complex due to the interaction between the varying different sizes of particles coupled with the formation of hydration products that can begin to form once water is added to the cement.

2.4.1 Concentrated Suspension of Solid Particles

Particles within a typical suspension are subject to multiple different forces that coexist. First, there are those of colloidal nature that arise from interaction between particles (Barnes et al., 1989). These interactions can be either attractive, caused from electrostatic or van der Waal's forces, or repulsive, which also are caused by electrostatic forces. Recently, chemical admixtures have been developed for use in concrete that create repulsive charges between particles in order to reduce flocculation and increase workability.

Another force is the Brownian randomizing force, which is dependent on the size of the particle. These forces can strongly affect particles smaller than one µm in size, e.g., cement grains. This force ensures that particles are in constant movement, making any description of the spatial distribution of the particles a time average (Barnes et al., 1989).

Because of the size of coarse aggregate the above forces have little effect. However, viscous forces, the result of different velocities between particles and the surrounding liquid, are largely responsible for the behavior of the coarse aggregate within concrete. In the case of concrete, segregation is a problem that exists when the gravitational forces overcome these three forces, resulting in separation of the coarse aggregate. What can be concluded from this material is that the macroscopic workability of a concrete is strongly dependent on microscopic interactions.

2.5 SUMMARY

The intent of this material is to aid the reader in understanding the complexity involved with obtaining reliable measurements of concrete workability in practice. It has been shown that maintaining a determined level of workability is desirable for all parties involved in concrete construction. Determining the level of workability desired for a particular application varies with individual and project specifics.

Understanding and measuring concrete behavior is a difficult task because it is a composite material. Modification of any of the individual components or environment in which the material is used can result in different outcomes. A summary of the effects of these modifications was discussed. However, it should not be concluded that these behaviors occur in all circumstances.

A brief introduction to rheology as applied to concrete has been included. Because of the manner in which some concrete is placed, efforts have focused on measuring the rheological components of concrete in order to qualify its workability. Since simplified behavior of concrete resembles the Bingham model, recent work has focused on devices whose measurements are proportional to yield stress and plastic viscosity. Because concrete is a composite material it is more prone to exhibit non-linear responses with increased shear rates. Therefore, the phenomena of shear thinning and thickening were discussed.

Lastly, the forces that act upon solid particles within a suspended system were discussed. In summary the above material was presented to aid the reader in comprehending the need for the remainder of this report. It is not meant to be all encompassing of the vast amount of work that has been completed on this topic.

CHAPTER 3. EVALUATION OF FEDERAL HIGHWAY ADMINISTRATION'S VIBRATING SLOPE APPARATUS

3.1 INTRODUCTION

The Vibrating Slope Apparatus (VSA), a new device for testing the workability of low-slump concrete, was developed for the Federal Highway Administration (FHWA) by the Waterway Experiment Station of the Army Corps of Engineers in 2001. Upon receipt of a prototype VSA from the Army Corps of Engineers, FHWA fabricated three, slightly modified VSAs for use in evaluation of the new test procedure.

The purpose for development of the VSA was because officials at FHWA recognized the lack of suitable tests being used to qualify the workability of low-slump concrete, commonly used for highway pavements. Researchers of the International Center for Aggregates Research (ICAR) Project 105, which had the objective of identifying or developing a new test method suitable for testing high-microfine concrete, were interested in determining if the VSA would be capable of fulfilling the goals of ICAR Project 105. A proposal for use of the VSA was prepared and submitted to FHWA and was approved. The VSA arrived in Austin, Texas, in December 2002.

3.2 VIBRATING SLOPE APPARATUS AND TEST PROCEDURE

The VSA is a box chute in which a concrete sample is placed and consolidated. After consolidation, the chute is raised to a predetermined angle, the end of the chute or chute gate is removed and a vibrator, mounted to the base of the chute, is turned on to evacuate the concrete sample from the chute (Figure 3.1). The chute is mounted upon three load cells that monitor the system's mass during testing. The data collected from the load cells are then used to plot a mass versus time relationship. The derivative of an n^{th} degree polynomial fitted to these data represents the mass flow rate, which describes the concrete behavior when subjected to the shear force imposed by gravity from the inclined chute and vibration forces. In order to achieve a multiple-point test result, the concrete must be tested at two different shear rates. These different shear rates are obtained by performing the test at two different chute angles. The maximum flow rate obtained from each test is then plotted against the chute angle for which the test was run. The slope of the line connecting these points is considered to be the workability index, which is believed to be related to dynamic viscosity. The intercept of this line, or yield offset, is thereby believed to be related to yield stress. Together these two values qualify the workability of a concrete mixture (Wong et al., 2000).

Figure 3.1 Concrete Sample Discharging From Chute under Vibration during Test

3.2.1 Equipment

The VSA test procedure is composed of the hardware and the electronics needed to run the VSA and collect data. These two systems are briefly described. Additional information can be gained from the Army Corps of Engineers final project report (Wong et al., 2002)

3.2.1.1 Mechanical Components of VSA

The VSA consists of a Vibco SCR500 industrial vibrator with speed control mounted to the base of a 24-inch x 11.5-inch rectangular steel box or "chute" with 8.5-inch high walls. The steel chute is attached to an aluminum frame on one end by hinges that allow the chute to be elevated at the opposing end by use of a manual screw jack. The chute angle is determined by a magnetic angle indicator fixed to the side of the chute. The chute and support frame are separated from the remainder of the frame by three 500-pound load cells for use in monitoring the weight of the sample during testing. The forward portion of the frame supports the vibrator speed control and two electric control boxes, containing a signal conditioning board, AC to DC power converter and data acquisition unit, used for retrieving and conditioning data during testing. The components of the VSA are illustrated in a schematic of the apparatus (Figure 3.2) and photo (Figure 3.3).

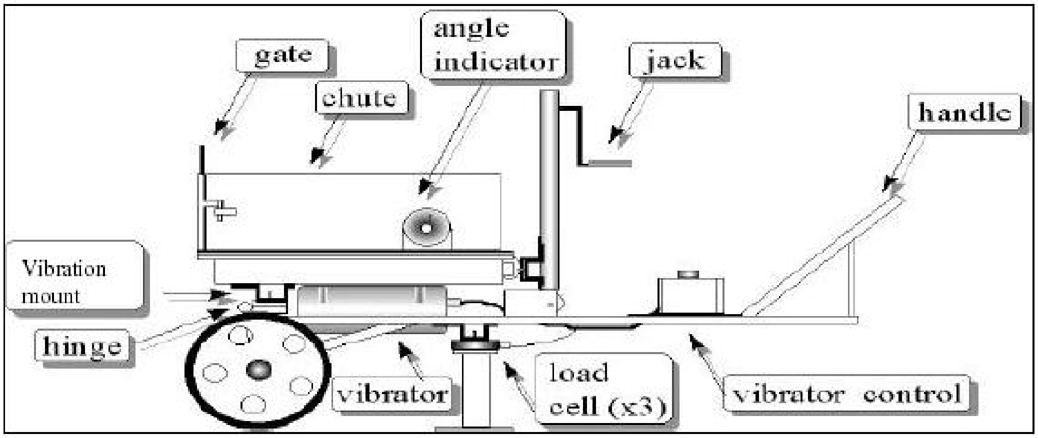


Figure 3.2 Schematic of Vibrating Slope Apparatus (Wong et al., 2000)

Figure 3.3 Vibrating Slope Apparatus Ready for Use

3.2.1.2 Electrical Components and Data Acquisition System of VSA

The VSA is run from a standard 120-volt alternating current (AC) receptacle. The Vibco vibrator requires 120-volt AC, which it receives from a switched dual receptacle mounted to the front of the VSA. The load cells however, require a direct current (DC) excitation which is supplied from an AC to DC converter, housed in the control box, adjacent the vibrator speed control. Before being fed through the data acquisition card to the computer, the three load cell signals are summed into a single signal by an analog summing amplifier. Operation, data collection, display and processing for the VSA are done through a program written in Hewlett Packard's Virtual Engineering Environment (HP-VEE) that is run from a laptop computer. After the test is run, a second program, also written in HP-VEE, is used to combine the results of multiple tests and calculate the workability index and yield offset.

3.2.2 Recommended Test Procedure

The test procedure recommended by the developers of the VSA is as follows (Wong et al., 2000):

1. Adjust the screw jack until the chute is level.
2. Dampen the chute with a mist of water, allowing free water to drain from the chute.
3. Ensure that the quick-remove chute gate is in position; place the freshly mixed concrete sample in the chute to a height four inches above the bottom of the chute.
4. Using the vibrator, vibrate the concrete to consolidate the sample.
5. Raise the angle of the chute to ten degrees, open the gate and press the program start key to start the data acquisition and vibrator simultaneously.
6. Once the majority of concrete has flowed from the chute, clean the residual concrete out of the chute, re-level the chute and replenish and consolidate the sample to begin the second test under a new chute angle.

3.2.3 ICAR 105 Test Procedure

To obtain as much information as possible for a particular concrete mixture the procedure for testing recommended by Wong et al. (2000) was expanded. The modified test procedure used by ICAR 105 is consistent with the original intent of the developers. Instead of taking measurements from only two chute angles, five chute angles were tested. Depending on the consistency of the concrete, the first chute angle was either five or ten degrees, the later being used for less flowable concrete. The chute was then raised in five-degree increments until five different angles had been tested. Upon initial testing of five different chute angles it was apparent that the duration of the test, approximately 45 minutes, was sufficient for hydration products to begin to form, thereby altering the workability of the concrete from the first test. In order to qualify the degree of workability lost, slump measurements were taken before testing began and then again when testing was completed.

It is important to note that only one and a half cubic feet of concrete were mixed, enough material to fill the chute once and conduct an air content test, per ASTM C 231, which required the disposal of a quarter cubic foot of material. The concrete used for the initial slump test was taken from a wheel barrow, before it was tested in the VSA. The sample used for the second slump test was concrete that had already undergone testing in the VSA. It is acknowledged that subjecting the concrete to vibration forces from the VSA may have altered the workability; however, in order to gain as much data from as many mixtures as possible in an allotted time, the preparation of a sample large enough so that concrete was not reused was not practical.

3.3 EVALUATION PLAN

When Wong et al. (2000) began development of the VSA, criteria such as cost, durability, sophistication etc. which needed to be met in order for the device to be feasible for use were defined. ICAR researchers were concerned not only with the results obtained from the VSA, but were also concerned with other aspects of the apparatus: ease of use, practicality, time required, etc. The final VSA report discussed design criteria for the VSA. These criteria are similar to criteria laid out by participants of ICAR 105. However, the bulkiness and complexity of the VSA indicate that opinions differ between the two groups. The following objectives were laid out and an evaluation plan formatted, by the ICAR team, in order to most effectively evaluate the VSA as an applicable test method for high-microfines concrete.

1. Determine the significance of the workability index and yield offset.
2. Determine the influence of the chute angle.
3. Determine if two chute angles are sufficient.
4. Identify ways to simplify the device or test method.
5. Determine the range of workability that can be tested.

To evaluate the VSA a series of concrete mixtures was prepared and tested using the VSA at the Construction Materials Research Laboratory. ACI 211 guidelines were followed in preparing the initial control mixtures, which were then systematically modified, by adding supplementary cementitious materials (SCMs), a chemical admixture, or water to achieve different levels of workability. The mortar fraction of the river gravel control mixture was also modified for additional data. All together 26 different concrete mixtures were prepared and tested by the VSA.

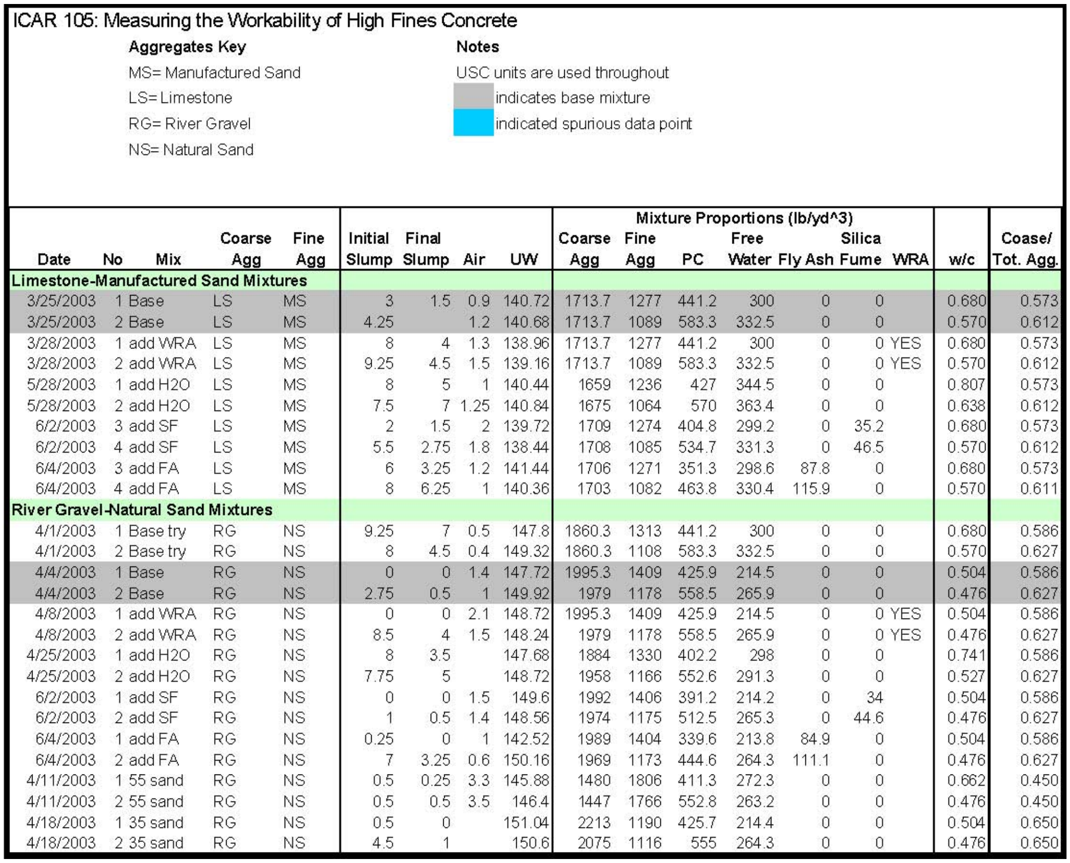
3.4 MATERIAL USED FOR EVALUATION

Two locally available combinations of aggregates, a crushed limestone with manufactured sand and river gravel with natural sand, were used for the mixtures (aggregate gradations are included in Appendix A). The Colorado River gravel had a maximum aggregate size of one inch. The natural sand used with the river gravel was also from the Colorado River. The second material, a crushed limestone, containing minimal chert fragments, from Round Rock, Texas, was crushed to a maximum aggregate size of one inch. The manufactured sand, from the same source, underwent further processing and was washed to remove excess microfines. A Type F fly ash (Source: Rockdale, Texas), supplied by Boral, and silica fume (Force 10,000 D®), a product of Grace Construction Materials, were the two SCMs used. WRDA 64®, a type A and D water-reducing admixture produced by Grace Construction Materials, was used to increase the mixture workability. Type 1 cement, produced locally by Capitol Cement, was used for all mixtures.

3.5 TEST RESULTS

Four different control mixtures, two from each aggregate source, were designed, prepared and modified to evaluate the VSA. Test results will be reviewed in order of aggregate type and the workability modification method, followed by a complete overview of all results. Table 3.1 is a list of the mixture proportions and Table 3.2 the test results. The shaded values in Table 3.2 indicate spurious data points. These values therefore, have been recorded, but are not used for the purpose of comparison with other test data. Further discussion regarding the validity of the obtained results is in Section 3.6.

Table 3.1 Summary of Mixture Proportions



ICAR 105: Measuring the Workability of High Fines Concrete

Aggregates Key

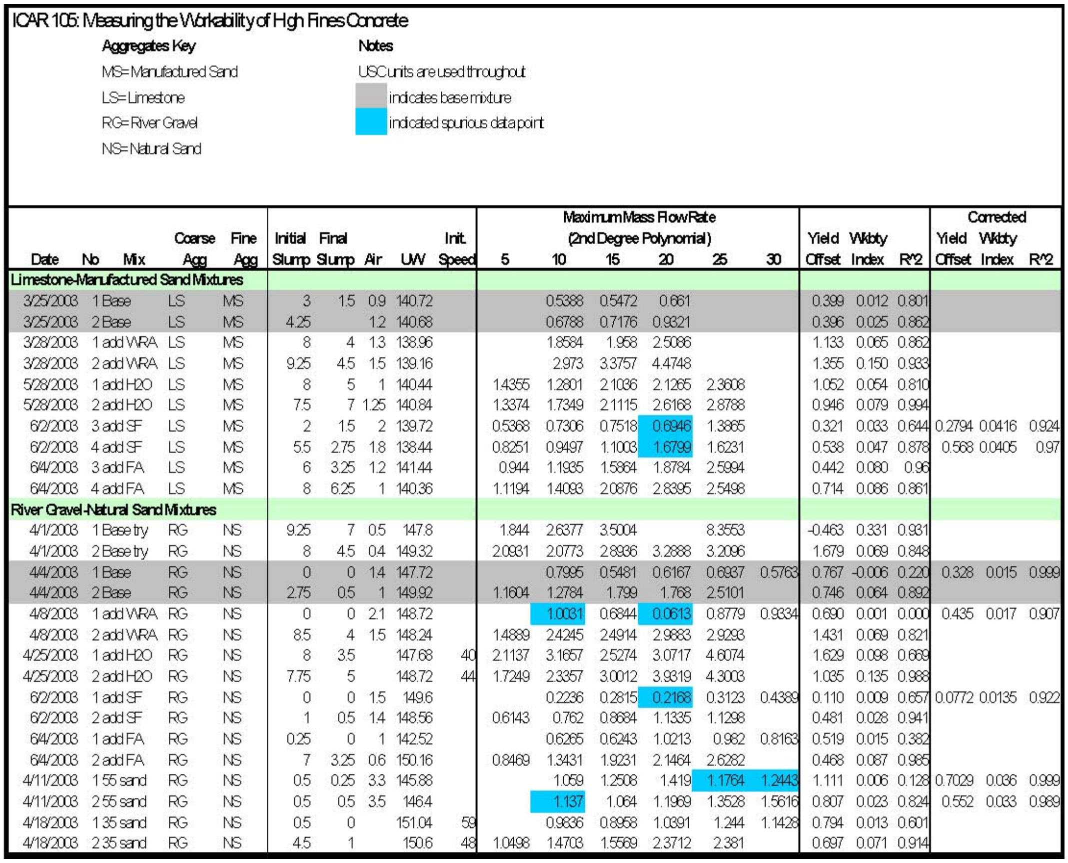
MS= Manufactured Sand
LS= Limestone
RG= River Gravel
NS= Natural Sand

Notes

USC units are used throughout
▨ indicates base mixture
🟦 indicated spurious data point

									Mixture Proportions (lb/yd^3)								
Date	No	Mix	Coarse Agg	Fine Agg	Initial Slump	Final Slump	Air	UW	Coarse Agg	Fine Agg	PC	Free Water	Fly Ash	Silica Fume	WRA	w/c	Coase/ Tot. Agg.
Limestone-Manufactured Sand Mixtures																	
3/25/2003	1	Base	LS	MS	3	1.5	0.9	140.72	1713.7	1277	441.2	300	0	0		0.680	0.573
3/25/2003	2	Base	LS	MS	4.25		1.2	140.68	1713.7	1089	583.3	332.5	0	0		0.570	0.612
3/28/2003	1	add WRA	LS	MS	8	4	1.3	138.96	1713.7	1277	441.2	300	0	0	YES	0.680	0.573
3/28/2003	2	add WRA	LS	MS	9.25	4.5	1.5	139.16	1713.7	1089	583.3	332.5	0	0	YES	0.570	0.612
5/28/2003	1	add H2O	LS	MS	8	5	1	140.44	1659	1236	427	344.5	0	0		0.807	0.573
5/28/2003	2	add H2O	LS	MS	7.5	7	1.25	140.84	1675	1064	570	363.4	0	0		0.638	0.612
6/2/2003	3	add SF	LS	MS	2	1.5	2	139.72	1709	1274	404.8	299.2	0	35.2		0.680	0.573
6/2/2003	4	add SF	LS	MS	5.5	2.75	1.8	138.44	1708	1085	534.7	331.3	0	46.5		0.570	0.612
6/4/2003	3	add FA	LS	MS	6	3.25	1.2	141.44	1706	1271	351.3	298.6	87.8	0		0.680	0.573
6/4/2003	4	add FA	LS	MS	8	6.25	1	140.36	1703	1082	463.8	330.4	115.9	0		0.570	0.611
River Gravel-Natural Sand Mixtures																	
4/1/2003	1	Base try	RG	NS	9.25	7	0.5	147.8	1860.3	1313	441.2	300	0	0		0.680	0.586
4/1/2003	2	Base try	RG	NS	8	4.5	0.4	149.32	1860.3	1108	583.3	332.5	0	0		0.570	0.627
4/4/2003	1	Base	RG	NS	0	0	1.4	147.72	1995.3	1409	425.9	214.5	0	0		0.504	0.586
4/4/2003	2	Base	RG	NS	2.75	0.5	1	149.92	1979	1178	558.5	265.9	0	0		0.476	0.627
4/8/2003	1	add WRA	RG	NS	0	0	2.1	148.72	1995.3	1409	425.9	214.5	0	0	YES	0.504	0.586
4/8/2003	2	add WRA	RG	NS	8.5	4	1.5	148.24	1979	1178	558.5	265.9	0	0	YES	0.476	0.627
4/25/2003	1	add H2O	RG	NS	8	3.5		147.68	1884	1330	402.2	298	0	0		0.741	0.586
4/25/2003	2	add H2O	RG	NS	7.75	5		148.72	1958	1166	552.6	291.3	0	0		0.527	0.627
6/2/2003	1	add SF	RG	NS	0	0	1.5	149.6	1992	1406	391.2	214.2	0	34		0.504	0.586
6/2/2003	2	add SF	RG	NS	1	0.5	1.4	148.56	1974	1175	512.5	265.3	0	44.6		0.476	0.627
6/4/2003	1	add FA	RG	NS	0.25	0	1	142.52	1989	1404	339.6	213.8	84.9	0		0.504	0.586
6/4/2003	2	add FA	RG	NS	7	3.25	0.6	150.16	1969	1173	444.6	264.3	111.1	0		0.476	0.627
4/11/2003	1	55 sand	RG	NS	0.5	0.25	3.3	145.88	1480	1806	411.3	272.3	0	0		0.662	0.450
4/11/2003	2	55 sand	RG	NS	0.5	0.5	3.5	146.4	1447	1766	552.8	263.2	0	0		0.476	0.450
4/18/2003	1	35 sand	RG	NS	0.5	0		151.04	2213	1190	425.7	214.4	0	0		0.504	0.650
4/18/2003	2	35 sand	RG	NS	4.5	1		150.6	2075	1116	555	264.3	0	0		0.476	0.650

Table 3.2 Summary of Test Results



ICAR 105: Measuring the Workability of High Fines Concrete

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NS= Natural Sand

Notes
US Units are used throughout
▨ indicates base mixture
🟦 indicated spurious data point

Date	No	Mix	Coarse Agg	Fine Agg	Initial Slump	Final Slump	Air	UW	Init. Speed	Maximum Mass Flow Rate (2nd Degree Polynomial)						Yield Offset	Wkbty Index	R^2	Corrected		
										5	10	15	20	25	30				Yield Offset	Wkbty Index	R^2
Limestone-Manufactured Sand Mixtures																					
3/25/2003	1	Base	LS	MS	3	1.5	0.9	140.72			0.5388	0.5472	0.661			0.399	0.012	0.801			
3/25/2003	2	Base	LS	MS	4.25		1.2	140.68			0.6788	0.7176	0.9321			0.396	0.025	0.862			
3/28/2003	1	add WRA	LS	MS	8	4	1.3	138.96			1.8584	1.958	2.5086			1.133	0.065	0.862			
3/28/2003	2	add WRA	LS	MS	9.25	4.5	1.5	139.16			2.973	3.3757	4.4748			1.355	0.150	0.933			
5/28/2003	1	add H2O	LS	MS	8	5	1	140.44		1.4355	1.2801	2.1036	2.1265	2.3608		1.052	0.054	0.810			
5/28/2003	2	add H2O	LS	MS	7.5	7	1.25	140.84		1.3374	1.7349	2.1115	2.6168	2.8788		0.946	0.079	0.994			
6/2/2003	3	add SF	LS	MS	2	1.5	2	139.72		0.5368	0.7306	0.7518	0.6946	1.3865		0.321	0.033	0.644	0.2794	0.0416	0.924
6/2/2003	4	add SF	LS	MS	5.5	2.75	1.8	138.44		0.8251	0.9497	1.1003	1.6799	1.6231		0.538	0.047	0.878	0.568	0.0405	0.97
6/4/2003	3	add FA	LS	MS	6	3.25	1.2	141.44		0.944	1.1935	1.5864	1.8784	2.5994		0.442	0.080	0.96			
6/4/2003	4	add FA	LS	MS	8	6.25	1	140.36		1.1194	1.4093	2.0876	2.8395	2.5498		0.714	0.086	0.861			
River Gravel-Natural Sand Mixtures																					
4/1/2003	1	Base try	RG	NS	9.25	7	0.5	147.8		1.844	2.6377	3.5004		8.3553		-0.463	0.331	0.931			
4/1/2003	2	Base try	RG	NS	8	4.5	0.4	149.32		2.0931	2.0773	2.8936	3.2888	3.2096		1.679	0.069	0.848			
4/4/2003	1	Base	RG	NS	0	0	1.4	147.72			0.7995	0.5481	0.6167	0.6937	0.5763	0.767	-0.006	0.220	0.328	0.015	0.999
4/4/2003	2	Base	RG	NS	2.75	0.5	1	149.92		1.1604	1.2784	1.799	1.768	2.5101		0.746	0.064	0.892			
4/8/2003	1	add WRA	RG	NS	0	0	2.1	148.72			1.0031	0.6844	0.0613	0.8779	0.9334	0.690	0.001	0.000	0.435	0.017	0.907
4/8/2003	2	add WRA	RG	NS	8.5	4	1.5	148.24		1.4889	2.4245	2.4914	2.9883	2.9293		1.431	0.069	0.821			
4/25/2003	1	add H2O	RG	NS	8	3.5		147.68	40	2.1137	3.1657	2.5274	3.0717	4.6074		1.629	0.098	0.669			
4/25/2003	2	add H2O	RG	NS	7.75	5		148.72	44	1.7249	2.3357	3.0012	3.9319	4.3003		1.035	0.135	0.988			
6/2/2003	1	add SF	RG	NS	0	0	1.5	149.6			0.2236	0.2815	0.2168	0.3123	0.4389	0.110	0.009	0.657	0.0772	0.0135	0.922
6/2/2003	2	add SF	RG	NS	1	0.5	1.4	148.56		0.6143	0.762	0.8684	1.1335	1.1298		0.481	0.028	0.941			
6/4/2003	1	add FA	RG	NS	0.25	0	1	142.52			0.6265	0.6243	1.0213	0.982	0.8163	0.519	0.015	0.382			
6/4/2003	2	add FA	RG	NS	7	3.25	0.6	150.16		0.8469	1.3431	1.9231	2.1464	2.6282		0.468	0.087	0.985			
4/11/2003	1	55 sand	RG	NS	0.5	0.25	3.3	145.88			1.059	1.2508	1.419	1.1764	1.2443	1.111	0.006	0.128	0.7029	0.036	0.999
4/11/2003	2	55 sand	RG	NS	0.5	0.5	3.5	146.4			1.137	1.064	1.1969	1.3528	1.5616	0.807	0.023	0.824	0.552	0.033	0.989
4/18/2003	1	35 sand	RG	NS	0.5	0		151.04	59		0.9836	0.8958	1.0391	1.244	1.1428	0.794	0.013	0.601			
4/18/2003	2	35 sand	RG	NS	4.5	1		150.6	48	1.0498	1.4703	1.5569	2.3712	2.381		0.697	0.071	0.914			

3.5.1 River Gravel with Natural Sand

Two mixtures, one having minimal workability (zero inch slump) and the other moderate workability (two and a half inch slump) make up the control mixtures for river gravel and natural sand. The initial mixtures were designed following ACI 211 guidelines. However, the consistency of these mixtures exceeded expected results; therefore, water was removed from both mixtures making control mixtures RG1 and RG2.

3.5.1.1 Modification of Mixtures RG1 and RG2 with Water and Mid-Range Water Reducer

Laboratory work using rheometers has indicated that the increased workability gained from the addition of a water-reducing admixture is gained through a reduction in the mixture yield stress. Water, on the other hand, sometimes added in the field to increase the workability of a low-workability mixture, decreases both the yield stress and viscosity of a mixture. In order to determine if the VSA was able to detect this relationship, RG1 was modified by adding water and a water reducing admixture separately. In this case the VSA performed well in identifying the expected relationship (Figure 3.4). Addition of the mid-range water reducer resulted in a decreased yield stress with little change to the workability index, where the addition of water changed both yield stress and workability index. A key point to note from Figure 3.4 is that even when the mid-range water reducer was added to RG1, the measured slump was still zero inches. The VSA, on the other hand, was able to distinguish the change in workability, where the slump was not.

It should be noted that a decrease in yield stress corresponds to an increased y-intercept, whereas an increased slope or workability index indicates a decrease of mixture viscosity. These two values react contrary to their rheological counterparts; therefore, care should be taken when evaluating VSA test results.

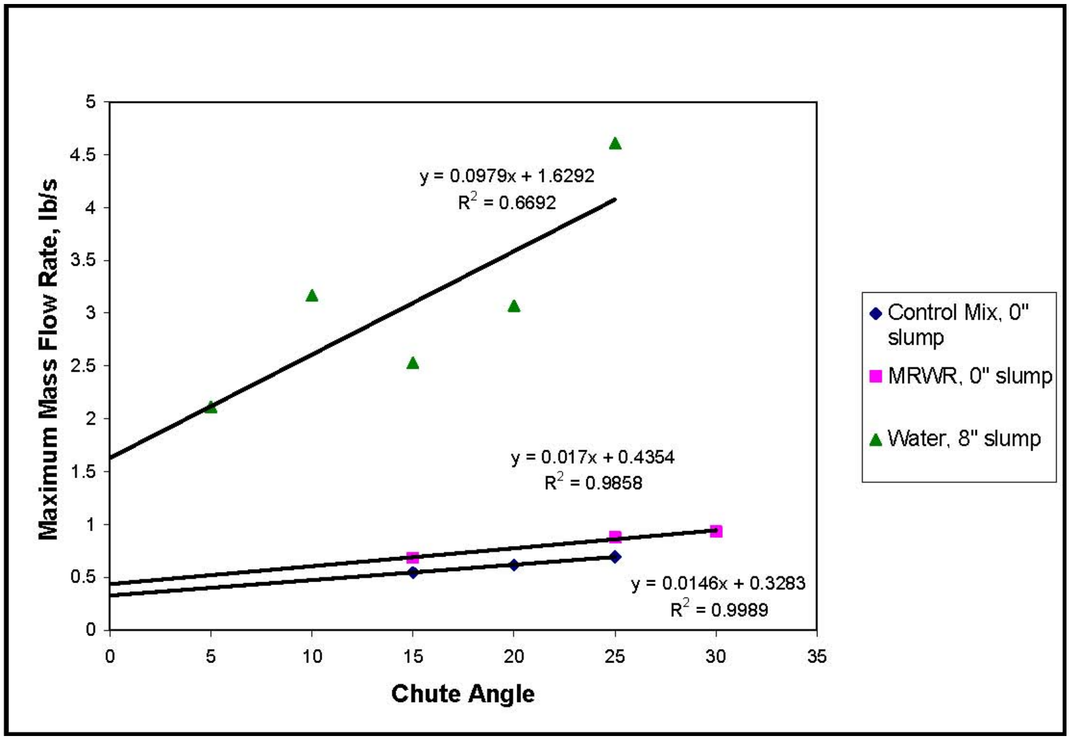


Figure 3.4 Effect of Adding Water Reducer versus Adding Water, Mixture RG1

The VSA was also able characterize this relationship in the higher consistency mixture, RG2. Further evidence is provided in Figure 3.5 that the VSA possesses the ability to differentiate between mixtures with varying workability, due to different means of modification. Somewhat of a best-case scenario is seen in Figure 3.5, where each result was as expected and the amount of scatter between individual measurements is minimal.

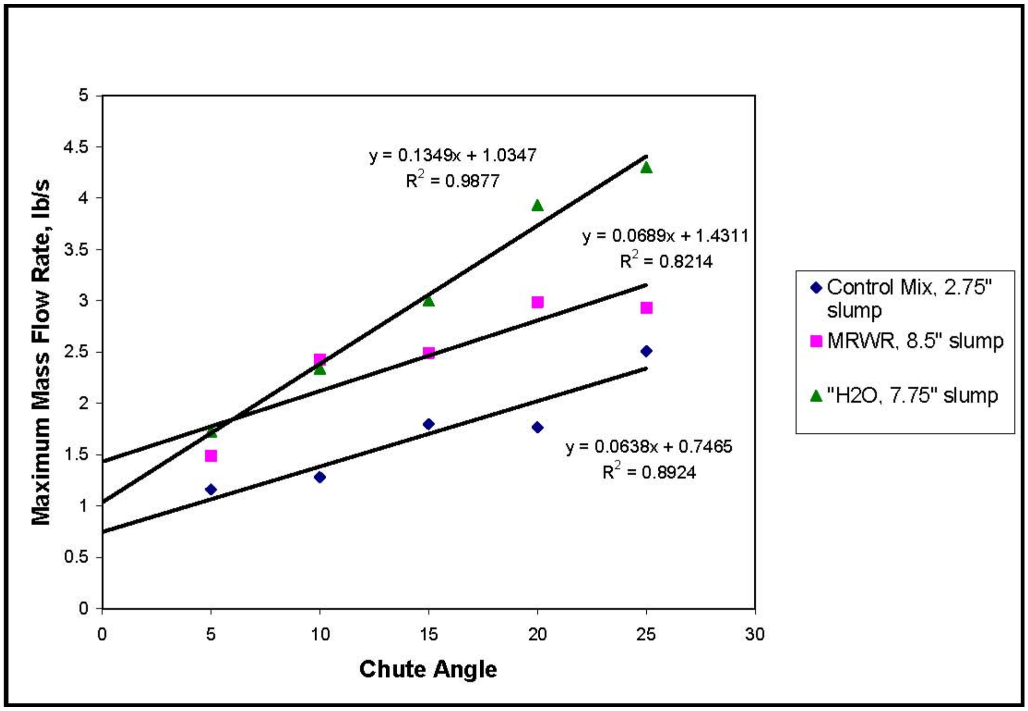


Figure 3.5 Effect of Adding Water Reducer versus Adding Water, Mixture RG2

3.5.1.2 Modification of Mixtures RG1 and RG2 with SCMs

The workability of RG1 and RG2 were further modified with the addition of fly ash and silica fume. The effects these SCMs had on RG1 are depicted in Figure 3.6. Past research has shown that partial replacement of cement with fly ash will increase the workability of a mixture, by decreasing the yield stress and viscosity. In the case of RG1 the y-intercept increases denoting a decrease to the mixture yield stress as expected. However, the workability index remains relatively constant, indicating little change to mixture viscosity. There is, however, considerable scatter (R^2 value of 0.38) among the individual test results. As previously noted spurious data points were removed; however, in this case no measurements were removed because no single point could be differentiated from the group. A strong linear relationship was the result of measurements taken from RG1, when an eight percent replacement of silica fume was used. The results for this mixture, when compared to those of the control, are an increase in yield stress and viscosity. Together, the changes of these variables constitute a decrease in concrete workability, as visual observations confirmed.

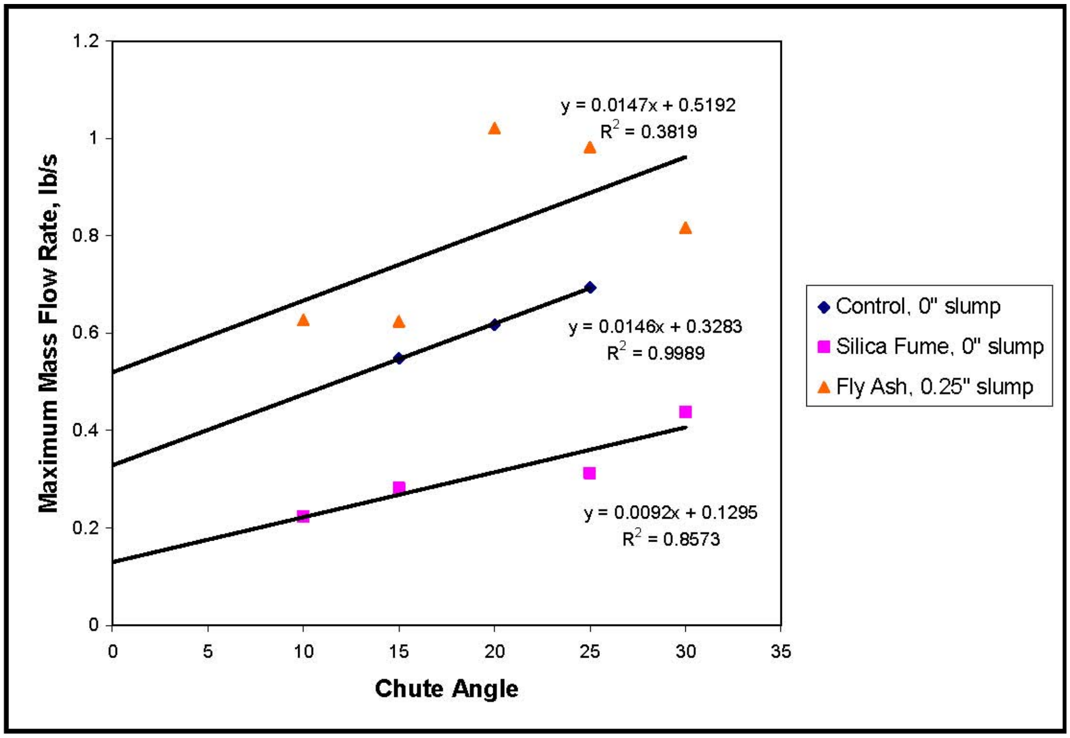


Figure 3.6 Effects of SCMs on RG1

The SCM supplementation results for mixture RG2 are shown in Figure 3.7. In this case the use of silica fume had similar results as those in RG1, as expected. The use of 20% replacement of fly ash in this case decreased the mixture viscosity. However, due to the maximum flow rate values not being significantly higher then those of the control mixture, the data suggest that the yield stress increased. The increase in yield stress, however, is opposed by a significant increase, 2-3/4 inches to 7 inches, in slump cone measurements. The results of this test point toward a limitation of the VSA in accurately differentiating between two mixtures, one having been modified with a decrease in yield stress and viscosity, when the flow rate response is greater than the previous mixture, but not enough to bring the y-intercept above the previous value for the control mixture. In this case the inconsistent performance of the VSA is likely due to the significant increase in consistency between mixtures. It should be emphasized that the VSA was designed to measure low-to-moderate concrete workability.

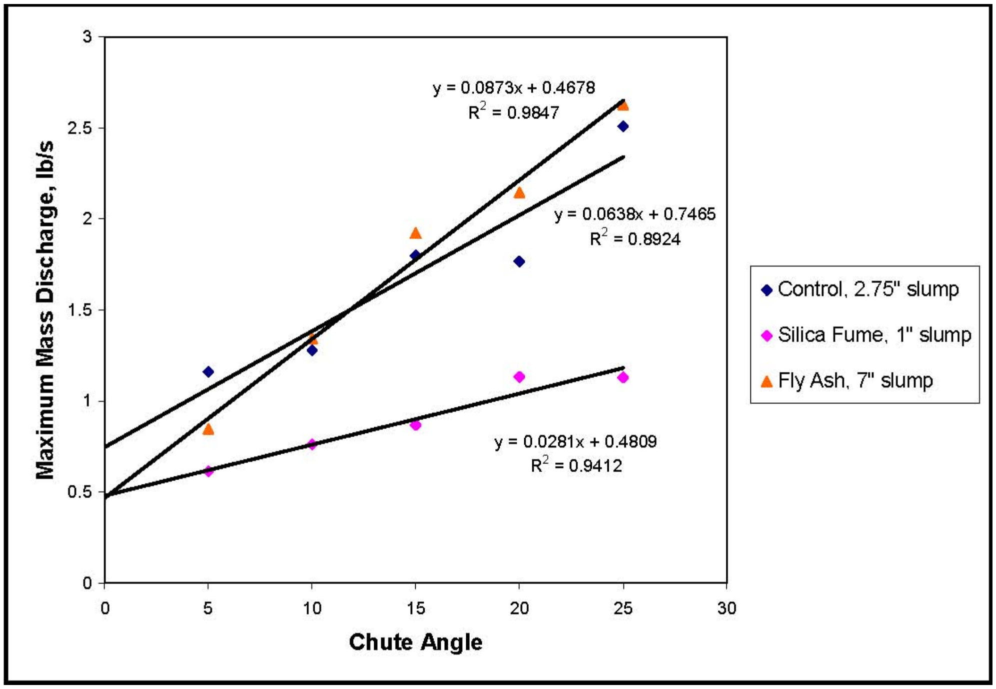


Figure 3.7 Effects of SCMs on RG2

3.5.1.3 Modification of Mixtures RG1 and RG2 by Changing Aggregate Proportions

Another approach used to modify the workability of the control mixtures was to change the percentage of coarse aggregate while keeping the total quality of aggregate constant by increasing or decreasing the sand content respectively. History along with laboratory testing has shown, depending on the aggregate, that a 60 to 40 coarse aggregate to sand ratio (by mass) will result in the most workable concrete (Sceszy, 1997). Mixture RG1 had a coarse aggregate-to-total aggregate percentage of 58.6. This mixture was modified by changing the coarse aggregate percentage to 45 and 65 percent.

The mixtures were prepared and then tested by the VSA and the results plotted in Figure 3.8. The results indicate that in both cases the workability increased instead of decreasing as expected. The increase in workability of these modified mixtures is further supported by slump cone measurements that increased by half an inch.

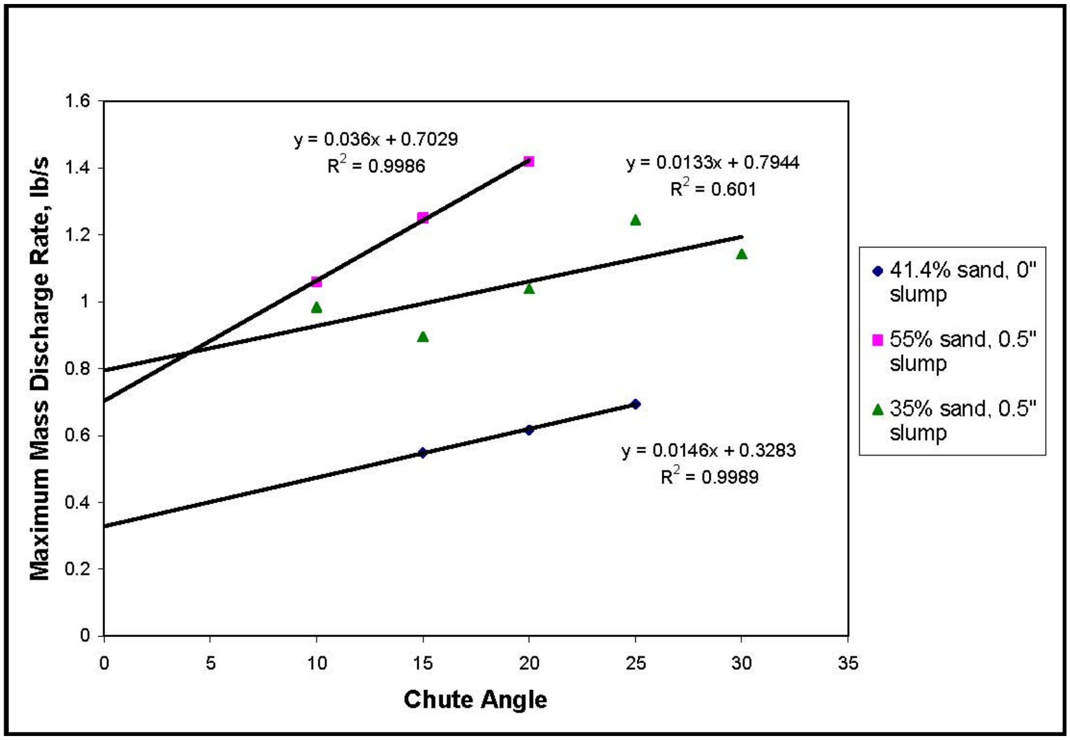


Figure 3.8 Effect of Changing Coarse Aggregate Content on Mixture RG-1

Although the results were not as expected, the data do not discredit the validity of the VSA. What can be learned is that the VSA was able to differentiate between two mixtures with obviously different workability, where as a single point test from the slump cone was not.

The higher-consistency mixture, RG2, had its coarse aggregate percentage changed from 62.7 percent to 45 and 65 percent. These mixtures were tested and the results indicate a decrease in workability for the lower coarse aggregate percentage and a subtle increase for the higher value (Figure 3.9).

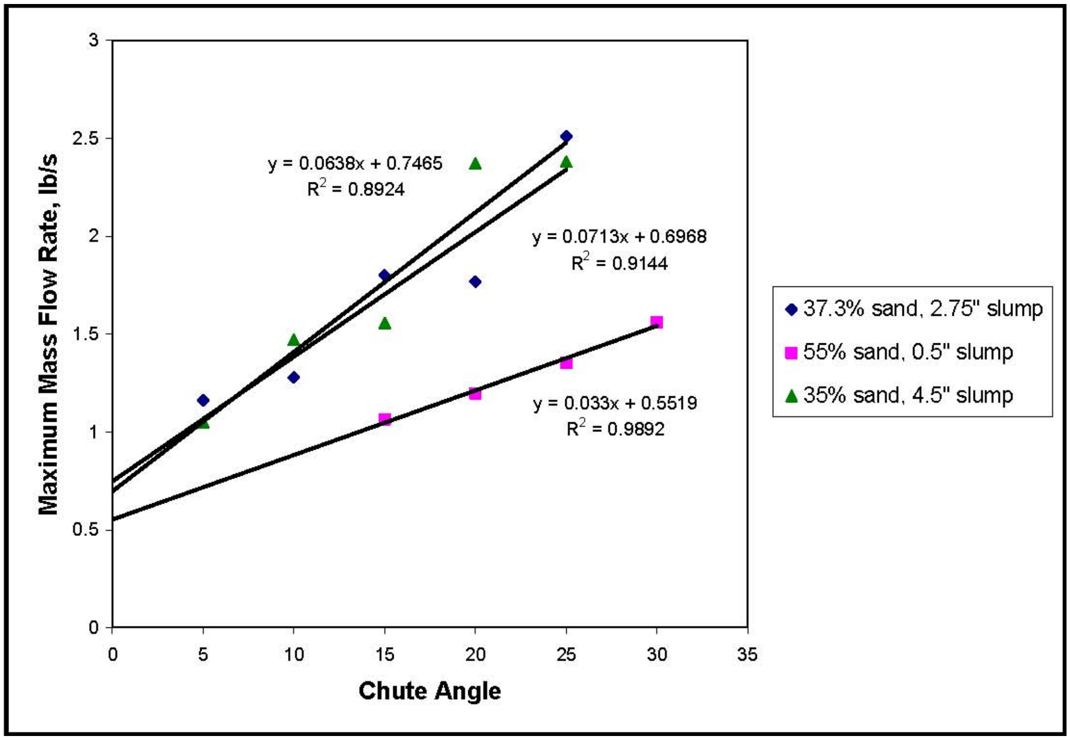


Figure 3.9 Effect of Changing Coarse Aggregate Content on Mixture RG2

Without additional testing to establish a true optimal coarse-to-fine aggregate ratio, application of these results is limited. However, relevant information that was gained includes:

1. The VSA is capable of distinguishing between mixtures where the workability has been modified by altering the coarse-to-fine aggregate ratio.
2. The VSA is able to differentiate between mixtures with similar workability that were achieved by altering the coarse-to-fine aggregate ratio.

3.5.2 Limestone with Manufactured Sand

For the limestone aggregate two control mixtures were prepared, one with a slump of 3 inches and the other 4-1/4 inches. These two mixtures were then modified by adding water, a mid-range water reducing agent, fly ash and silica fume. The coarse aggregate content was not modified, due to the limited value gained from the data taken from RG1 and RG2.

3.5.2.1 Modification of Mixtures LS1 and LS2 with Water and Mid-Range Water Reducer

The consistency of the limestone control mixtures was increased by adding water and a water-reducing admixture. The data were expected to follow similar patterns as characterized in RG1 and RG2. For LS1 modification by these means resulted in the consistency increasing from an initial three inch slump to that equivalent with an eight-inch slump. The results illustrated in Figure 3.10 for LS1 further prove that the VSA is capable of differentiating between mixtures of similar workability. These results, however, do not correlate as well with those measured in RG1. In each case the workability index, thought to be an indirect measurement of viscosity, increased. This increase was anticipated when water was added to the mixture, but was not expected for the mixture modified by the mid-range water reducer. Yet, the increases in the workability index and yield offset are believed to be representative of the mixture characteristics and not erroneous data. The mid-range water reducer increased the workability index (Figure 3.10). Although this result was the anticipated, this outcome is credible. In summary, it is believed that the depiction of the mixture workability is an accurate representation.

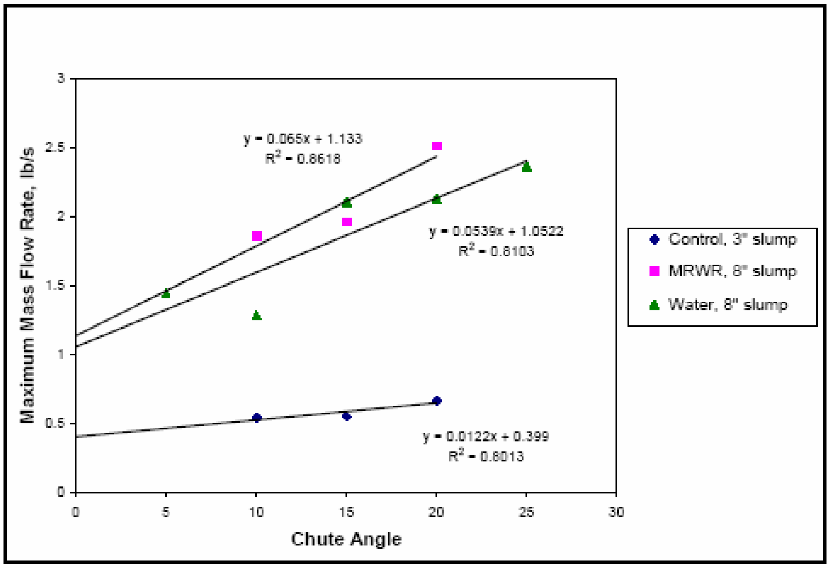


Figure 3.10 Effect of Adding MRWR versus Water on Mixture LS1

Similar results were obtained when LS2 was modified in the same fashion. The addition of water resulted in an increase to the workability index as well as an increase to the yield offset. The same changes occurred for the mixture modified with the water-reducing admixture, whose consistency was considerably higher then its control and even that of the mixture with added water. The addition of a mid-range water reducer has similar effects on the mixture workability index and yield offset as that of water, as shown by the results of LS1 and LS2. The unanticipated increase of the workability index when the water-reducing admixture was added in mixtures LS1 and LS2, contrary to the results obtained for RG1 and RG2, is believed to be linked to the change in aggregate. Although there were changes to all components of the mixture, the use of a crushed coarse and fine aggregate is most likely responsible for this change.

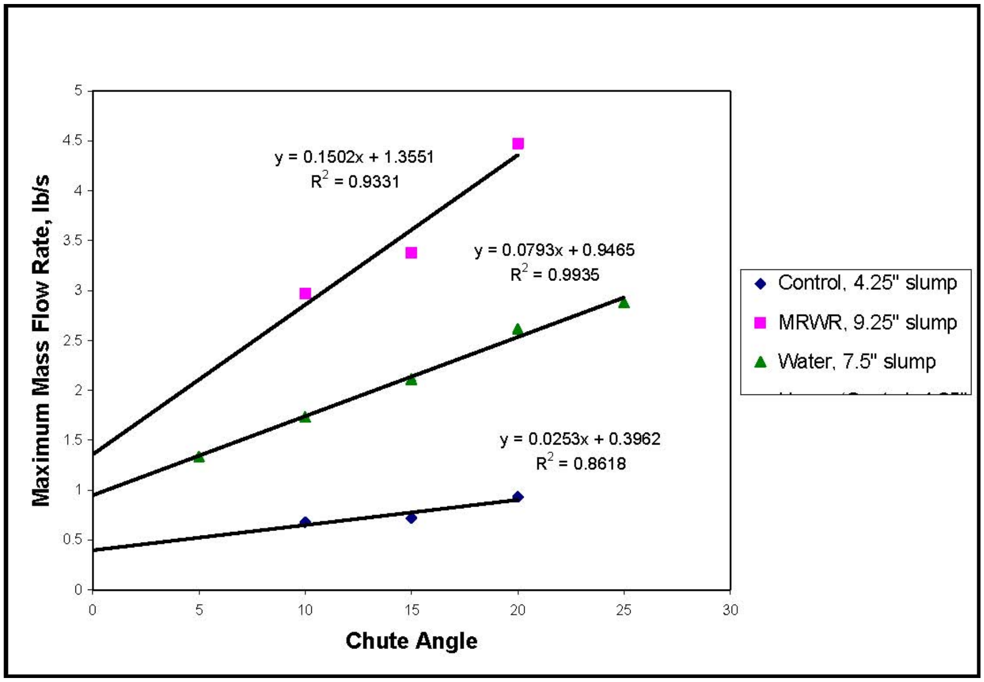


Figure 3.11 Effect of Adding MRWR versus Water for Mixture LS2

3.5.2.2 Modification of Mixtures LS1 and LS2 with SCMs

Silica fume and class F fly ash modified the workability of both limestone control mixes. Ample amounts of research on the effects of SCMs have shown that when silica fume is added in levels of high concentration it will have adverse effects on mixture workability by increasing both yield stress and viscosity. Fly ash, on the other hand, has the opposite effect on workability as that of silica fume. Therefore, because the effects of these two SCMs result in changes to both the viscosity and yield strength in no particular fashion it is difficult to determine if indeed the VSA is measuring proportional values.

The effects of the addition of these two materials to LS1 are shown in Figure 3.12. It should be noted from this figure that the addition of fly ash decreased the mixture's viscosity but had little effect on the yield stress. On the other hand, the addition of silica fume also decreased the viscosity, contrary to what was expected. This decrease in viscosity indicated by a higher workability index or slope of the fitted line, resulted in a y-intercept value less than that of the control, indicating higher yield strength. It is difficult to say with certainty if the combinations of these two variables resulted in either an increase or decrease to the workability of the mixture. This case serves as a good example of the limitations of single-point tests. In this particular instance the slump cone indicates that the mixture workability decreased, whereas the increased viscosity may have made this mixture more workable.

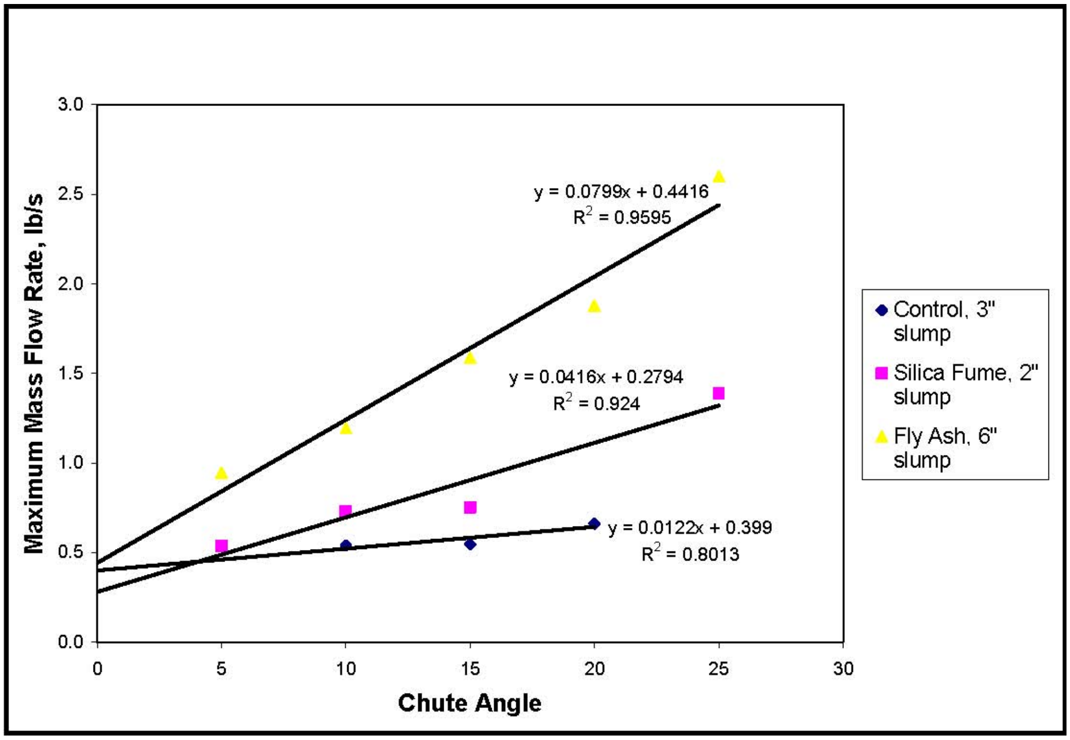


Figure 3.12 Effects of SCMs on LS1

Similar results were obtained when these SCMs were added in their previous proportions to LS2 (Figure 3.13). The data indicate that the addition of fly ash and silica fume resulted in decreases of yield strength and viscosity, indicating more workable mixtures. The inconsistency of an increase in workability with the addition of silica fume is concerning. Yet, this increase is also supported by an increase in slump measurements, from 4-1/4 inches to 5-1/2 inches. This evidence together strongly suggests that the mixture workability did indeed increase. However, with the levels of quality control in place to prevent inconsistent results, an explanation for this occurrence is unknown.

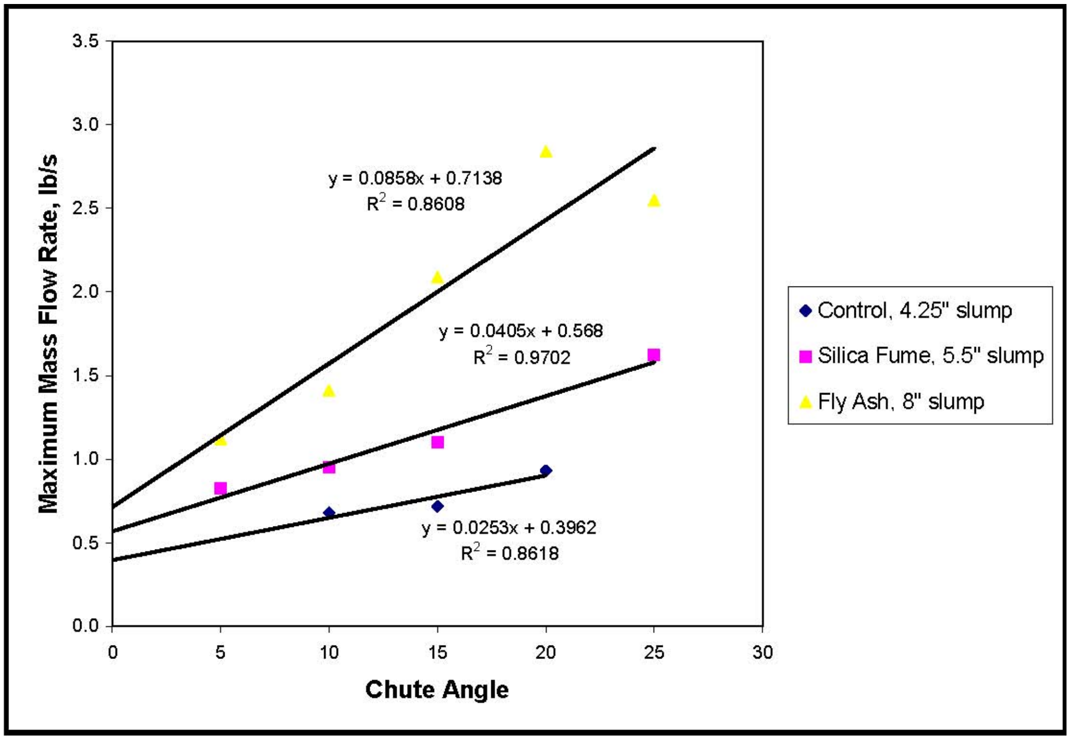


Figure 3.13 Effects of SCMs on LS2

3.5.3 Comparison between VSA Results and Slump Cone Measurements

A slump measurement of each mixture was taken before and after the concrete was tested by the VSA. With the slump cone being the most popular workability test device used today, to the point were concrete workability is often qualified in inches of slump, it seems logical to compare the measurements taken by the VSA to slump measurements.

Linear relationships have been established between slump and yield stress (Hu et al. 1996, Ferraris and De Larrard 1998). Therefore, if Wong's (2002) prediction that the VSA yield offset is proportional to yield stress then a relationship should exist between yield offsets and slump measurements. However, when the data are plotted (Figure 3.14), a considerable amount of scatter exists. In conclusion, theory indicates that a relationship should exist between the fundamental rheological properties of a concrete and the properties measured by the VSA. Present data show a subtle bilinear relationship, but more testing is needed in order to develop an accepted relationship.

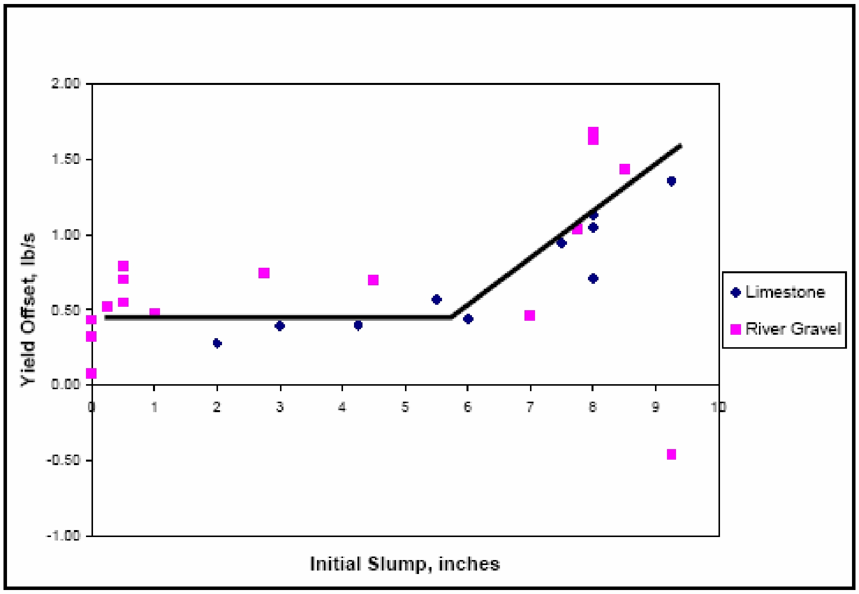


Figure 3.14 VSA Yield Offset Versus Initial Slump Measurements

Concrete viscosity also influences slump cone measurements however, to less of a degree than yield stress. A similar correlation to that in Figure 3.14 is also found when the Wong workability index is plotted against slump cone measurements (Figure 3.15).

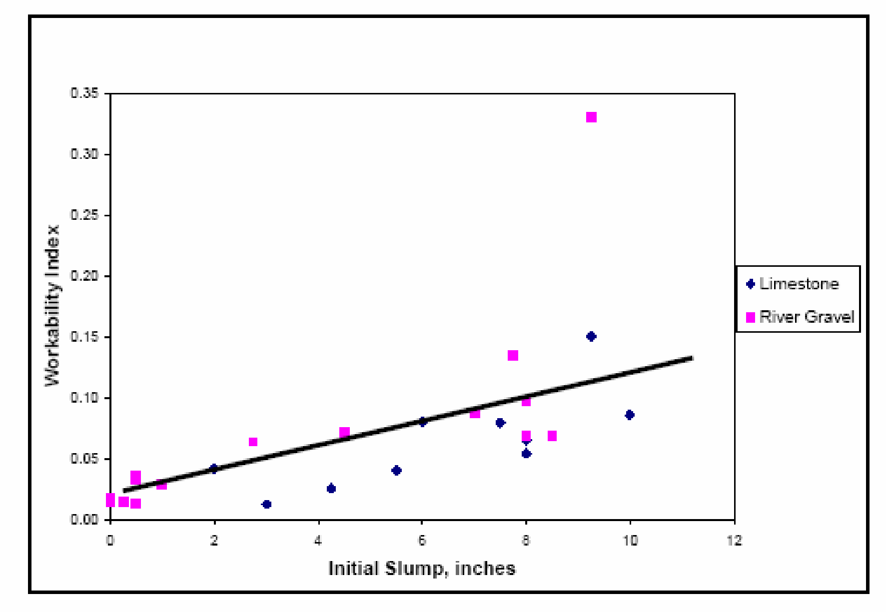


Figure 3.15 VSA Workability Index versus Initial Slump Measurements

Overall, the positive correlation between the results of these two workability measurements support that Wong's workability index and yield offset are a representation of concrete workability.

3.5.4 Complete Result Overview

When all results are viewed together various opinions of the effectiveness of the VSA to classify concrete workability can be reached. In dealing with workability it is more difficult to grasp the effectiveness of a new technique than if measurements of strength were the property being measured. This is because even with all the workability test devices available, the most widely used and trusted qualification technique is experience, and without being present during the testing of the VSA it is difficult for any person to say whether the results are representative of the mixture workability or not. The following discussion of the effectiveness of the VSA is made based upon many tests using the VSA with concrete of a wide range of workability.

The VSA is well capable of following established trends of varying workability as indicated in several cases by the test results (Figures 3.4 and 3.5). However, in other cases the VSA seems less capable of doing so (Figures 3.7 and 3.10). The theory of using vibration and flow rates to qualify low-consistency concrete seems to be sound. Two issues related to the results that are worthy of note are:

1. In several cases the variability of the results is excessive if only two chute angles were used as recommended by the developers; depending on the angles, used significantly different results could be obtained. This point is illustrated in Figure 3.16.
2. As was illustrated in Figure 3.7, when a mixture was modified effectively to increase the slope of its flow curve with little translation upward, the result was a yield offset lower then that of the control, indicating an increase in yield strength, which likely did not take place.

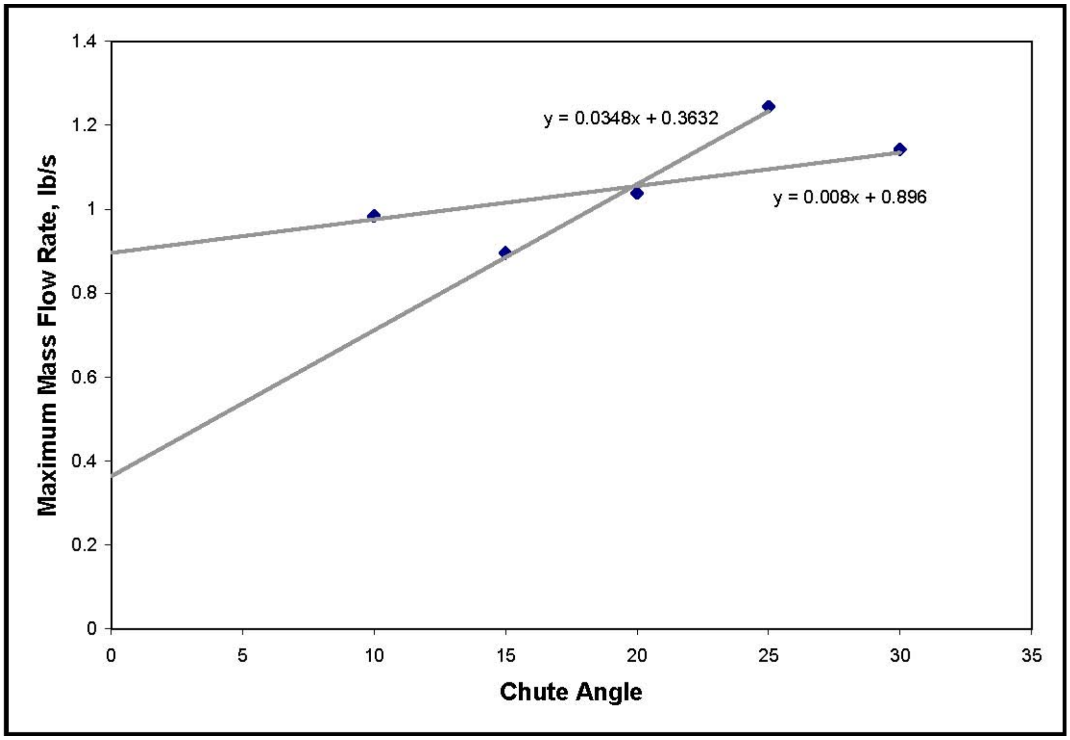


Figure 3.16 Illustration of Varying Test Results Possible when too Few Chute Angles are Tested, Mixture 1 on 4/18/2003

Overall, the initial testing of the VSA indicates that it is able to determine changes in concrete workability. However, in the opinion of this author, the two issues associated with the collected data discussed above; along with several other problems with the apparatus itself, need to be addressed before the test would be ready for use in the field.

3.6 REFINEMENT OF TEST RESULTS

As was explained, the maximum flow rate for each chute angle was selected after an n^{th} degree curve was fit to the raw data. Therefore, the maximum flow rate usually occurred at the beginning of the test when the chute was nearly full. Observations during the first round of testing coupled with poor correlations between measurements of different chute angles suggested that a better means of data reduction may exist. The reason why selection of a maximum flow rate at the beginning of a test is not representative is that when the chute gate was removed and vibration started; in cases where low consistency mixtures were tested, a portion of the sample would shear due to the vertical face at the end of the chute where the chute gate had been removed. Because of the low consistency of the mixture, this sheared portion skewed the fitted curve, resulting in a higher flow rate representing a less-flowable mixture. Observations of the flow behavior from the chute also indicated that a more uniform flow rate occurred after approximately 50 to 75 percent of the sample had been evacuated from the chute.

3.6.1 Alternative Method for Selecting Data Points

These two observations led to the development of two experimental methods of selecting a refined maximum flow rate. The focus of these methods was to select a flow rate away from the immediate beginning of the test in order to obtain a more uniform and representative reading.

3.6.1.1 Method A

Method A is defined by selection of a discharge rate after a certain percentage of the total mass discharge for 40-seconds of discharge. The intention of this approach was to select a single consistent point where the mass flow rate is sampled. A 40 second interval was chosen that begins when the first portion of the sample leaves the chute. The total amount of concrete discharged in this interval is then calculated and the flow rate selected that corresponds with the point where 75 percent of the total concrete has been discharged. The three steps in selecting a new flow rate following Method A are illustrated in Figure 3.17.

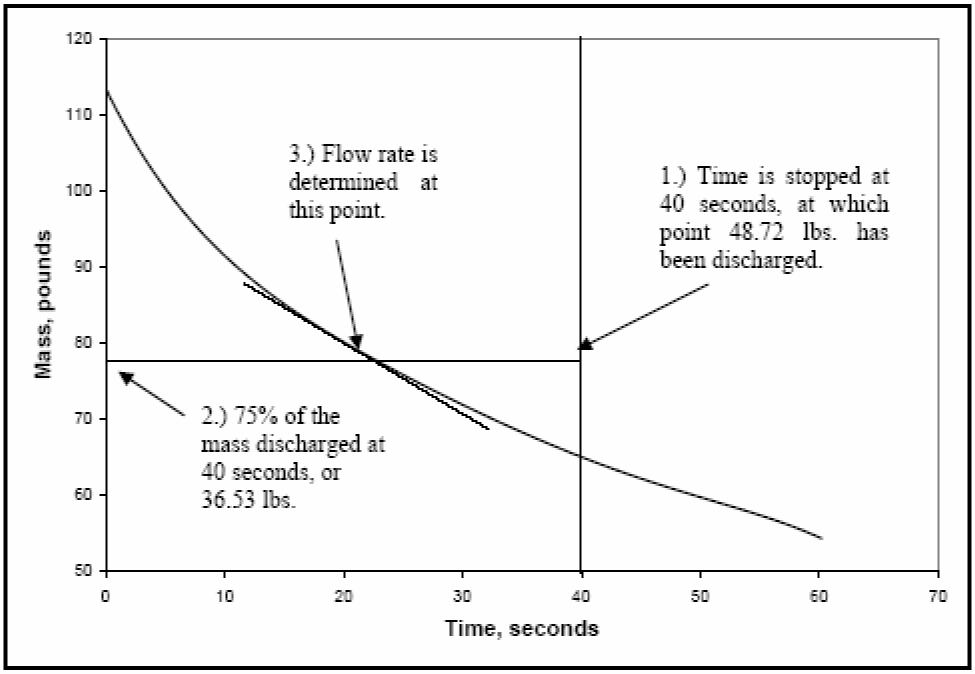


Figure 3.17 Mass versus Time Plot for LS-MS Mixture 1 6-4-03, 15 Degree Chute Angle, 5th Degree Curve Fit (Method A)

3.6.1.2 Method B

Method B, similar to Method A, consists of measuring the quality of material that exits the chute for a period of 40 seconds, beginning when flow initiates. The difference between the two methods is that instead of selecting a single flow rate at a given point, the average flow rate is found between two points. The three steps in selecting a new flow rate following Method B are illustrated in Figure 3.18.

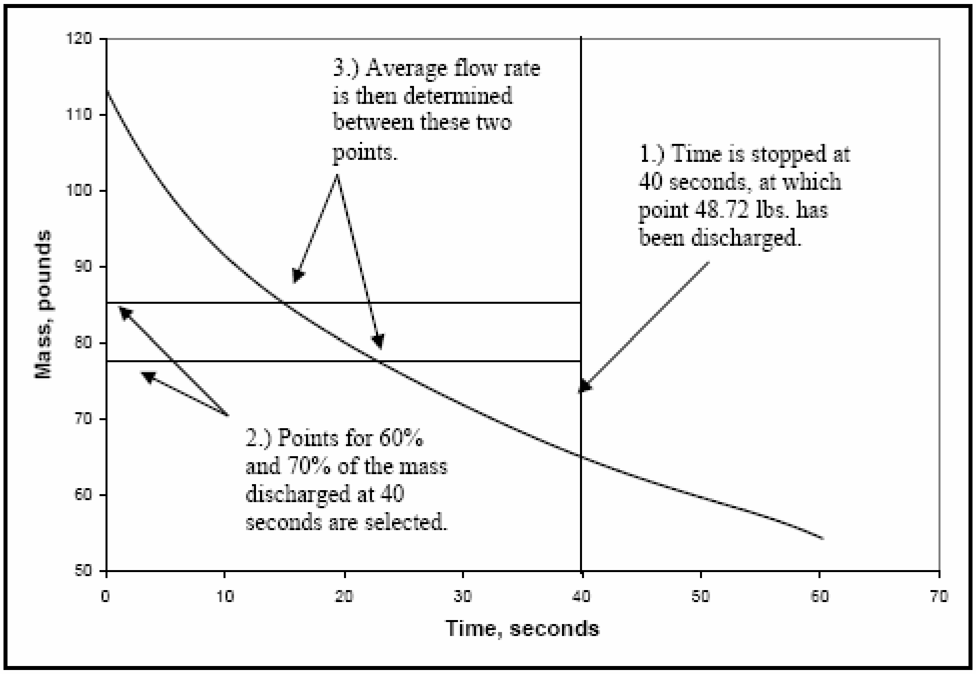
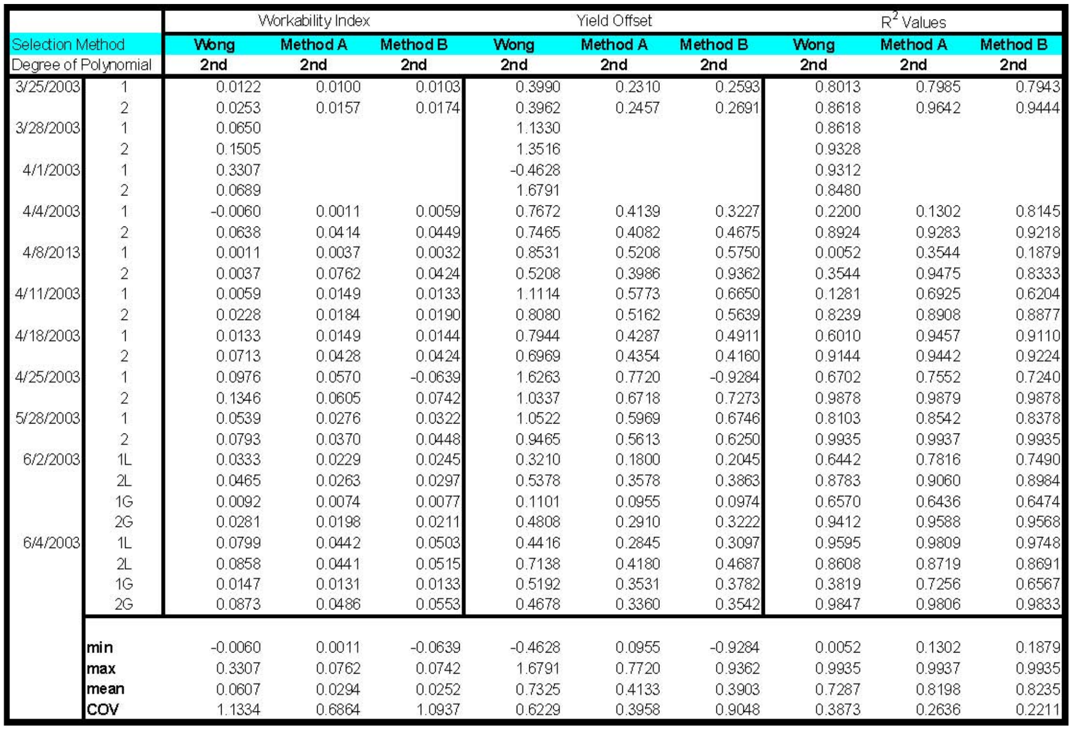


Figure 3.18 Mass versus Time Plot for LS-MS Mixture 1 6-4-03, 15 Degree Chute Angle, 5th Degree Curve Fit (Method B)

3.6.2 Value Gained from Refinement of Results

Using Methods A and B new maximum flow rates were determined from the raw data. The corresponding workability index and yield offset were then calculated for these new flow rates. The new values obtained from the complete raw data, fitted with a second degree polynomial, are listed in Table 3.3. Little significance can be obtained from the individual values themselves. However, it is evident that the new processes used increase the correlation between individual measurements. The gaps that occur in the table on 3/28/2003 and 4/1/2003 occur because the test was not run for a complete forty seconds, because the majority of the sample had left the chute in less time.

Table 3.3 Comparison of Measurements Obtained from Methods A and B to Wong Values



		Workability Index			Yield Offset			R^2 Values		
Selection Method		**Wong**	**Method A**	**Method B**	**Wong**	**Method A**	**Method B**	**Wong**	**Method A**	**Method B**
Degree of Polynomial		**2nd**	**2nd**	**2nd**	**2nd**	**2nd**	**2nd**	**2nd**	**2nd**	**2nd**
3/25/2003	1	0.0122	0.0100	0.0103	0.3990	0.2310	0.2593	0.8013	0.7985	0.7943
	2	0.0253	0.0157	0.0174	0.3962	0.2457	0.2691	0.8618	0.9642	0.9444
3/28/2003	1	0.0650			1.1330			0.8618		
	2	0.1505			1.3516			0.9328		
4/1/2003	1	0.3307			-0.4628			0.9312		
	2	0.0689			1.6791			0.8480		
4/4/2003	1	-0.0060	0.0011	0.0059	0.7672	0.4139	0.3227	0.2200	0.1302	0.8145
	2	0.0638	0.0414	0.0449	0.7465	0.4082	0.4675	0.8924	0.9283	0.9218
4/8/2013	1	0.0011	0.0037	0.0032	0.8531	0.5208	0.5750	0.0052	0.3544	0.1879
	2	0.0037	0.0762	0.0424	0.5208	0.3986	0.9362	0.3544	0.9475	0.8333
4/11/2003	1	0.0059	0.0149	0.0133	1.1114	0.5773	0.6650	0.1281	0.6925	0.6204
	2	0.0228	0.0184	0.0190	0.8080	0.5162	0.5639	0.8239	0.8908	0.8877
4/18/2003	1	0.0133	0.0149	0.0144	0.7944	0.4287	0.4911	0.6010	0.9457	0.9110
	2	0.0713	0.0428	0.0424	0.6969	0.4354	0.4160	0.9144	0.9442	0.9224
4/25/2003	1	0.0976	0.0570	-0.0639	1.6263	0.7720	-0.9284	0.6702	0.7552	0.7240
	2	0.1346	0.0605	0.0742	1.0337	0.6718	0.7273	0.9878	0.9879	0.9878
5/28/2003	1	0.0539	0.0276	0.0322	1.0522	0.5969	0.6746	0.8103	0.8542	0.8378
	2	0.0793	0.0370	0.0448	0.9465	0.5613	0.6250	0.9935	0.9937	0.9935
6/2/2003	1L	0.0333	0.0229	0.0245	0.3210	0.1800	0.2045	0.6442	0.7816	0.7490
	2L	0.0465	0.0263	0.0297	0.5378	0.3578	0.3863	0.8783	0.9060	0.8984
	1G	0.0092	0.0074	0.0077	0.1101	0.0955	0.0974	0.6570	0.6436	0.6474
	2G	0.0281	0.0198	0.0211	0.4808	0.2910	0.3222	0.9412	0.9588	0.9568
6/4/2003	1L	0.0799	0.0442	0.0503	0.4416	0.2845	0.3097	0.9595	0.9809	0.9748
	2L	0.0858	0.0441	0.0515	0.7138	0.4180	0.4687	0.8608	0.8719	0.8691
	1G	0.0147	0.0131	0.0133	0.5192	0.3531	0.3782	0.3819	0.7256	0.6567
	2G	0.0873	0.0486	0.0553	0.4678	0.3360	0.3542	0.9847	0.9806	0.9833
	min	-0.0060	0.0011	-0.0639	-0.4628	0.0955	-0.9284	0.0052	0.1302	0.1879
	max	0.3307	0.0762	0.0742	1.6791	0.7720	0.9362	0.9935	0.9937	0.9935
	mean	0.0607	0.0294	0.0252	0.7325	0.4133	0.3903	0.7287	0.8198	0.8235
	COV	1.1334	0.6864	1.0937	0.6229	0.3958	0.9048	0.3873	0.2636	0.2211

To view the effects of the new selection processes, the new values for workability index and yield offset were plotted against their respective Wong values (Figures 3.19 and 3.20). A reasonable linear correlation between the Wong workability index values and those obtained from Methods A and B is shown in Figure 3.19. What should be noted from this correlation is that the Wong values are more sensitive, as indicated by a slope of less a one for the line fit to the data, a those determined from Method A or B. Comparisons were also made, although not illustrated here, between test results obtained from Methods A and B with mixture proportions and VSA parameters. These comparisons showed that in some cases, the use of alternate methods changed trends – both in expected and unexpected directions.

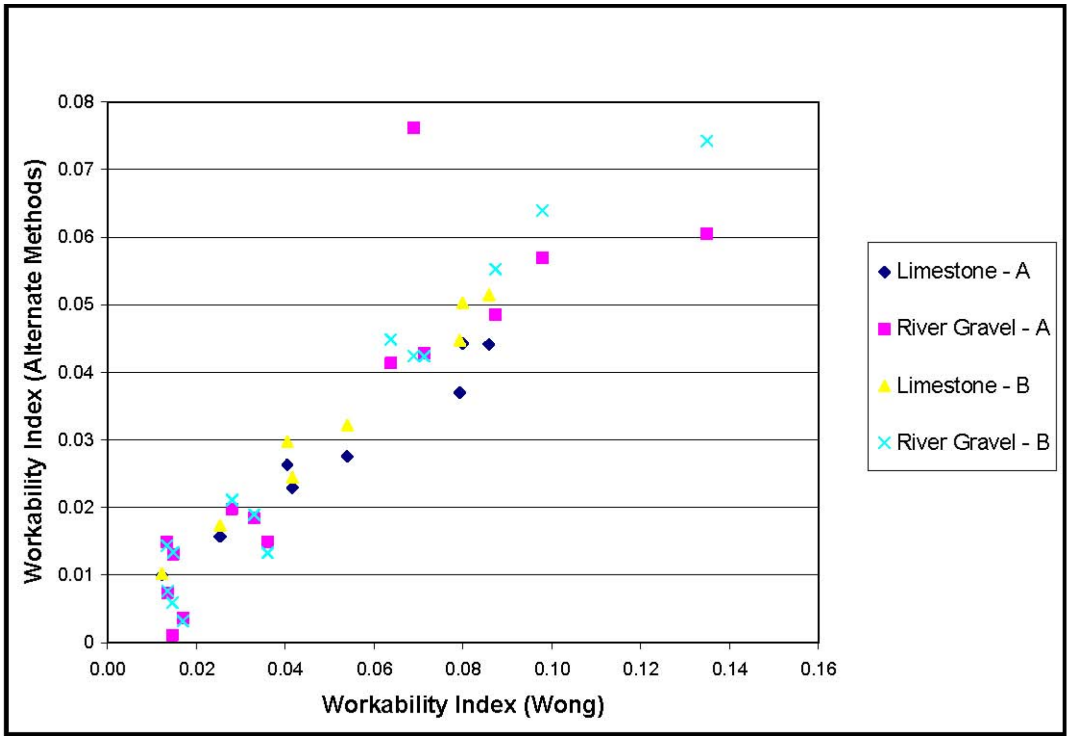


Figure 3.19 Comparison of Workability Index between Wong and Alternate Methods A and B

A similar correlation is found, having a slope of less a one, when Wong yield offset values are compared to those determined by Methods A or B (Figure 3.20).

Together, this evidence indicates that although refinement of the approach in which flow rate values are selected from the raw data does indeed increase the measure of correlation between measurements, there is no added benefit to the overall outcome that would justify the added effort to obtain these values.

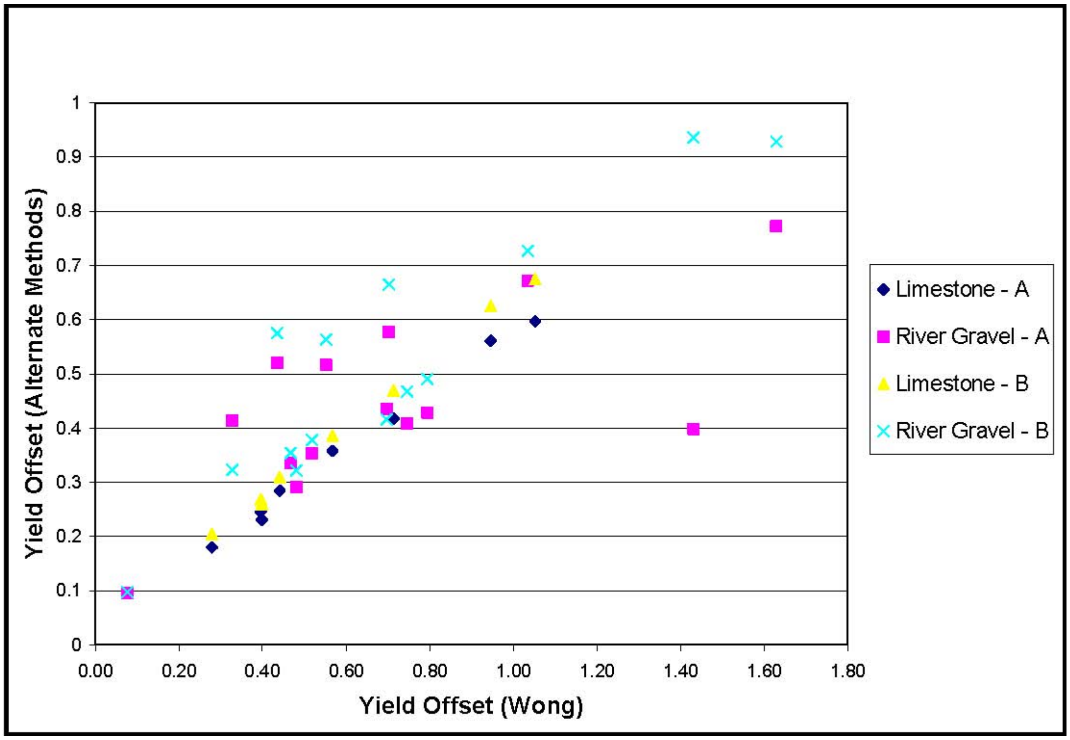
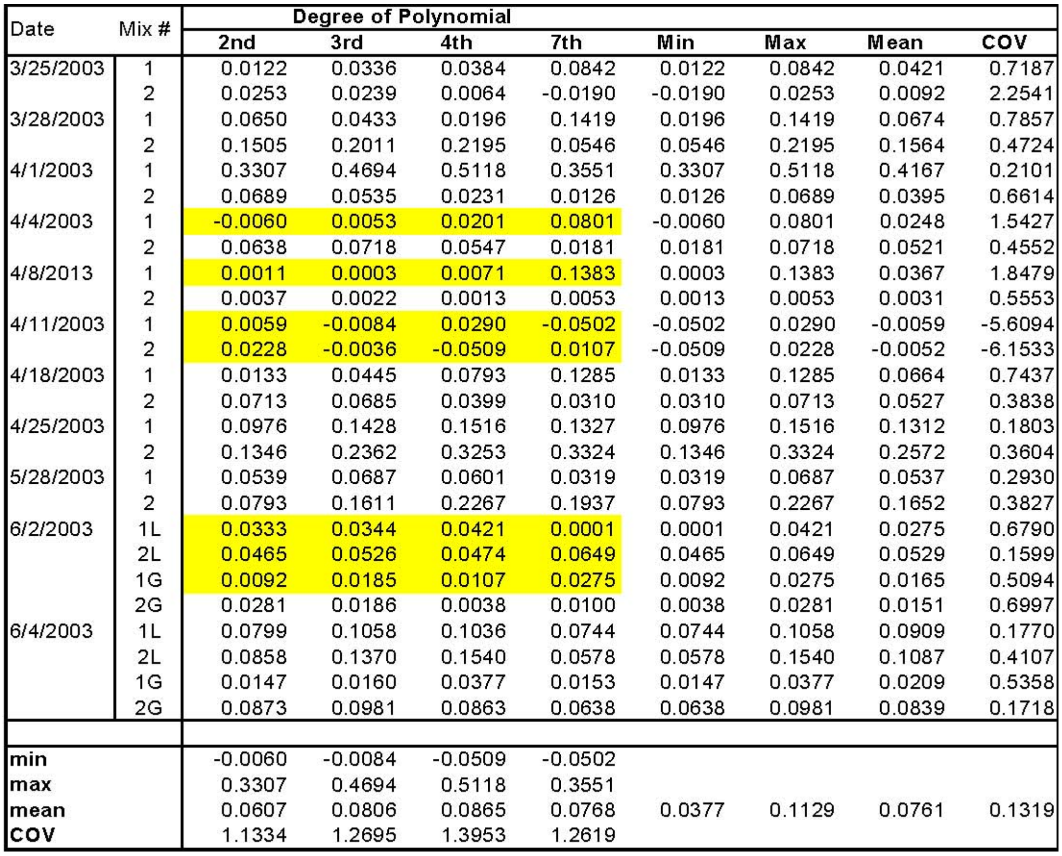


Figure 3.20 Comparisons of Yield Offsets for Wong and Alternate Methods A and B

3.6.3 Effects of Differing Degrees of Polynomials

The final report that accompanied the VSA did not specify what degree of polynomial should be fitted to the data. The report did recommend using the program default values. Therefore, the data collected were fitted with the default curve or second-degree polynomial. After testing was completed, the data were further examined. During this examination the raw data were also fitted with third, fourth and seventh-degree polynomials and their respective workability index and yield offsets were recalculated. Workability indexes are listed in Table 3.4 and yield offset values in Table 3.5 for the varying degrees of polynomials fit to the raw data. The highlighted cells in these tables denote values that have had spurious data points removed before their workability values were calculated.

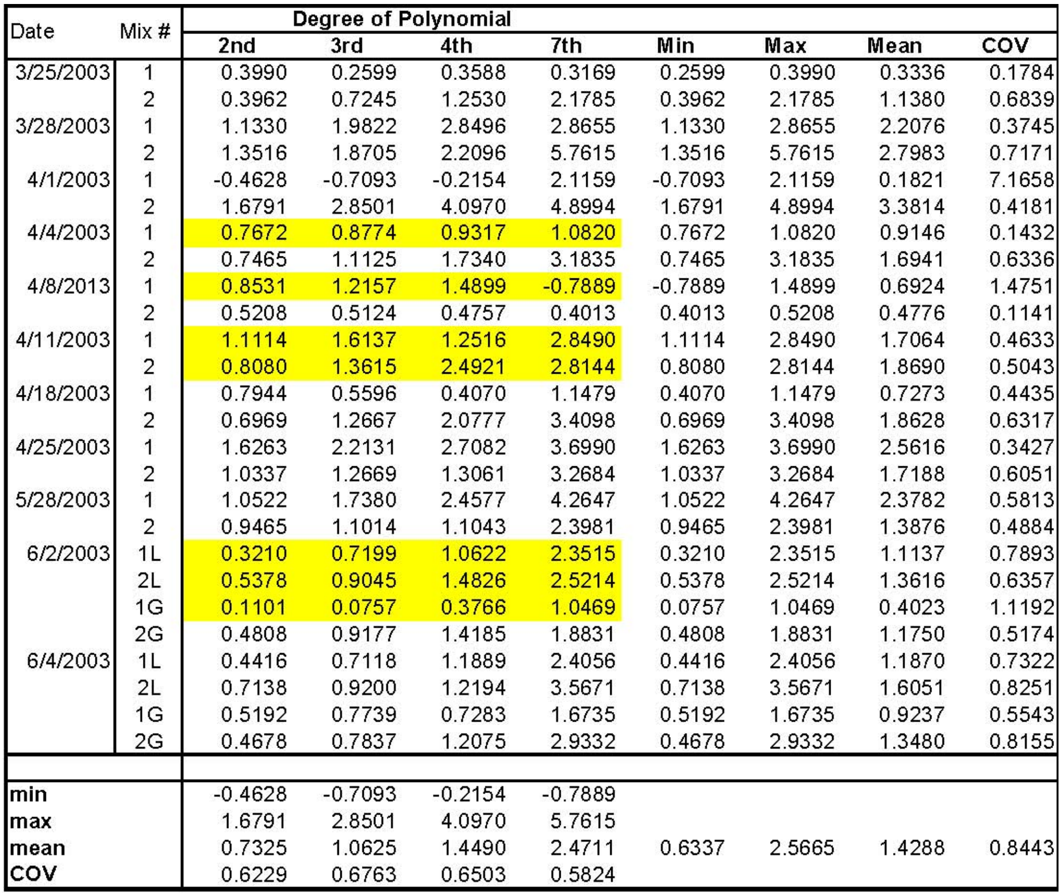
Table 3.4 Comparison of Workability Index Terms for Different Degrees of Polynomials



Date	Mix #	Degree of Polynomial							
		2nd	3rd	4th	7th	Min	Max	Mean	COV
3/25/2003	1	0.0122	0.0336	0.0384	0.0842	0.0122	0.0842	0.0421	0.7187
	2	0.0253	0.0239	0.0064	-0.0190	-0.0190	0.0253	0.0092	2.2541
3/28/2003	1	0.0650	0.0433	0.0196	0.1419	0.0196	0.1419	0.0674	0.7857
	2	0.1505	0.2011	0.2195	0.0546	0.0546	0.2195	0.1564	0.4724
4/1/2003	1	0.3307	0.4694	0.5118	0.3551	0.3307	0.5118	0.4167	0.2101
	2	0.0689	0.0535	0.0231	0.0126	0.0126	0.0689	0.0395	0.6614
4/4/2003	1	-0.0060	0.0053	0.0201	0.0801	-0.0060	0.0801	0.0248	1.5427
	2	0.0638	0.0718	0.0547	0.0181	0.0181	0.0718	0.0521	0.4552
4/8/2013	1	0.0011	0.0003	0.0071	0.1383	0.0003	0.1383	0.0367	1.8479
	2	0.0037	0.0022	0.0013	0.0053	0.0013	0.0053	0.0031	0.5553
4/11/2003	1	0.0059	-0.0084	0.0290	-0.0502	-0.0502	0.0290	-0.0059	-5.6094
	2	0.0228	-0.0036	-0.0509	0.0107	-0.0509	0.0228	-0.0052	-6.1533
4/18/2003	1	0.0133	0.0445	0.0793	0.1285	0.0133	0.1285	0.0664	0.7437
	2	0.0713	0.0685	0.0399	0.0310	0.0310	0.0713	0.0527	0.3838
4/25/2003	1	0.0976	0.1428	0.1516	0.1327	0.0976	0.1516	0.1312	0.1803
	2	0.1346	0.2362	0.3253	0.3324	0.1346	0.3324	0.2572	0.3604
5/28/2003	1	0.0539	0.0687	0.0601	0.0319	0.0319	0.0687	0.0537	0.2930
	2	0.0793	0.1611	0.2267	0.1937	0.0793	0.2267	0.1652	0.3827
6/2/2003	1L	0.0333	0.0344	0.0421	0.0001	0.0001	0.0421	0.0275	0.6790
	2L	0.0465	0.0526	0.0474	0.0649	0.0465	0.0649	0.0529	0.1599
	1G	0.0092	0.0185	0.0107	0.0275	0.0092	0.0275	0.0165	0.5094
	2G	0.0281	0.0186	0.0038	0.0100	0.0038	0.0281	0.0151	0.6997
6/4/2003	1L	0.0799	0.1058	0.1036	0.0744	0.0744	0.1058	0.0909	0.1770
	2L	0.0858	0.1370	0.1540	0.0578	0.0578	0.1540	0.1087	0.4107
	1G	0.0147	0.0160	0.0377	0.0153	0.0147	0.0377	0.0209	0.5358
	2G	0.0873	0.0981	0.0863	0.0638	0.0638	0.0981	0.0839	0.1718
min		-0.0060	-0.0084	-0.0509	-0.0502				
max		0.3307	0.4694	0.5118	0.3551				
mean		0.0607	0.0806	0.0865	0.0768	0.0377	0.1129	0.0761	0.1319
COV		1.1334	1.2695	1.3953	1.2619				

A considerable change in magnitude can result when the degree of polynomial fit to the data is changed as the values in Tables 3.4 and 3.5 indicate. Therefore, results should not be compared between tests if the degree of polynomial used to reduce the data is not the same.

Table 3.5 Comparison of Yield Offset Terms for Different Degrees of Polynomials



Date	Mix #	Degree of Polynomial							
		2nd	**3rd**	**4th**	**7th**	**Min**	**Max**	**Mean**	**COV**
3/25/2003	1	0.3990	0.2599	0.3588	0.3169	0.2599	0.3990	0.3336	0.1784
	2	0.3962	0.7245	1.2530	2.1785	0.3962	2.1785	1.1380	0.6839
3/28/2003	1	1.1330	1.9822	2.8496	2.8655	1.1330	2.8655	2.2076	0.3745
	2	1.3516	1.8705	2.2096	5.7615	1.3516	5.7615	2.7983	0.7171
4/1/2003	1	-0.4628	-0.7093	-0.2154	2.1159	-0.7093	2.1159	0.1821	7.1658
	2	1.6791	2.8501	4.0970	4.8994	1.6791	4.8994	3.3814	0.4181
4/4/2003	1	0.7672	0.8774	0.9317	1.0820	0.7672	1.0820	0.9146	0.1432
	2	0.7465	1.1125	1.7340	3.1835	0.7465	3.1835	1.6941	0.6336
4/8/2013	1	0.8531	1.2157	1.4899	-0.7889	-0.7889	1.4899	0.6924	1.4751
	2	0.5208	0.5124	0.4757	0.4013	0.4013	0.5208	0.4776	0.1141
4/11/2003	1	1.1114	1.6137	1.2516	2.8490	1.1114	2.8490	1.7064	0.4633
	2	0.8080	1.3615	2.4921	2.8144	0.8080	2.8144	1.8690	0.5043
4/18/2003	1	0.7944	0.5596	0.4070	1.1479	0.4070	1.1479	0.7273	0.4435
	2	0.6969	1.2667	2.0777	3.4098	0.6969	3.4098	1.8628	0.6317
4/25/2003	1	1.6263	2.2131	2.7082	3.6990	1.6263	3.6990	2.5616	0.3427
	2	1.0337	1.2669	1.3061	3.2684	1.0337	3.2684	1.7188	0.6051
5/28/2003	1	1.0522	1.7380	2.4577	4.2647	1.0522	4.2647	2.3782	0.5813
	2	0.9465	1.1014	1.1043	2.3981	0.9465	2.3981	1.3876	0.4884
6/2/2003	1L	0.3210	0.7199	1.0622	2.3515	0.3210	2.3515	1.1137	0.7893
	2L	0.5378	0.9045	1.4826	2.5214	0.5378	2.5214	1.3616	0.6357
	1G	0.1101	0.0757	0.3766	1.0469	0.0757	1.0469	0.4023	1.1192
	2G	0.4808	0.9177	1.4185	1.8831	0.4808	1.8831	1.1750	0.5174
6/4/2003	1L	0.4416	0.7118	1.1889	2.4056	0.4416	2.4056	1.1870	0.7322
	2L	0.7138	0.9200	1.2194	3.5671	0.7138	3.5671	1.6051	0.8251
	1G	0.5192	0.7739	0.7283	1.6735	0.5192	1.6735	0.9237	0.5543
	2G	0.4678	0.7837	1.2075	2.9332	0.4678	2.9332	1.3480	0.8155
min		-0.4628	-0.7093	-0.2154	-0.7889				
max		1.6791	2.8501	4.0970	5.7615				
mean		0.7325	1.0625	1.4490	2.4711	0.6337	2.5665	1.4288	0.8443
COV		0.6229	0.6763	0.6503	0.5824				

3.7 FINAL COMMENTS ON EVALUATION OBJECTIVES

Five questions were initially posed that needed to be answered in order to evaluate the VSA. A work plan was then created with these five questions in mind. Throughout review of the data, different tests have shown strengths and weaknesses of the VSA. The objectives that were raised before evaluation began are listed below along with a discussion on what was learned about the VSA.

3.7.1 Determine the Significance of the Workability Index and Yield Offset

Wong (2000) hypothesized that the yield offset, measured by the VSA, is related to yield stress and the workability index is related to plastic viscosity. Hence, a mixture with low viscosity and yield stress will flow quickly from the chute, characterized by a high workability index and yield offset. Admixtures with known effects were added to control mixtures in order to determine if the VSA was capable of following historically established trends. In most all cases the VSA was able to follow the anticipated results when an admixture or water was added to the control mixture. The VSA detected a reduction in yield strength when the water reducer was added. Correspondingly a reduction in both yield strength and viscosity was measured when water was added to increase the workability of the mixture. Similar results were also measured when SCMs and the coarse-to-fine aggregate ratio were used to modify mixture workability. Without having measured the true rheological components, yield strength and viscosity, it cannot be said if the VSA measurements were representative of the true changes. However, from the data gathered it appears that Wong's theory that the yield offset and workability index measured by the VSA are indeed proportional representations of the rheological characteristics, yield strength and viscosity, of a concrete mixture.

3.7.2 Determine the Influence of the Chute Angle

The majority of mixtures prepared were tested at five different chute angles, ranging from 5 to 30 degrees, with the first angle being either five or ten degrees depending on the consistency of the concrete. During data reduction, some data were considered to be outliers and ignored. These outliers are shaded in blue in Table 3.2. As can be seen from this figure no data were ever rejected for 5 and 15 degree chute angles. This occurrence is believed to have occurred randomly and no conclusion is drawn that these chute angles return better measurements. Overall, there does not seem to be a significant influence on the results of the VSA due to the influence of the chute angle.

3.7.3 Determine if Two Chute Angles are Sufficient

Wong recommended that a test include two test angles and if additional information was needed about the concrete, more tests at additional angles should be performed. In order to gain as much information as possible on each individual mixture, the ICAR test procedure consisted of measuring flow at five different angles. What was learned from testing five different angles is that the time involved is excessive, allowing the workability of the mixture to change with time and in some cases the measurements taken from five different chute angles to be poorly correlated. The results of this poor correlation were discussed and the possible outcomes of only measuring two chute angles were illustrated in Figure 3.16. The results of these tests indicate that two chute angles are not sufficient to represent a concrete.

3.7.4 Identify Ways to Simplify the Device or Test Method

In the final report that accompanied the VSA the developers suggested that the VSA could be simplified by adding an embedded data acquisition unit to replace the laptop computer. Other methods that were identified during evaluation of the VSA by ICAR researchers include:

1. Replacing the steel chute siding with aluminum or reinforced plastic to lower the overall weight of the unit, making the device easier to move.
2. Redesign of the handle on the forward portion of the VSA to distribute more of the chute weight to the wheels when being moved.

3.7.5 Determine the Range of Workability that can be Tested

The range of workability tested ranged from low, zero-inch slump, to high, 9-1/4 inches. Although development of the VSA was focused on testing of low consistency concrete, there were no relationships discovered that indicated better results were obtained from lower-consistency mixtures then those of high-consistency. One issue with testing of higher consistency mixtures worth note is that when mixtures of higher consistency were consolidated excess water was brought to the top of the sample. This slurry-like substance would then move to the rear of the chute when it was elevated and quickly discharge once vibration had begun. Therefore, the discharge of this slurry increased the flow rate at the beginning of the test, skewing results. Overall, use of the VSA seems appropriate for use on concretes with consistencies ranging from low-to-moderate workability.

In summary, there is ample evidence that the VSA is more suitable than other tests currently being used to differentiate between mixtures of similar workability. However, the issues that arise when thoughts of replacing a slump cone or Kelly ball with the VSA for day-to-day measurements of workability are the effort and time required to conduct a single test, the increased level of competence needed to operate the VSA over a slump cone, increased cost of equipment, validity of results and scatter among results.

CHAPTER 4 EVALUATION OF INSTRUMENTED VIBRATING SLOPE APPARATUS

4.1 INTRODUCTION

An initial evaluation of the Federal Highway Administration's (FHWA) Vibrating Slope Apparatus (VSA) for characterizing the workability of concrete resulted in the conclusion that this instrument would not fulfill the requirements of the International Center for Aggregates Research (ICAR) Project 105, which had the objective of developing a practical field test for low-slump concrete. At approximately the same time, the graduate students working on ICAR 105 traveled to Cleveland, Ohio, to participate in a week-long evaluation of concrete rheometers held at Masterbuilders, Inc. After the rheometer comparison was completed, interested parties were invited to participate in a workshop hosted by parties involved in the ICAR 105 project to discuss qualification of concrete workability.

One of the discussion topics was the results from the VSA initial evaluation, completed as part of ICAR Project 105. The focus of this discussion was to discuss the problems identified with the VSA and suggest alternatives for further evaluation. Clarissa Ferraris of the National Institute of Standards and Technology (NIST), a consultant to ICAR, stated that concrete with lower workability, as intended for use in the VSA, cannot be qualified using rheological science because it does not possess properties of a fluid. Instead, vibration - the method by which concrete, of this consistency, is placed and consolidated - should be the focus of qualification. Therefore, the VSA needed to be instrumented to qualify the vibration before further testing could take place.

4.2 REVISION OF THE VSA TEST

4.2.1 Identified Problems

There were three problems identified with the initial VSA test method that needed to be addressed before further testing; these problems were:

1. The initial testing procedure called for two different chute angles. This requirement meant that after completing an initial cycle at the first angle, the chute had to be cleaned of the remaining concrete, lowered, refilled and consolidated before another cycle could begin. With testing being conducted in a laboratory environment by two workers, a complete test required approximately 25 minutes, during which time the concrete workability can change if hydration products form. Field conditions require test results in less than five minutes. It should be noted that initial testing was conducted at five different chute angles, thereby extending the time to complete a test to 45 minutes.
2. The second problem occurred when the gate was removed from the raised chute and vibration began. Due to the vertical face at the bottom of the chute, the top portion of the sample would often shear and fall from the chute. This is illustrated in Figure 4.1; a plot of mass versus test time in which a sudden decrease is shown at the beginning of the test. The size of the sheared concrete became an issue during interpretation of the results, when the maximum flow rate was selected. At times when the consistency of the mixture was low, little concrete flowed from the chute while under vibration. Therefore, the sheared portion of the sample significantly distorted the fitted flow curve, resulting in an incorrect maximum flow rate. The inaccurate flow rate was then used to calculate the workability index resulting in a misrepresentative workability index for the concrete.

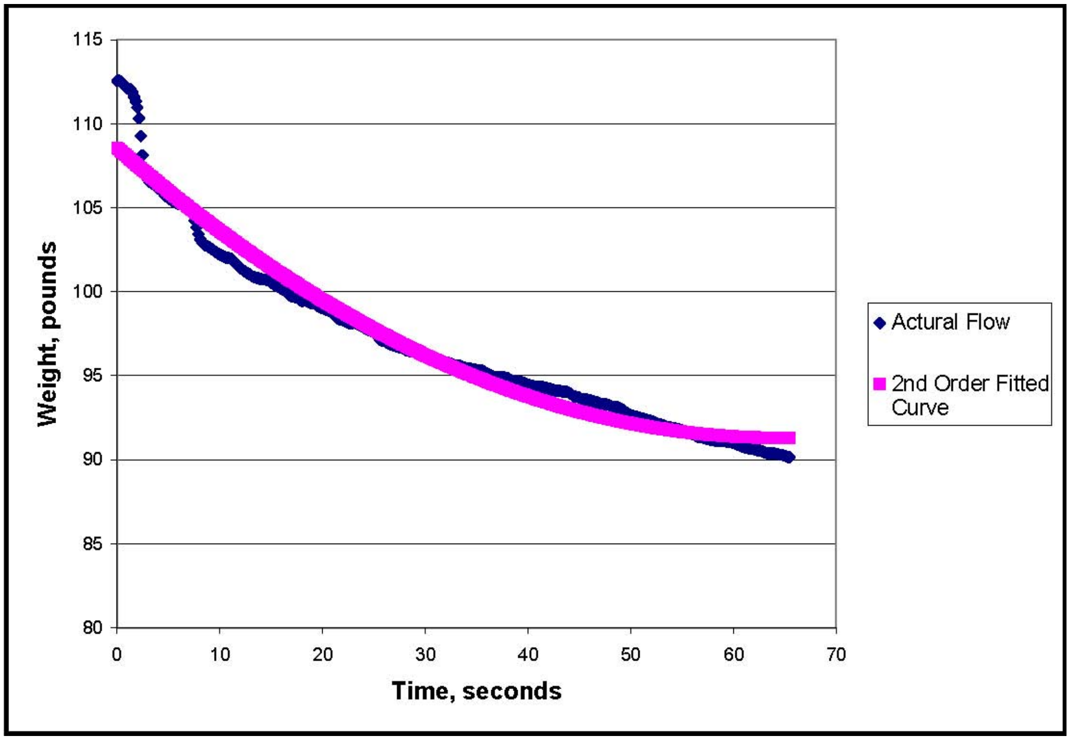


Figure 4.1 Original VSA Plot Illustrating Shear Failure, Identified by Sharp Mass Loss at Beginning of Test (Five degree slope, Mixture 1, 6/2/2003)

3. The third problem was found during interpretation of the data gained from initial analysis. Instead of selecting the minimum of two chute angles needed to construct the flow versus chute angle plot, five angles were used. In several cases when these five angles were plotted it was discovered that an inverse relationship between chute angle and flow rate could result, if the test were run at the appropriate two points.

4.2.2 Problem Solutions

To resolve the first and third problem the new test procedure would need to be performed at only one chute angle. Therefore, flow rate needed to be plotted against a new variable. Vibration was selected to replace chute angle in the new test procedure. In order to qualify vibration, amplitude and frequency, an accelerometer needed to be mounted on the chute.

To combine both frequency and amplitude of the vibrating chute into one variable, Equation 4.1 was used. As with the previous test procedure, there needed to be two data points to satisfy the requirement for a multiple-point test (Tattersall, 1983). The first point would be the energy required to initiate flow in the chute. It has been suggested by De Larrard (1993) that the energy required to initiate flow can be related to the yield stress of concrete. The second point would be the energy resulting from maximum vibration. These two measurements of energy could be plotted against flow, as were chute angles in the original test procedure.

Equation 4.1

$$E = 2*\Pi^2*f^2*A^2*M$$

where: A = vibration amplitude (mm)
f = vibration frequency (hz)
M = Mass under vibration (kg)

To resolve the second problem, a new gate was constructed. Instead of being flat, creating a vertical face, the gate was built in the shape of a wedge, thereby creating a 45° sloped surface when the chute was level (Figure 4.2). The sloped surface eliminated the vertical face at the end of the chute and, therefore, the probability of shear failure. The idea for the wedge was modeled after the LCL apparatus developed in France (De Larrard, 1993).

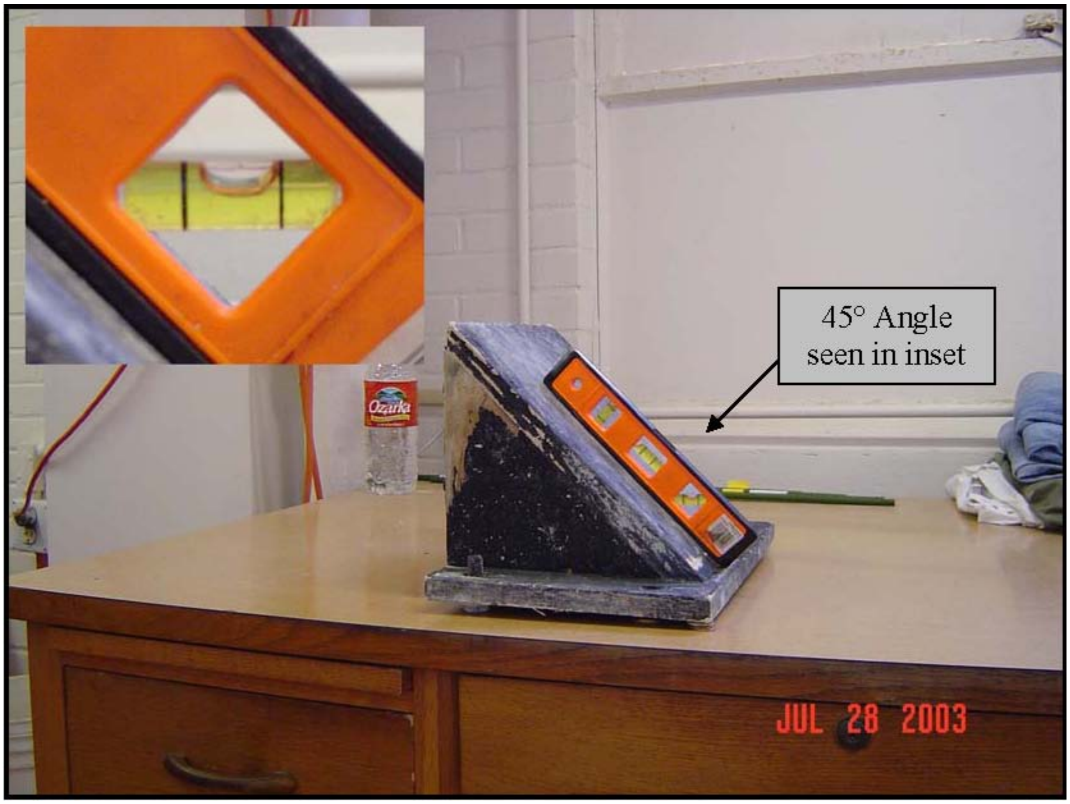


Figure 4.2   45° Wedged Gate Used During Revised VSA Testing Procedure

After revision, the steps involved in the new VSA test method are:

1. Place and consolidate a sample of concrete in the chute to a distance four inches from top of the chute.
2. Raise the chute to the predetermined angle. An angle of 15 degrees was chosen based on results of initial testing.
3. Remove wedged gate from chute.
4. Simultaneously start the data acquisition system and vibrator, making sure that the dial on the vibrator control is turned to zero.
5. Slowly increase the vibrator control until flow is initiated. Record this dial setting.
6. Turn the dial to full for the remainder of the test.
7. End the test when the majority of concrete has flowed from the chute.

The events that take place after the initiation of the test are illustrated in Figure 4.3. Several important features of the test are shown in this figure; they include:

1. A smooth transition where flow begins to occur. No abrupt loss of mass due to shear failure occurred after the new chute wedge was used.
2. After the flow initiation dial setting is recorded, the vibration is increased to 100 percent where a relatively constant frequency is maintained throughout the remainder of the test.
3. Due to the loss of mass, amplitude gradually increases during the test.

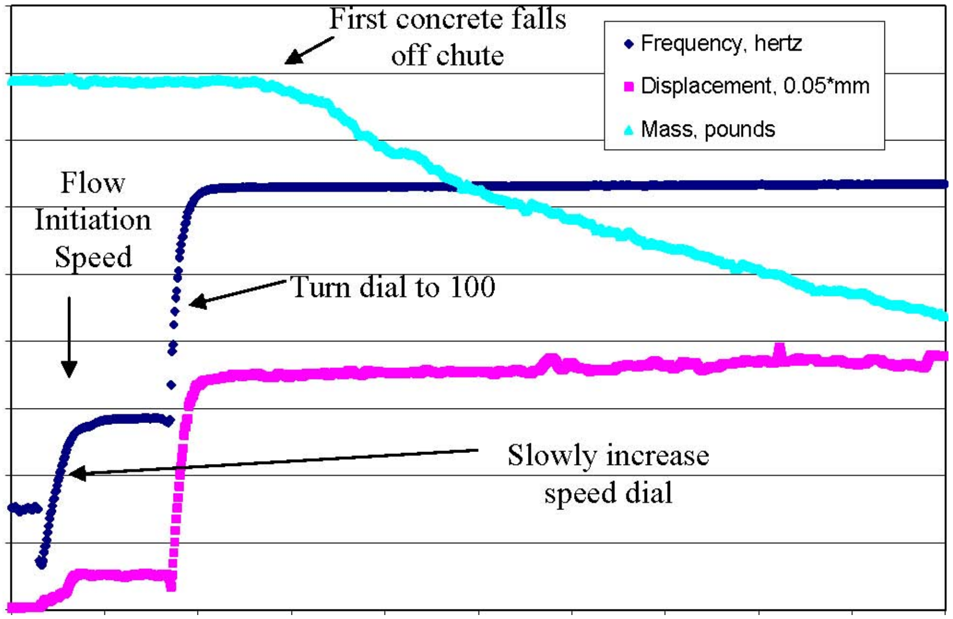


Figure 4.3 Typical Test Results (Mixture 2, 7-2-2003)

4.3 IMPLEMENTATION OF REVISIONS

The accelerometer chosen for this purpose was the Crossbow model CXL50LP3, capable of measuring acceleration in all three axes. A new data acquisition system was also purchased to collect signal data from the accelerometer. The system selected for this purpose was a LabJack model U12.

To mount the accelerometer, the chute was removed from the VSA frame. Once removed, 11 locations were drilled and tapped on the bottom of the base of the chute (Figure 4.4). The chute was then replaced and each location was tested by the accelerometer, to determine the appropriate mounting location for testing. In conducting this test, it was discovered that the chute was moving in all three axes. However, the displacement in the X axis, per the coordinate system in Figure 4.4, was approximately a tenth of the displacement occurring in the other two axes. Therefore, it was believed that this movement could be ignored during interpretation of test results. After each location was tested, location seven was selected as the location with the most representative vibration characteristics. Figure 4.5 is a plot of the amplitudes measured, in the Y and Z axes, at location seven, under full vibration. Illustrates in this plot are that the displacements in these two axes are out of phase. Therefore, the resultant of these two displacements was used to determine the energy in Equation 4.1.

It should be noted that the VSA was never intended to be instrumented in this manner. However, when measurements taken at location seven were compared to the manufacturer's specifications, they were found to be within limits, evidence of a sound procedure.

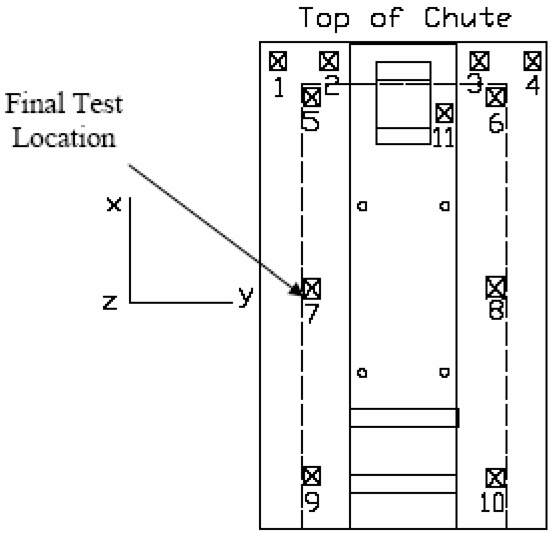


Figure 4.4 Schematic of Accelerometer Mount Locations, Along With Final Location

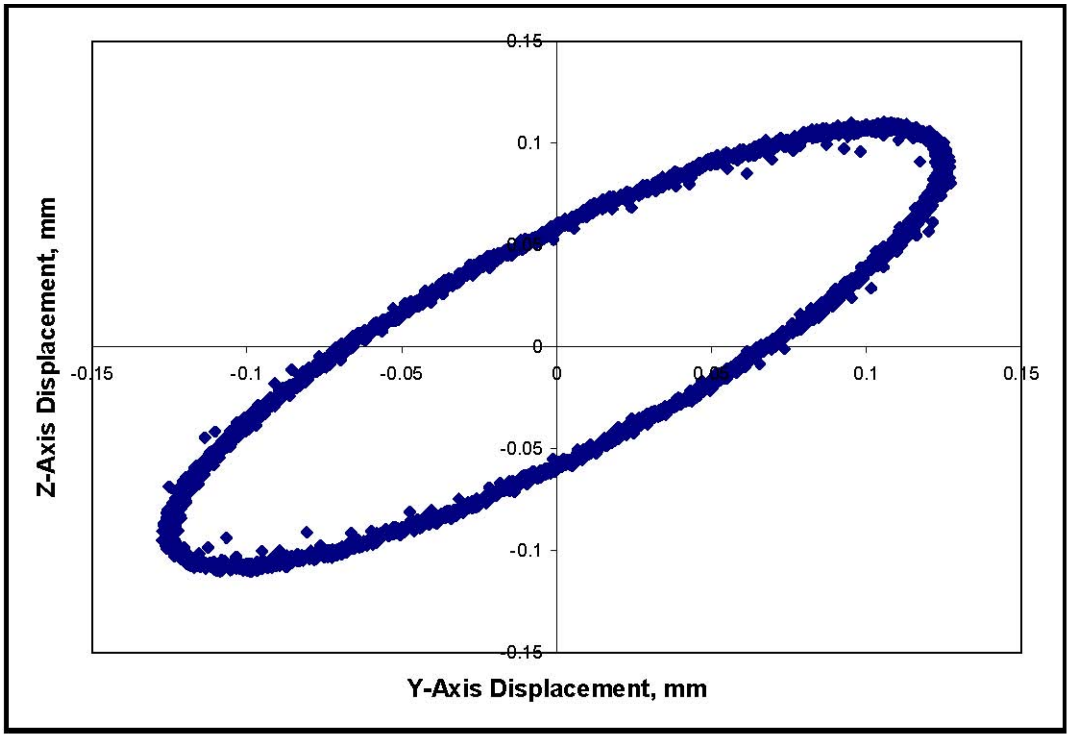


Figure 4.5 Displacement of VSA Chute With Vibrator Dial Set at 100

4.4 REVISED TEST PROCEDURE

One of the desired characteristics of a new device, to characterize the workability of concrete, is that it be capable of distinguishing the difference between two concretes that show the same workability when tested with a single-point test, such as the slump cone, specified by ASTM C 143. To test for this characteristic, six standard mixtures were designed following ACI 211 guidelines. The workability of the control mixtures was then altered by either adding a mineral or chemical admixture, adding or removing water, or modifying the percentage of coarse to fine aggregate. All together, eleven different mixtures were prepared and mixed consecutively, thereby eliminating varying workability due to differential moisture contents present in the aggregate. The control mixture was also repeated as mixture eight to establish a degree of consistency during the mixing.

The process followed for preparation of the materials and mixing of concrete will be briefly explained. The day before mixing, aggregate was moved from its stock pile to the mixing room in five-gallon buckets. When crushed limestone aggregate was used, it was first moved to the mixing room where it was immersed in water for 24 hours to satisfy the absorption capacity of the relatively porous aggregate. Next, the coarse and fine aggregates were separately placed in a mixer and mixed for 3 to 5 minutes. Once the material had been properly blended, in order to obtain a uniform gradation and moisture content, samples were dried in a microwave oven. While the material dried, batch qualities were weighed and placed in five-gallon buckets and sealed with a lid. After the samples had reached an oven-dry condition, moisture corrections were made to the batched qualities. The batched materials remained in the mixing room overnight before being mixed the following day.

The following day the prepared materials, minus water, were placed in a four-cubic-foot mixer. The mixer was run for a brief period to obtain a homogenous mixture of the dry materials. Actual mixing time began when water was added to the mixer. All mixtures were mixed in the same manner: three minutes on, followed by two minutes resting and then mixed again for two minutes. When either an air-entrainment or water-reducing admixture was used, approximately half a pound of water would be kept to dilute the admixture before it was added during the rest period. Once mixing was completed the concrete was placed in a wheelbarrow, where it was removed for each test. All mixtures were tested for air content, unit weight and slump, in accordance with ASTM standards. Slump flow measurements were also taken after the initial slump cone reading had been recorded. Horizontal and vertical measurements of the sample were taken after being vibrated on a vibrating table for increments of two seconds. Mixture 1 conducted on 7/18/2003, a 1.5-inch-slump concrete, is illustrated in Figure 4.6 after being vibrated on the vibrating table for 20 seconds.

Figure 4.6 Slump Flow of Mixture 1 on July 18, 2003, an Initial 1.5-inch Slump, after 20 Seconds on Vibrating Table

4.5 DATA REDUCTION

In order to work with both sets of data, from the accelerometer and load cell on a coincidental time line, both signals were collected by the LabJack data acquisition unit and software. The load cell data were later reduced in the same manner as they were by the original VSA software.

The accelerometer data were retrieved in the form of voltage readings proportional to acceleration measured in g’s. These raw data were then run through a LabView program, written to extract frequency and amplitude of vibration. These values were used to calculate the energy from Equation 4.1, which was then evaluated along with flow data to establish appropriate trends from the testing.

Test results were compared to slump cone readings. It is widely known that slump measurements are not a good measure of workability, but in the absence of other meaningful tests, slump readings were used. It is not surprising, therefore, that the results do not show the best correlation.

Individual test results were also compared to eliminate any bias that may result from comparison with inappropriate methods. This approach proved helpful in proving the modified VSA test procedure is capable of detecting previously established trends. For example, a trend associated with the addition of a water-reducing admixture would be interpreted by a decrease in flow initiation energy along with an increase in flow rate.

4.6 TEST RESULTS

The initial intent of replacing chute angle with vibration properties was a direct replacement, resulting in a plot of energy versus flow rate. However, once testing began, it was apparent that other relationships between these two variables could be made. Ferraris (Ferraris, 2003) had previously recommended that a workability index, calculated by dividing one variable by another, might be useful to qualify workability. This type of index would be ideal because it would allow replacement of single-point test results without the addition of complicated charts and graphs. Overall, numerous comparisons were made between the results of the modified VSA test and the other quality-control tests. As previously discussed, efforts were also made to compare individual results with those of the group.

Many comparisons were made with little or no promising outcome; therefore, these efforts will not be discussed. The following section is a summary of the results. Table B.1 and Table B.2, located in APPENDIX B, contain a complete summary of the data obtained.

The results will be presented in the approximate order that the data were obtained during testing, beginning with flow initiation, followed by flow rates along with respective energies. Combinations of these two variables will be done next along with a comparison of measurements against water-to-cementitious materials ratio and coarse aggregate content.

4.6.1 Flow Initiation

Once the chute had been filled, consolidated and raised to the predetermined angle, the chute wedge was removed. The data acquisition system and vibrator were then started, at which time the operator began to increase the speed dial until the concrete sample began to flow or move in the chute. This dial setting was recorded; the dial was then increased to full for the remainder of the test. The frequency and amplitude of vibration at flow initiation were later determined from the accelerometer data and the concrete flow initiation energy was calculated. The relationship between flow initiation energies and dial readings is illustrated in Figure 4.7.

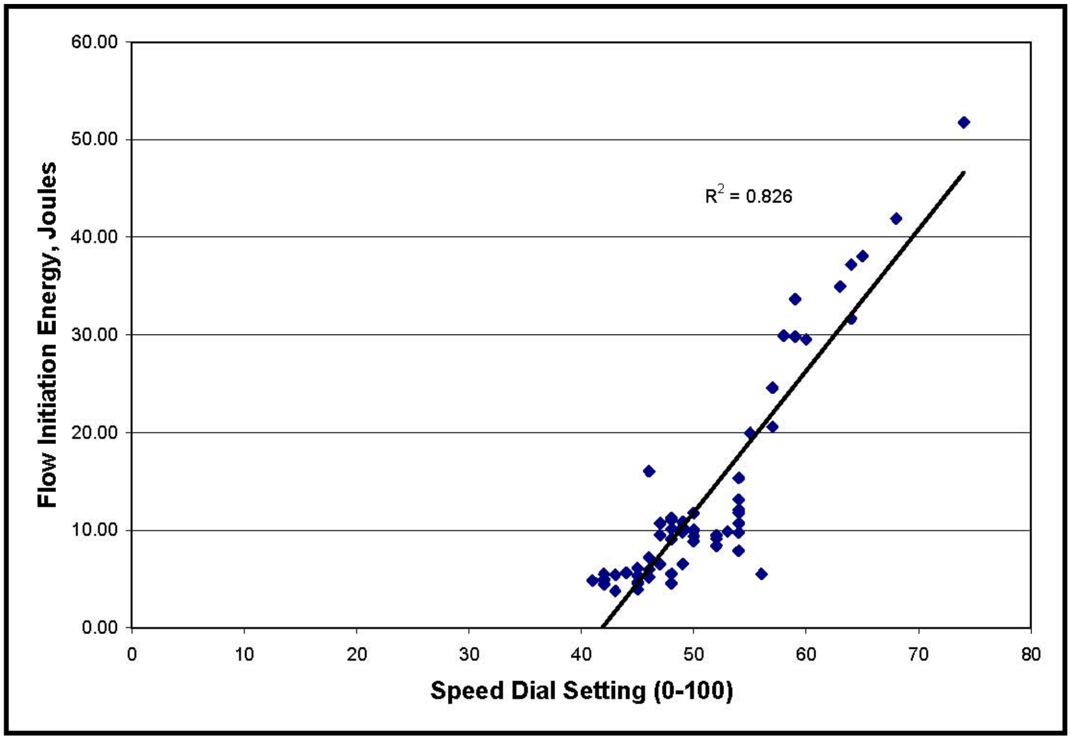


Figure 4.7 Flow Initiation Energy versus Speed Dial Setting

A moderately linear relationship is illustrated in Figure 4.7 between the two variables. Due to the nature of the equipment used and the three variables - frequency, amplitude and mass - used in Equation 4.1, a more linear fit would be difficult to obtain. Frequency and amplitude have also been plotted against the speed dial settings to demonstrate the scatter within these variables (Figures 4.8 and 4.9).

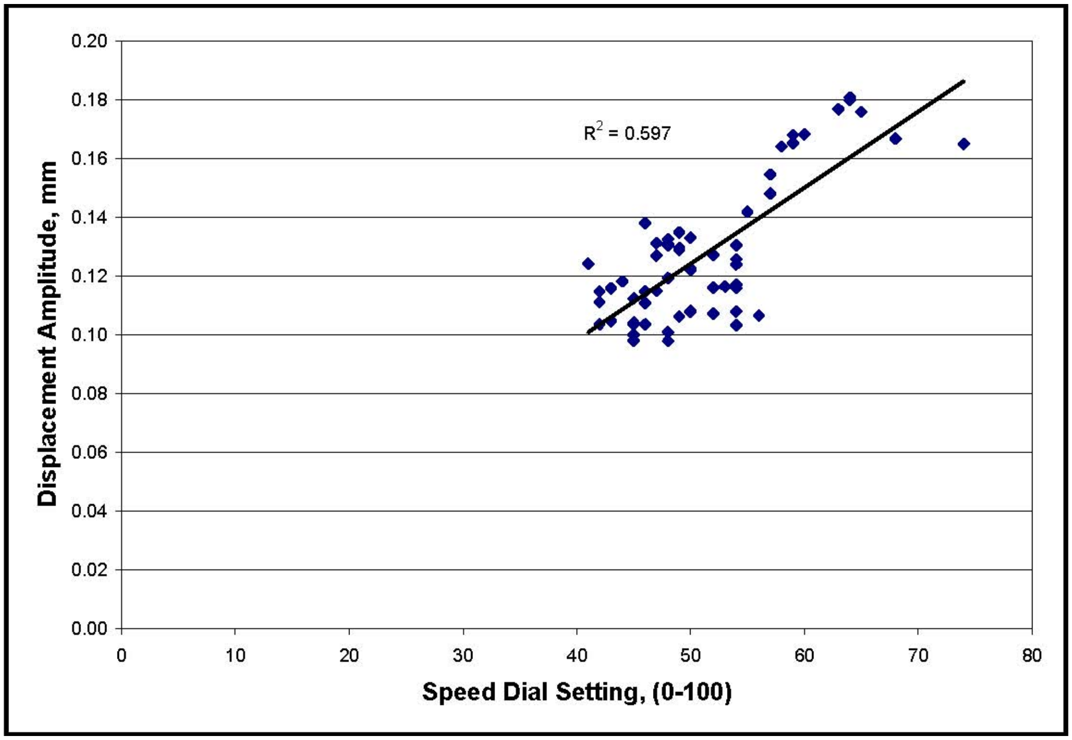


Figure 4.8 Initiation Amplitude versus Speed Dial Setting

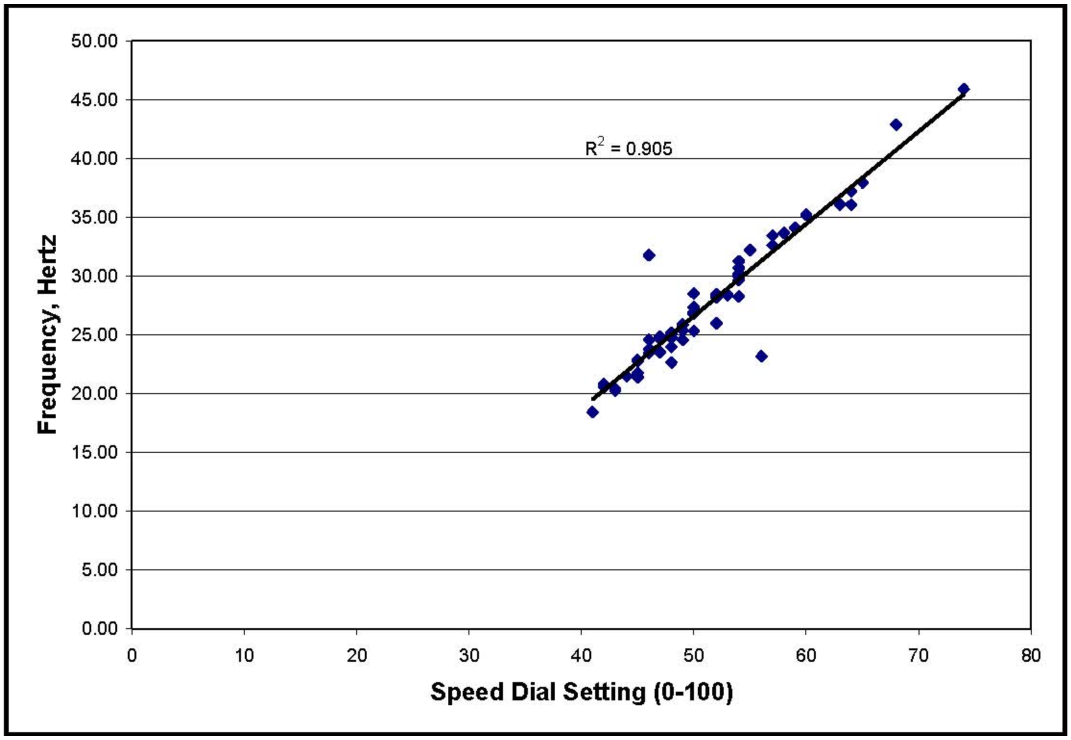


Figure 4.9 Initiation Frequencies versus Speed Dial Setting

Following the recommendation from De Larrard that initiation energy could be a measure of yield stress, the flow initiation energies above were plotted against slump cone measurements (Figure 4.10).

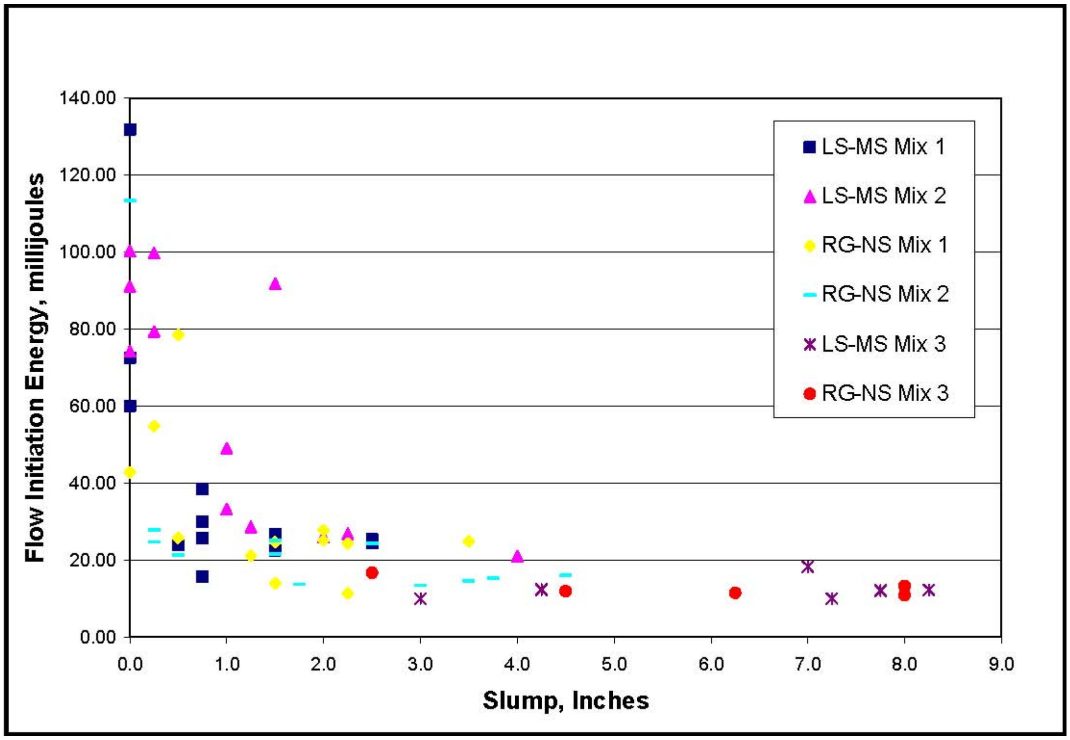


Figure 4.10 Flow Initiation Energy versus Slump Cone Measurements

The data seem to show signs of an exponential relationship. However, this relationship is considerably less noticeable when an individual series is viewed. The correlation further diminishes at slump measurements above 2.5 to 3 inches. The findings for this relationship are:

1. The use of flow initiation energy to qualify the static strength of a concrete mixture returns reasonable results for lower concrete consistencies.
2. The test is capable of distinguishing between different mixtures where slump cone measurements are not.
3. The scatter of the results is high. This is likely due to incompatibilities between the accelerometer, capable of making precise measurements, and the VSA was not designed for this amount of precision.

4.6.2 Flow Rate Data

Once flow had begun the vibrator speed control was increased to full. The new chute wedge allowed concrete to flow from the chute in a more uniform manner, eliminating the problem of a shear plane at the bottom of the chute. After completing several initial testing sequences and viewing the resulting data, it was evident that qualification of concrete workability with the available variables – mass flow rate and system energy – could be approached in several ways. Comparison of mass flow rate with energy proved problematic. The problem with this approach is that once concrete begins leaving the chute the mass of the system is changed, resulting in a different energy. This change is further amplified by an increase in amplitude due to the loss of mass. The frequency of the system is also susceptible to change due to variations in the other variables. However, proportionally this change was negligible when compared to amplitude and mass. Overall, the likelihood of useful results being returned from this approach seems small; therefore, other approaches were focused on. However, efforts are still being made to determine better relationships from the results.

With erratic fluctuations of energy throughout the test, restricting the possibility of a continuous relationship, individual points throughout the test were investigated. A correlation was found when initial flow rate, the derivative of the fitted line at time 0, was plotted against slump measurements (Figure 4.11). Between slumps of zero and three inches, a linear relationship is easily seen. However, the relationship is not as well defined for slumps three inches and higher. A possible explanation for the diminished relationship is that the concrete yield stress is less for concrete with higher-consistency. Therefore, where the chute angle may not have much influence on lower-consistency mixtures, the shear stress added to the system in these cases may be responsible for the greater amounts of scatter seen in the results. Therefore, the initial flow rate of these higher-consistency mixtures is a function of the chute angle and energy from vibration, not just vibration energy. The correlation between these two variables, for low-consistency concrete, seems logical because each test measures the ability of concrete to flow.

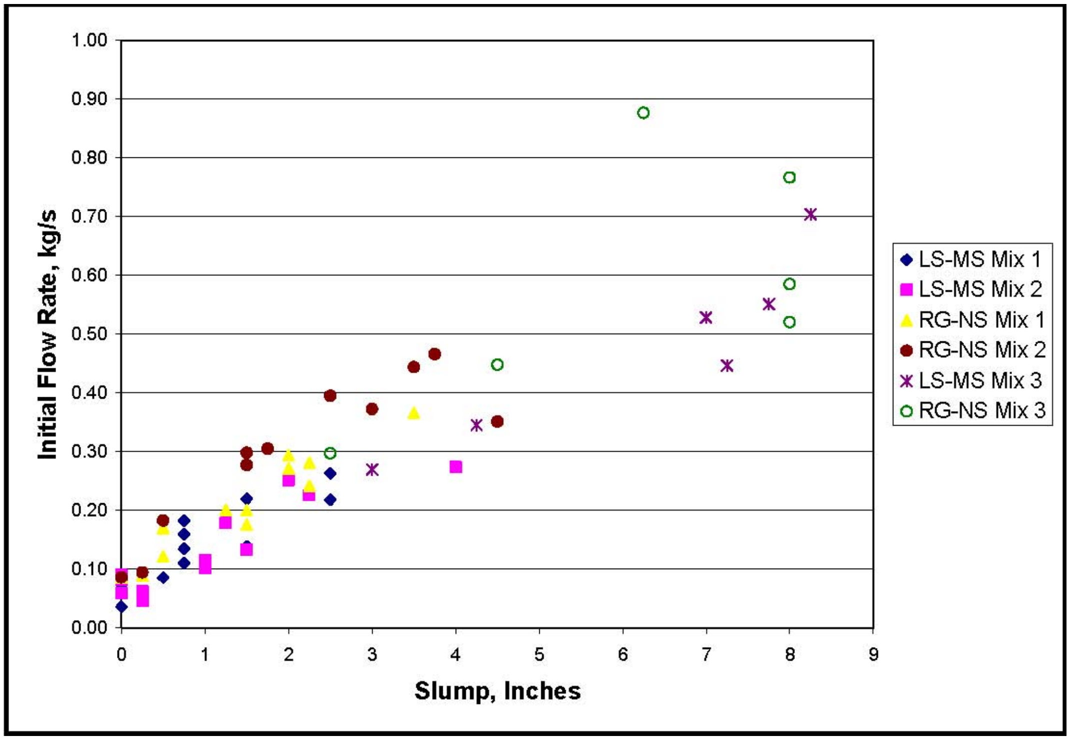


Figure 4.11 Initial Flow Rate versus Slump Measurements

The process by which the initial flow rate is selected for an individual test is further explained below. A plot illustrating the mass loss over time will be used in the example (Figure 4.12).

The data are plotted against time or duration of the test. Next, an n^{th} degree polynomial was fit to the data. In this example a second degree polynomial has been fitted to the data in order to simplify the calculations.

$$\text{Concrete Mass} = 0.0002*X^2 - 0.087*X + 48.239$$

The equation of this fitted line represents the mass of concrete left in the chute at any given time during the test. The mass flow rate or change in concrete mass with respect to time is calculated by taking the derivative of this equation.

$$\text{Mass Flow Rate} = 0.0004*X - 0.087$$

The last step in evaluating the initial flow rate is to evaluate the mass flow rate equation at time zero.

Initial Flow Rate = 0.0004*(0) – 0.087 = -0.087

The above initial flow rate was calculated from the data obtained from Mixture 1 prepared on 7/2/2003 and can be verified from Table B.1 in Appendix B.

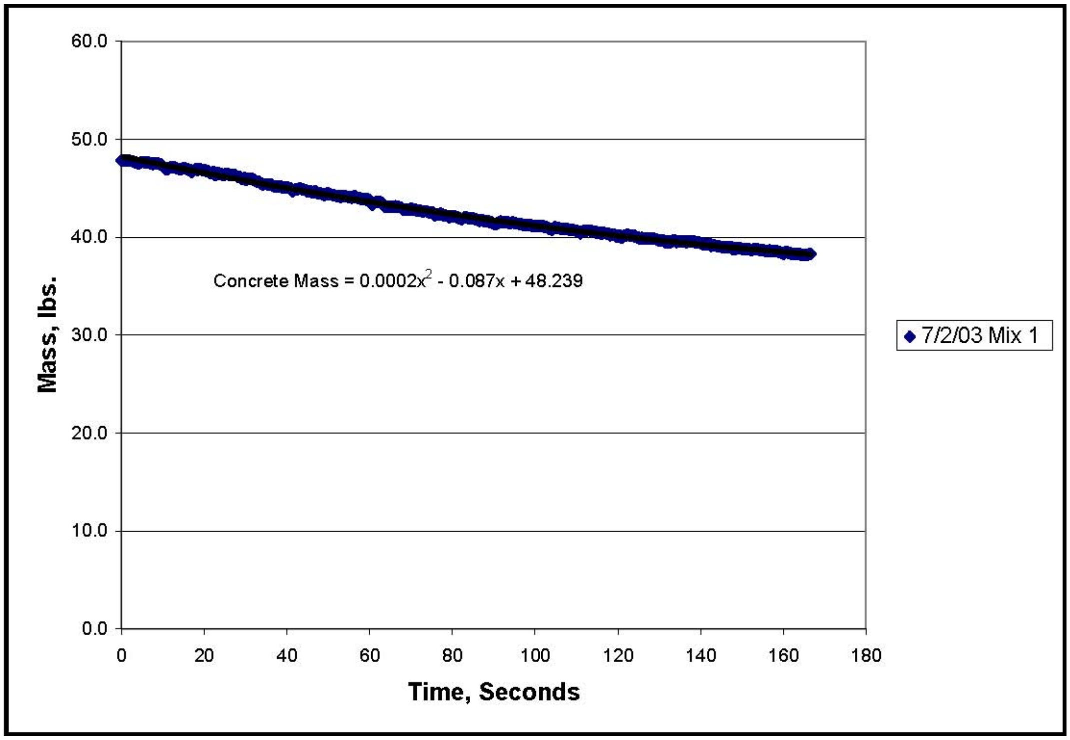


Figure 4.12 Process Followed in Selection of Initial Flow Rate

Initial flow rates were then divided by the average energy imparted to the sample for the first second under full speed. Since energy is dependent on frequency, amplitude and mass, the energy measured before a significant amount of concrete left the chute is close to uniform. Using this type of ratio allows concrete to be qualified by a single number when a multi-point test is used. Concretes with similar flow characteristics are distinguished when a ratio between initial flow rate and energy are used (Figure 4.13).

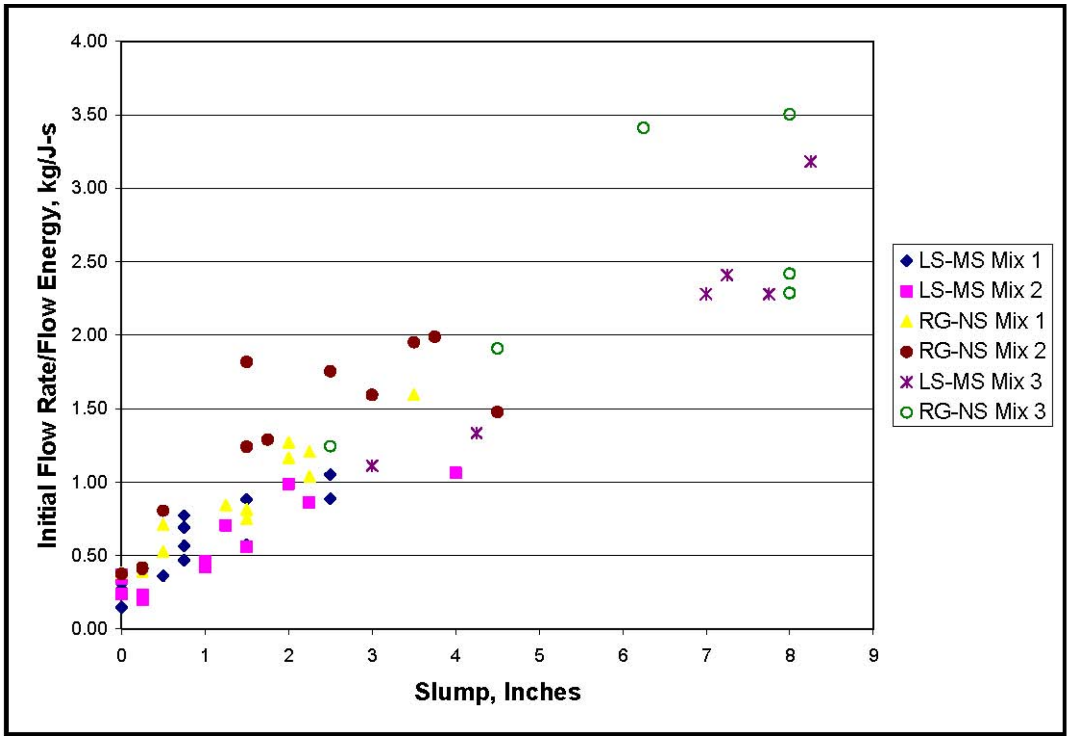


Figure 4.13 Initial Flow Rate/Flow Energy versus Slump

4.6.3 Flow Initiation with Flow Rate Data

Once the above relationships, between flow initiation and flow rate with slump measurements, had been established, these two variables were combined to form a ratio or workability index. The workability index was calculated using Equation 4.2.

Equation 4.2

$$\text{Workability Index} = Q_i/E_i \text{ (kg/J-s)}$$

where: Q_i = initial flow rate (kg/s)

E_i = flow initiation energy (joules)

By combining two measurements, in ratio format, a single number can qualify the workability of concrete. The workability index responds in the same manner as slump measurements. A higher number, gained by either decreasing the viscosity, which results in increased flow volumes, or yield stress indicates a more workable concrete. Another benefit gained by using a workability index is that changes in both the viscosity and yield stress of the mixture are accounted for, where these changes are not measured in other single-point workability tests. A plot of the calculated workability index of the concretes tested against their respective slump measurements is shown in Figure 4.14.

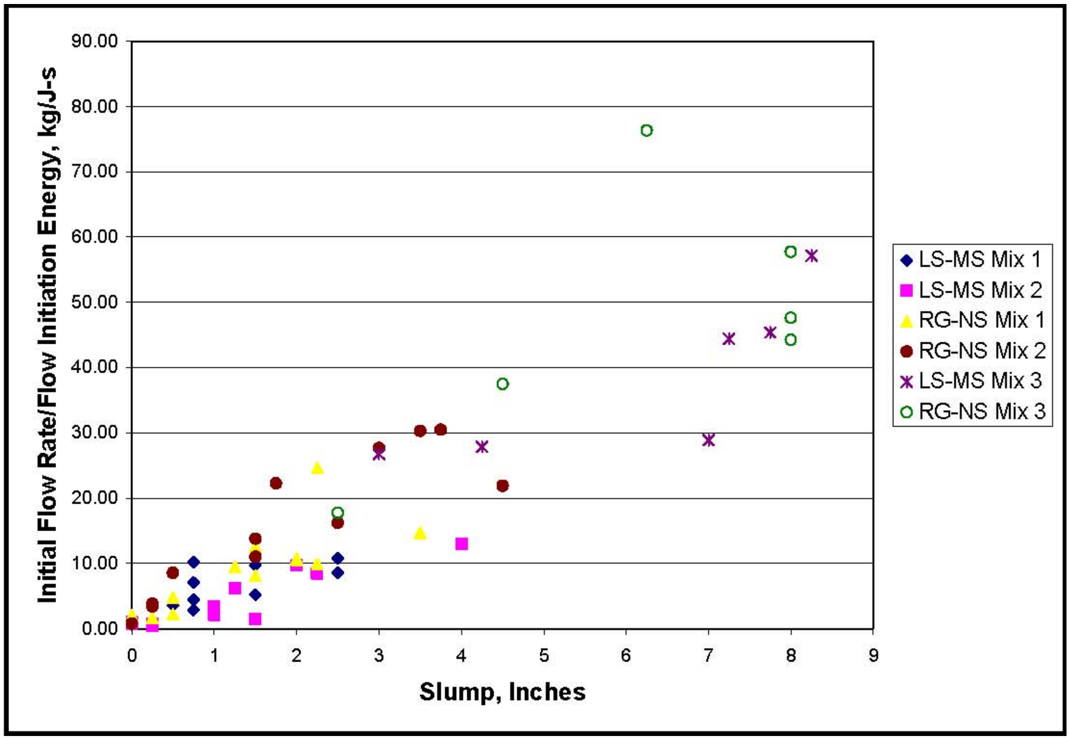


Figure 4.14 Plot Showing Positive Relationship of Workability Index and Slump Measurements

A good relationship for low workability index and slump is demonstrated in Figure 4.14. However, the relationship appears to diminish for concrete with a higher slump and workability index. This decrease is likely caused from a combination of increased scatter in both variables used to calculate the workability index, the cause of which was discussed in each respective section. It should be noted that the original VSA was developed to qualify the workability of low-consistency concrete, like those used for concrete paving. Therefore, the control mixtures prepared for use in testing the modified procedure were intended to perform within this range. Twelve mixtures of higher consistencies were tested to determine how the established relationship for lower consistencies carried for these mixtures. However, the focus was mainly kept on less-workable mixtures. Therefore, no conclusions should be made on the ability of this test method to define the workability of the later mixtures accurately until further testing is completed.

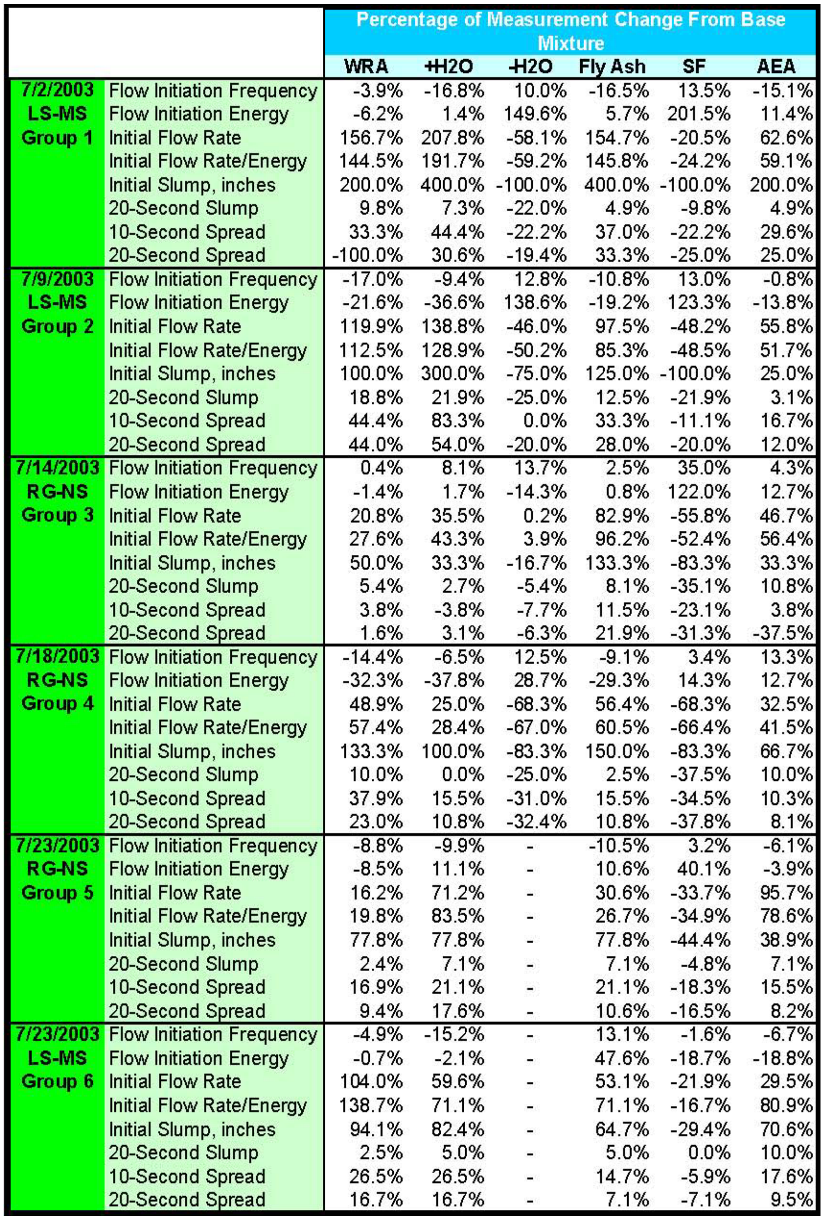
4.6.4 Comparison of Data with Established Trends

With there being a general agreement that the slump cone is inappropriate for measuring the workability of concrete, it seems meaningless to compare the measurements of the modified VSA with slump readings. However, since the slump cone is the commonly accepted test method used in the field for close to a century, it is understood that any new test method will need to build from established relationships made by the slump cone. For this reason, along with a lack of other options, the above comparisons and correlations were made. The ability of the modified VSA test method to distinguish between mixtures of similar workability, where the slump cone is not, is shown in Figures 4.10, 4.11, 4.13 and 4.14

Other relationships that were available for comparison were those that are commonly accepted among industry, gained by adding supplementary cementitious materials (SCM) or chemical admixtures. One example of these relationships would be the decrease in workability as the result of adding silica fume to a mixture. Fly ash, another SCM, was also used to modify the workability of the control mixtures. WRDA® 64, a Type A and Type D water-reducing admixture produced by Grace Construction Products, was also used to increase the workability of the control mixtures. Another chemical admixture Daravair®, an air-entraining agent (AEA), also a product from Grace Construction Materials, was used to entrain air into the mixtures because increased air contents are known to increase the workability of concrete. Overall, the control mixtures were modified six times each by either incorporating an SCM or chemical admixture into the mixture or adding or subtracting water.

The results that were obtained from the modified mixtures were then compared to those of the control mixture to determine if they followed these established trends. The comparisons are shown in Table 4.1. Overall, the modified VSA test followed the established relationships well. The results are illustrated in Table 4.1; therefore, discussion of the results will be brief, and emphasis will be made on results that do not follow expected patterns. Discussion is divided into six groups that coincide with six modifications of a control mixture.

Table 4.1 A Comparison of Modified VSA Test Results with Established Trends



		Percentage of Measurement Change From Base Mixture					
		WRA	+H2O	-H2O	Fly Ash	SF	AEA
7/2/2003 LS-MS Group 1	Flow Initiation Frequency	-3.9%	-16.8%	10.0%	-16.5%	13.5%	-15.1%
	Flow Initiation Energy	-6.2%	1.4%	149.6%	5.7%	201.5%	11.4%
	Initial Flow Rate	156.7%	207.8%	-58.1%	154.7%	-20.5%	62.6%
	Initial Flow Rate/Energy	144.5%	191.7%	-59.2%	145.8%	-24.2%	59.1%
	Initial Slump, inches	200.0%	400.0%	-100.0%	400.0%	-100.0%	200.0%
	20-Second Slump	9.8%	7.3%	-22.0%	4.9%	-9.8%	4.9%
	10-Second Spread	33.3%	44.4%	-22.2%	37.0%	-22.2%	29.6%
	20-Second Spread	-100.0%	30.6%	-19.4%	33.3%	-25.0%	25.0%
7/9/2003 LS-MS Group 2	Flow Initiation Frequency	-17.0%	-9.4%	12.8%	-10.8%	13.0%	-0.8%
	Flow Initiation Energy	-21.6%	-36.6%	138.6%	-19.2%	123.3%	-13.8%
	Initial Flow Rate	119.9%	138.8%	-46.0%	97.5%	-48.2%	55.8%
	Initial Flow Rate/Energy	112.5%	128.9%	-50.2%	85.3%	-48.5%	51.7%
	Initial Slump, inches	100.0%	300.0%	-75.0%	125.0%	-100.0%	25.0%
	20-Second Slump	18.8%	21.9%	-25.0%	12.5%	-21.9%	3.1%
	10-Second Spread	44.4%	83.3%	0.0%	33.3%	-11.1%	16.7%
	20-Second Spread	44.0%	54.0%	-20.0%	28.0%	-20.0%	12.0%
7/14/2003 RG-NS Group 3	Flow Initiation Frequency	0.4%	8.1%	13.7%	2.5%	35.0%	4.3%
	Flow Initiation Energy	-1.4%	1.7%	-14.3%	0.8%	122.0%	12.7%
	Initial Flow Rate	20.8%	35.5%	0.2%	82.9%	-55.8%	46.7%
	Initial Flow Rate/Energy	27.6%	43.3%	3.9%	96.2%	-52.4%	56.4%
	Initial Slump, inches	50.0%	33.3%	-16.7%	133.3%	-83.3%	33.3%
	20-Second Slump	5.4%	2.7%	-5.4%	8.1%	-35.1%	10.8%
	10-Second Spread	3.8%	-3.8%	-7.7%	11.5%	-23.1%	3.8%
	20-Second Spread	1.6%	3.1%	-6.3%	21.9%	-31.3%	-37.5%
7/18/2003 RG-NS Group 4	Flow Initiation Frequency	-14.4%	-6.5%	12.5%	-9.1%	3.4%	13.3%
	Flow Initiation Energy	-32.3%	-37.8%	28.7%	-29.3%	14.3%	12.7%
	Initial Flow Rate	48.9%	25.0%	-68.3%	56.4%	-68.3%	32.5%
	Initial Flow Rate/Energy	57.4%	28.4%	-67.0%	60.5%	-66.4%	41.5%
	Initial Slump, inches	133.3%	100.0%	-83.3%	150.0%	-83.3%	66.7%
	20-Second Slump	10.0%	0.0%	-25.0%	2.5%	-37.5%	10.0%
	10-Second Spread	37.9%	15.5%	-31.0%	15.5%	-34.5%	10.3%
	20-Second Spread	23.0%	10.8%	-32.4%	10.8%	-37.8%	8.1%
7/23/2003 RG-NS Group 5	Flow Initiation Frequency	-8.8%	-9.9%	-	-10.5%	3.2%	-6.1%
	Flow Initiation Energy	-8.5%	11.1%	-	10.6%	40.1%	-3.9%
	Initial Flow Rate	16.2%	71.2%	-	30.6%	-33.7%	95.7%
	Initial Flow Rate/Energy	19.8%	83.5%	-	26.7%	-34.9%	78.6%
	Initial Slump, inches	77.8%	77.8%	-	77.8%	-44.4%	38.9%
	20-Second Slump	2.4%	7.1%	-	7.1%	-4.8%	7.1%
	10-Second Spread	16.9%	21.1%	-	21.1%	-18.3%	15.5%
	20-Second Spread	9.4%	17.6%	-	10.6%	-16.5%	8.2%
7/23/2003 LS-MS Group 6	Flow Initiation Frequency	-4.9%	-15.2%	-	13.1%	-1.6%	-6.7%
	Flow Initiation Energy	-0.7%	-2.1%	-	47.6%	-18.7%	-18.8%
	Initial Flow Rate	104.0%	59.6%	-	53.1%	-21.9%	29.5%
	Initial Flow Rate/Energy	138.7%	71.1%	-	71.1%	-16.7%	80.9%
	Initial Slump, inches	94.1%	82.4%	-	64.7%	-29.4%	70.6%
	20-Second Slump	2.5%	5.0%	-	5.0%	0.0%	10.0%
	10-Second Spread	26.5%	26.5%	-	14.7%	-5.9%	17.6%
	20-Second Spread	16.7%	16.7%	-	7.1%	-7.1%	9.5%

4.6.4.1 Group 1, Mixed July 2, 2003

Modification of this control mixture resulted in three inconsistent data points. These three points consisted of increasing flow initiation energies when extra water, fly ash and an AEA were used. All three adjustments to the control mixture decreased the yield strength, opposite of what was shown from the flow initiation energies. This anticipated decrease in yield stress is confirmed by slump cone measurements that increased 200 or 400 percent. These measurements of energy are a combination of three measured variables. In this case, the initiation frequency follows the expected pattern by decreasing. Therefore, either the mass of the sample or amplitude is responsible for these discrepancies. Measurements taken from the load cells show that in all three cases the mass of the sample increased from that of the control mixture. Therefore, it was believed that calculating the initiation energy per unit of mass would remedy this issue. This approach did work for the mixtures to which water and fly ash were added. However, greater initiation energy per unit of mass was still the case in the mixture to which an AEA was used. The initiation amplitude for all three mixtures did increase, but remained nearly constant for all three tests. Overall, after assessing all the variables involved, an explanation is still not apparent.

The remainder of the data within this set follows all the expected trends. In the three previously discussed cases the flow rates increased from the control mixture. These results also applied for the ratio between flow rate and energy.

4.6.4.2 Group 2, Mixed July 9, 2003

The same admixtures in the same proportions were added to this control mixture, for which the results followed the expected trends. The use of a WRA, fly ash, AEA or increased amounts of water all decreased the flow initiation energy and increased the flow rate under full vibration. The addition of silica fume or reduction of water gave opposite results.

4.6.4.3 Group 3, Mixed July 14, 2003

Four of the modifications made to the control mixture did not conform to the anticipated results. Slump measurements on the other hand followed the expected trends.

However, this may only be an indication that the expected patterns were established with the use of a slump cone.

The modification that reduced the available mixture water is unique because it was the only modification for which flow properties did not conform as expected. In all other cases, even where the flow initiation energy did not conform to the expected patterns, the flow measured under full speed always increased and decreased as expected.

4.6.4.4 Group 4, Mixed July 18, 2003

In this case all of the results conformed to the expected patterns except one; the use of an AEA again required more energy to initiate flow than its control mixture. Entraining air within the concrete matrix has historically been known to increase the workability. Therefore, the measurements taken by the VSA indicating a less workable mixture are not consistent. Perhaps the loss of workability measured can be explained from the loss of entrained air due to the vibration of the sample. To verify this prediction, air measurements would need to be taken before and after testing to verify that the vibration did decrease the quality of air within the matrix. Further testing will need to be completed before any conclusions can be reached.

4.6.4.5 Groups 5 and 6, Mixed July 23, 2003

Two different control mixtures with higher consistencies were modified to fill some of the gap left by the prior mixtures. Prior data have shown increased scatter at these higher consistencies; however, these comparisons show that the modified VSA appears able to follow established trends as well as it does for lower workable mixtures.

4.6.5 VSA Parameters versus Water-to-Cementitious Materials Ratio

It is well known that, all other factors being constant, an increase or decrease in the amount of water is the simplest way to alter the workability of a concrete. Therefore, all of the control mixtures were modified by adding or subtracting water. This resulted in two sets of data consisting of four mixtures with three different water-to-cementitious material (w/cm) ratios. (The fourth set of measurements was obtained from the repeated control mixture.) A second set of two mixtures containing six different w/cm ratios were also collected; these additional data were taken when water was added to an initial control mixture to obtain a higher consistency concrete for testing.

Four different series of data were plotted against measurements taken by the VSA to establish a relationship between these two variables. Because the addition of water to a mixture will increase the distance between adjacent particles resulting in decreased yield strength, the flow initiation energy was plotted against w/cm ratio. Due to the increased distance and extra water to act as a lubricant, an inverse relationship between these two variables was the expected result. All four series follow the expected relationship, illustrated in Figure 4.15, with varying degrees of correlation. The LS-MS Mixture 1 series exhibits the best correlation, which is close to linear. It should be noted that all sets of data contain two different measurements, one for the initial control mixture and the second for its repetition, for the same w/cm ratio. These measurements should coincide; however, in some cases a difference between measurements greater then 50% exists. These differences are further discussed in Section 4.6.7.

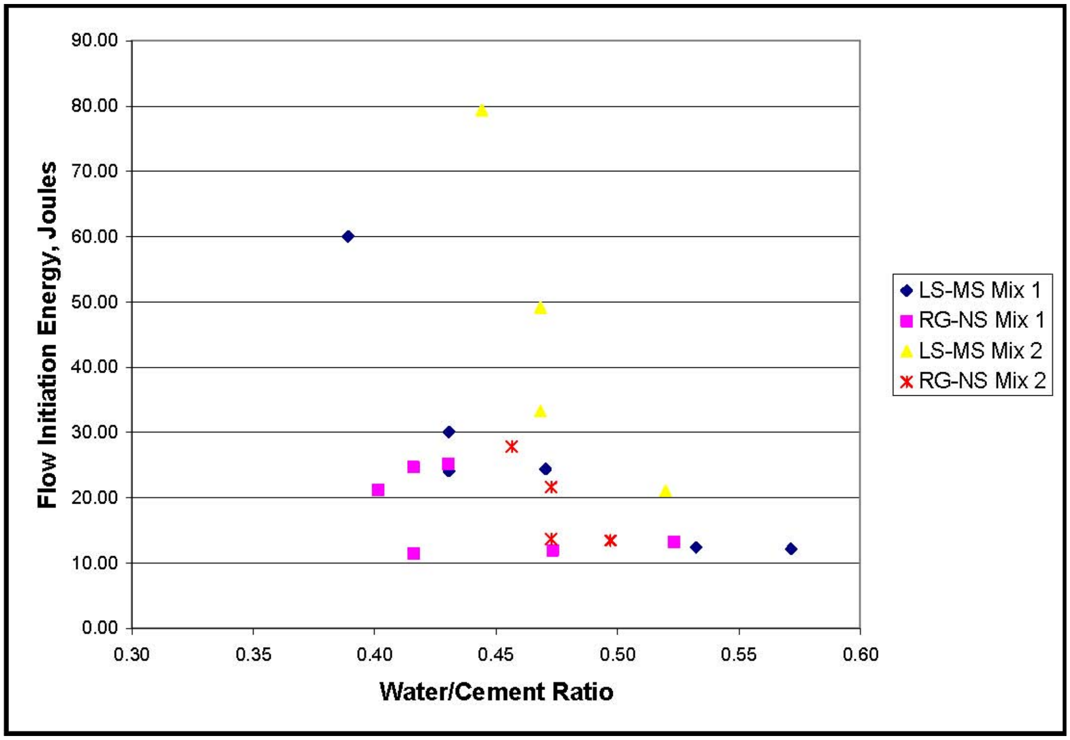


Figure 4.15 Flow Initiation Energy versus W/CM for Mixtures where Water is the Only Variable Changed

With other variables held constant, increased amounts of water not only decreased concrete yield stress, but also decreased the mixture viscosity. Since viscosity is a measurement of the internal resistance of a fluid to flow, w/cm ratios were plotted against the initial flow rates divided by the amount of energy imparted to the sample (Figure 4.16). In this case all four data series have relatively linear relationships, with the lowest R^2 value being 0.81 and the highest being 0.99. More data points are needed to further develop this relationship.

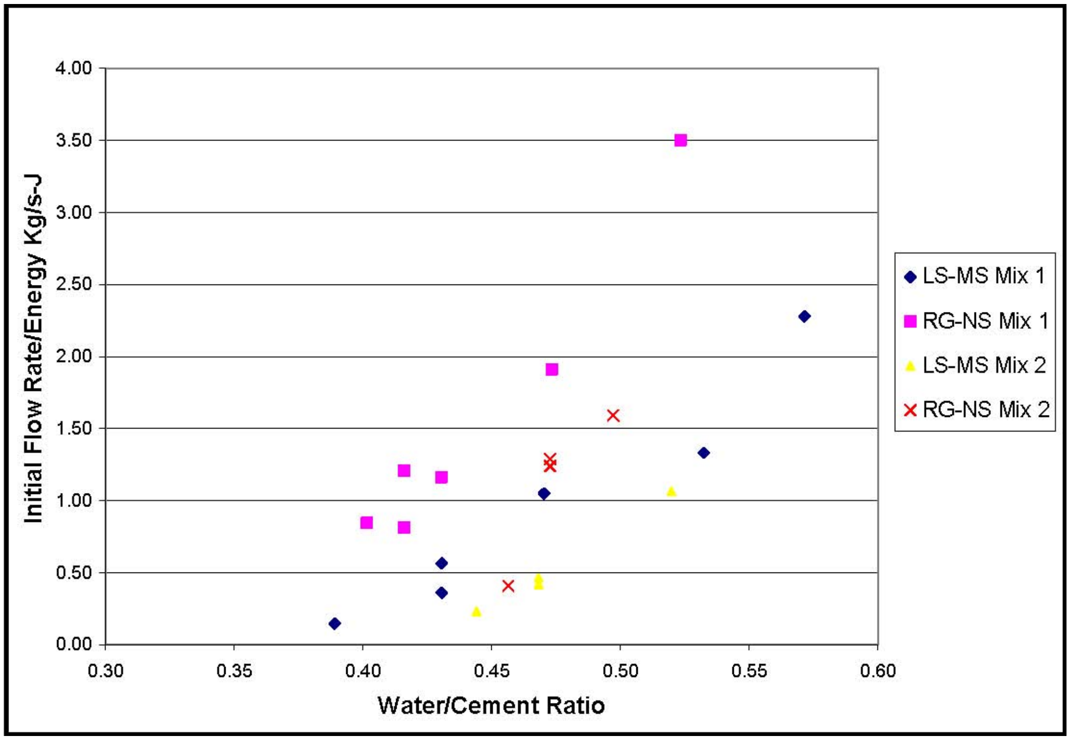


Figure 4.16 Initial Flow Rate/Energy versus Water-Cement Ratio where Water is the Only Variable Changed

4.6.6 VSA Parameters Versus Coarse Aggregate Fraction

Experience and research have shown that an optimal degree of concrete workability exists when the coarse and fine aggregate are mixed at a certain percentage (Scezsy, 1997). For this reason, the percentage of coarse aggregate to total aggregate was varied to determine if the VSA could determine the optimal percentage of coarse aggregate to maximize workability. For this approach optimal workability was defined where the yield stress, measured by flow initiation, and viscosity, measured by flow rate, are lowest and highest respectively.

Minimum flow initiation energies at approximately 60 percent coarse aggregate are shown in a plot of flow initiation energy versus coarse aggregate fraction (Figure 4.17). Three of the four data series show this pattern, where the fourth series, flow initiation energy, continues to decrease with increasing proportions of sand.

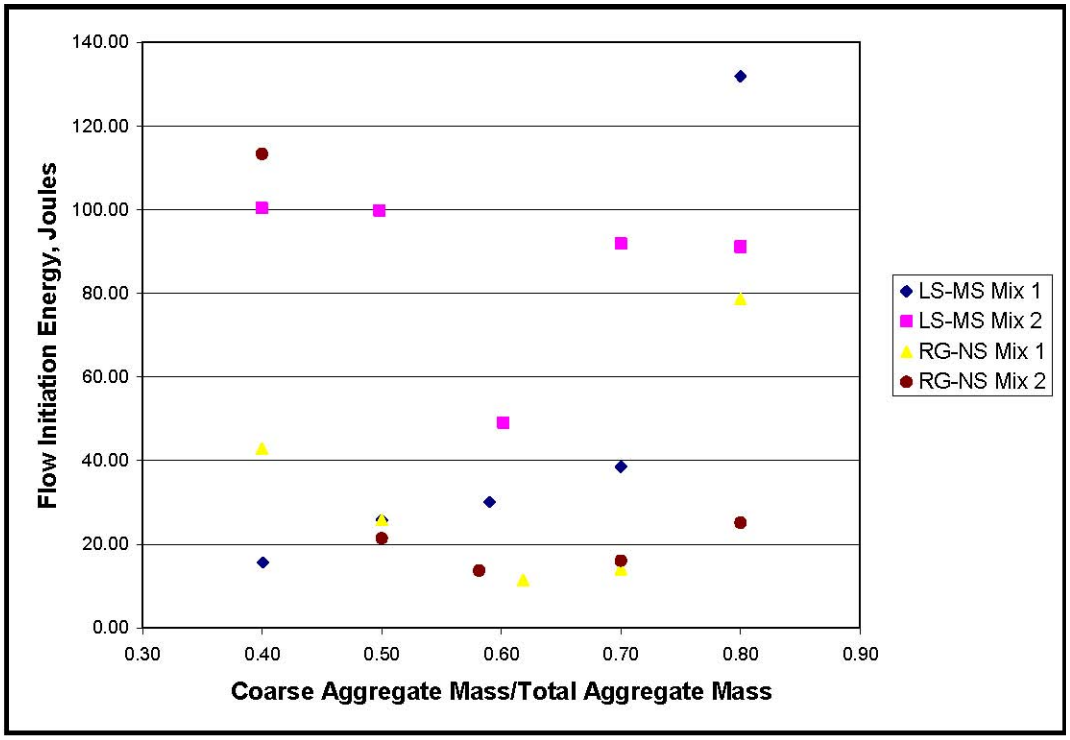


Figure 4.17 Flow Initiation Energy versus Coarse Aggregate Fraction

Distinguishable peaks occurring between 50 and 75 percent coarse aggregate content are demonstrated when flow rate data is plotted against coarse aggregate fraction (Figure 4.18). These values correspond well with those of the flow initiation energies. For instance, the LS-MS Mixture 2 minimum flow initiation energy occurs at 60%, which correlates well with its maximum flow rate occurring at 70%. By using these two values it can be concluded that an optimal workability for this mixture occurs at a coarse aggregate percentage between 60% and 70%. The VSA results also correspond well with results previously obtained with the use of a rheometer (Sceszy, 1997). Overall, the results indicate that the VSA is capable of distinguishing proper aggregate percentages needed to achieve the highest level of workability for a particular mixture.

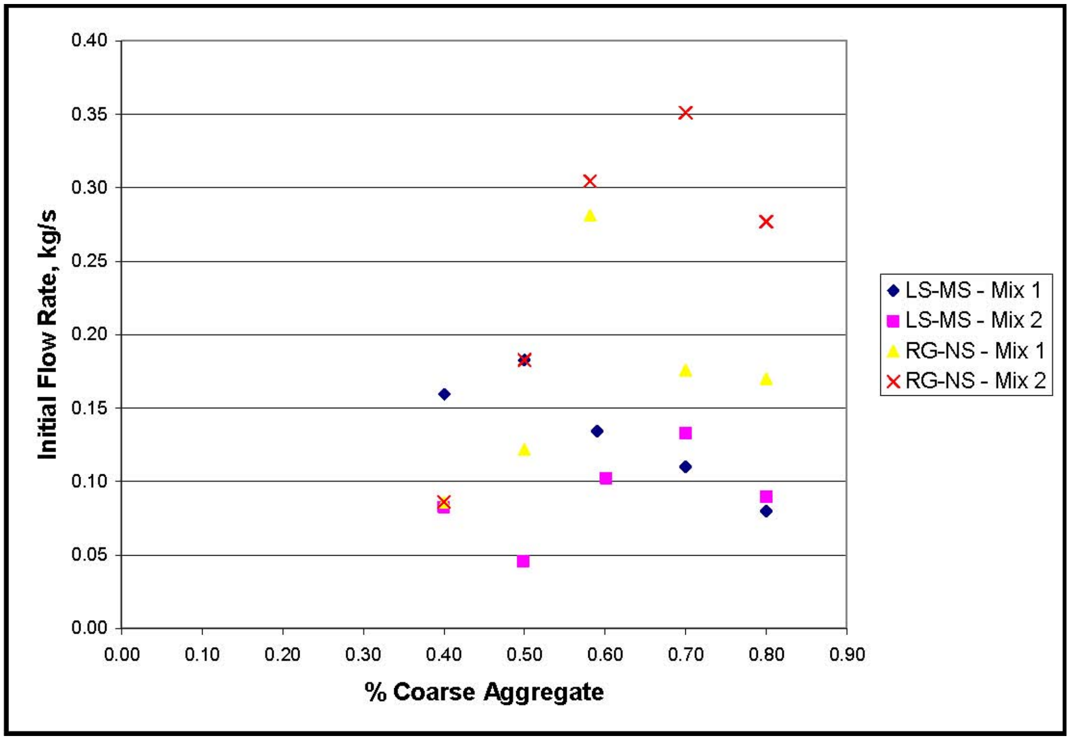


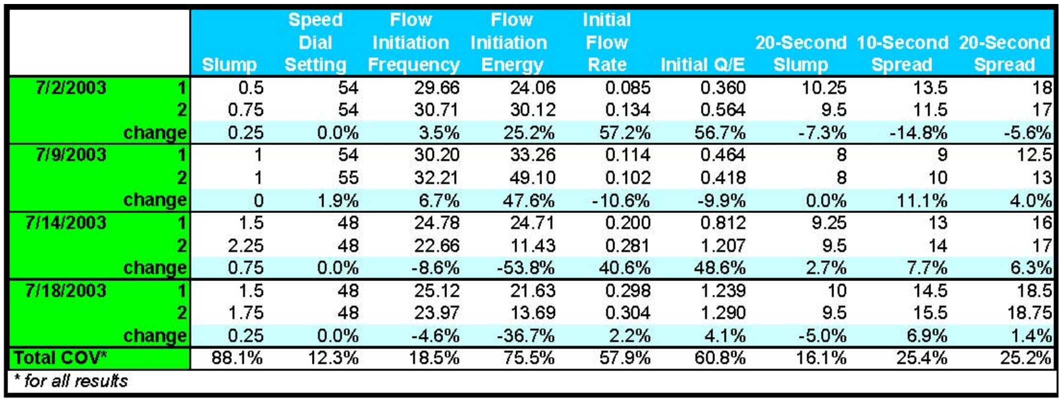
Figure 4.18 Initial Flow Rate versus Coarse Aggregate Fraction

4.6.7 VSA Parameters for Repeated Mixtures

It was previously noted that the control mixture was repeated as Mixture 8 in order to determine the degree of uniformity between mixtures. Slump measurements and speed-dial settings were close to or the same for all four repeated control mixtures (Table 4-2). This pattern, however, is not true for the other variables measured: flow initiation energy, initial flow rate or initial Q/E ratio. In fact, these three variables all have half of their measurements differing by at least 40%.

The variance of these measurements is disturbing after having reviewed other results that indicated a sound procedure. Some inconsistency was to be expected due to the nature of precise measurements being taken from an apparatus never intended for this purpose.

Table 4.2 Comparison of VSA Measurement Repeatability between Control Mixtures



		Slump	Speed Dial Setting	Flow Initiation Frequency	Flow Initiation Energy	Initial Flow Rate	Initial Q/E	20-Second Slump	10-Second Spread	20-Second Spread
7/2/2003	1	0.5	54	29.66	24.06	0.085	0.360	10.25	13.5	18
	2	0.75	54	30.71	30.12	0.134	0.564	9.5	11.5	17
	change	0.25	0.0%	3.5%	25.2%	57.2%	56.7%	-7.3%	-14.8%	-5.6%
7/9/2003	1	1	54	30.20	33.26	0.114	0.464	8	9	12.5
	2	1	55	32.21	49.10	0.102	0.418	8	10	13
	change	0	1.9%	6.7%	47.6%	-10.6%	-9.9%	0.0%	11.1%	4.0%
7/14/2003	1	1.5	48	24.78	24.71	0.200	0.812	9.25	13	16
	2	2.25	48	22.66	11.43	0.281	1.207	9.5	14	17
	change	0.75	0.0%	-8.6%	-53.8%	40.6%	48.6%	2.7%	7.7%	6.3%
7/18/2003	1	1.5	48	25.12	21.63	0.298	1.239	10	14.5	18.5
	2	1.75	48	23.97	13.69	0.304	1.290	9.5	15.5	18.75
	change	0.25	0.0%	-4.6%	-36.7%	2.2%	4.1%	-5.0%	6.9%	1.4%
Total COV*		88.1%	12.3%	18.5%	75.5%	57.9%	60.8%	16.1%	25.4%	25.2%

** for all results*

4.7 CONCLUSIONS

This report addresses modifications made to the VSA, developed by the Army Corps of Engineers for the FHWA, for measuring the workability of concrete. The three problems identified were remedied and an intensive testing regimen was used to test the effectiveness of the modified VSA to qualify and distinguish between mixtures of similar workability properly.

By replacing chute angle with energy measured from the vibrator mounted to the base of the chute, two of the problems, test time and the possibility of an inverse relationship between flow and chute angle, were removed from the test procedure. However, by instrumenting the chute to qualify the vibration being imparted to the concrete sample, a new problem became apparent. The problem was that the VSA chute moved in all three axes, instead of the vertical axis as expected. This was remedied by using the resultant, measured from the two dominant axes.

Replacement of the vertical chute gate with a wedge solved the third problem. Inspection of the flow data versus time and visual observations verified that this modification was successful.

A multitude of mixtures, using chemical admixtures, SCMs and varying coarse-to-fine aggregate combinations, were designed, mixed and tested in order to develop relationships between workability and modified VSA test results. The results of the test were compared to slump cone measurements. These comparisons successfully showed a degree of correlation between the two test procedures. However, this correlation seemed to be limited to slump measurements of three inches and less. It is thought that this upper limit appears due to the tendency of concrete to behave like a fluid, instead of at these consistencies and higher. It was helpful that a relationship appeared between the two tests and that discrepancies seemed to be explained by the ability of the modified VSA to distinguish between mixtures of similar workability. However, issues arose for the validity of the flow initiation energy as an effective measure of yield strength.

Results from the flow initiation energy did not strongly indicate that the test was capable of following historical trends. Different sets of data showed either an increase where a decrease was expected or a decrease where an increase was expected. Attempts to explain these discrepancies were made by calculating the quality of energy needed per unit of weight but these attempts were also unsuccessful. On the other hand, all but one result followed the expected trends for flow rate.

Overall, the theory of qualifying the amount of energy imparted to a concrete sample and measuring the flow that results seems strong for qualifying the workability of concrete. Modification of the VSA to test this theory gave mixed results, some of which can be explained and others that cannot. The original intent of modifying the test was that a method suitable for testing workability in the field would result. However, after completing the initial testing it seems apparent that the test device, in present form, is not appropriate for precise measurements. Attempts could be made to modify the existing VSA or a new device could be constructed to be used for more precise measurement; however, in doing so the possibility of making the VSA field compatible further diminishes.

4.8 RECOMMENDATIONS FOR FURTHER DEVELOPMENT

With evidence supporting the theory behind this work there seems logical reason to pursue further examination. Any portion of the testing procedure could be selected for further development. The following modifications to the procedure are suggested:

- More testing could be completed using different chute angles. The relationships between test results diminished above slumps of 2.5 to 3 inches. Perhaps lowering the chute angle to reduce the shear stress from gravity would return better results over this area of consistency.

- As previously mentioned the VSA could be refined to allow displacement in only one axis. This may limit the use of the test to laboratory purposes only, but would prove that energy and flow rates could be used to qualify concrete workability.
- Another modification that has been made and is currently being tested is reducing the weight of the chute. It is believe that more accurate results could be gained by using an aluminum chute that weighs significantly less than the existing chute because more energy would be available to move the concrete instead of the heavy steel chute.

There are other modifications that could be made to this testing procedure or device.

CHAPTER 5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY

The purpose of the ICAR 105 project was to identify or develop a new test method suitable for testing high-microfine concrete in a field environment. Recent work to qualify concrete workability has focused on the use of rheology. Research suggests that plastic concrete closely conforms to characteristics of a Bingham fluid that can be qualified by yield stress and plastic viscosity. Several concrete rheometers have been developed to measure yield stress and plastic viscosity of concrete. However, because concrete is a complicated suspension of aggregate in cement paste, operation of concrete rheometers is difficult, making them unsuitable for use in the field.

A prototype device, the Vibrating Slope Apparatus, was obtained for evaluation from FHWA in December 2002. Evaluation objectives were developed and a work schedule was formatted. Twenty-six mixtures were prepared and tested with the VSA. Upon completion of the initial testing, conclusions were drawn. Based upon these conclusions and input gained at the ICAR Workability Workshop, held in Cleveland, Ohio, in May, 2003, an accelerometer was mounted to the base of the VSA chute to record vibration properties during testing. A new wedged chute gate was also constructed. The initial VSA test procedure was modified to incorporate the changes and lessen the time required to complete a test. VSA re-evaluation consisted of testing 64 different concrete mixtures. Five groups of twelve mixtures were prepared consecutively and tested to lessen the effect of differential moisture contents between batches. The results of the second series of tests were evaluated and conclusions are presented in the next section.

5.2 CONCLUSIONS

The results of the data obtained from initial and re-evaluation of the VSA show that the VSA can be classified as a multiple-point test. It was able to differentiate between mixtures of similar workability; a single-point test, the slump cone, was not.

5.2.1 Initial Evaluation

Findings from the initial evaluation include:

- The VSA is capable of differentiating between mixtures of similar workability where a single-point test is not.
- Results of the test program indicate that the VSA is capable of characterizing established trends between control mixtures and those modified by admixtures and SCMs.

Although the conclusions seem to indicate that the original VSA procedure is suitable for qualifying the workability of concrete, other aspects of the test lessen its probability of successful implementation in the field. Mounting the VSA on wheels increases its mobility. However, its size and weight limit transportation to and around most construction sites. Accommodations may be made for its size. However, a second drawback is the time required to conduct a test. To obtain a multiple-point test result, the VSA must be run at no fewer than two chute angles requiring a test time of 25 minutes. This time factor led to modifications as part of this study which would produce test results within five minutes. Other drawbacks that were noted include shear failure at the vertical face of the sample when the chute gate is removed and variability of test results when the minimum of two chute angles are tested.

When data from initial evaluation were compiled efforts were made to redefine the method in which a maximum flow rate was selected in hopes of obtaining better results with less scatter. Two methods, Methods A and B, consisted of selecting a single or average flow rate after a determined amount of the concrete had exited the chute. When results obtained from the two methods were compared to Wong's values a fair linear correlation was found. Overall, the new methods increased the correlation between individual chute measurements; the linear relationship shows that the added effort is not justified.

5.2.2 Modified Evaluation

Evaluation of the data from the initial assessment was done in accordance with the developer's recommendations. When the VSA was modified different measurements were taken that required new methods of evaluation. Several different approaches, detailed in Chapter 4, returned similar conclusions. Findings from re-evaluation of the VSA include:

- A fair linear correlation between VSA measurements and those of the slump cone for mixtures whose slump was three inches or less.
- The VSA is capable of differentiating between mixtures of similar workability where a single-point test is not.
- Together, most measurements increased or decreased as expected when chemical admixtures or SCMs were used to modify the workability of control mixtures.

The decision to instrument the VSA introduced new problems that had to be solved. Because the VSA was not designed with the intent of being instrumented by an accelerometer, inconsistencies in the vibration measurements had to be accounted for during data reduction. However, the imprecise nature of the equipment remains an issue evidenced by the lack of repeatability between results of identical mixtures.

Overall, the problems identified for correction after the initial evaluation were solved by implementing the discussed changes. The duration of the test was reduced to an acceptable time, the possibility of shear failure at the face of the sample was removed and discrepancies between maximum flow rate and chute angles were eliminated by removing chute angle as a variable. Although the problems identified with the initial test method have been remedied it is still the opinion of the ICAR researchers that because of its size and need for a computer the VSA is not appropriate for implementation to the field at this time.

5.3 RECOMMENDATIONS FOR FURTHER WORK

Recommendations for further development of the VSA were included at the end of Chapter 4. This section is addressed towards the development of workability test devices as a whole. It was noted in this report that the most accepted measurement of workability is experience and judgment. One trend that is evident within the literature pertaining to test devices that have not gained acceptance is a lack of implementation effort. There may be qualification methods more suitable for measuring concrete workability than the slump cone. However, these devices have not become common use because of a lack of effort to bring the device from the laboratory to the field. By overlooking this step researchers are missing out on valuable contributions gained from field workers that may greatly benefit their approach. Valuable qualification data can also be gained from workers that can be fit to qualitative measurements taken by the new device, thereby, creating an index for later use.

One increasingly difficult task of developing a workability test device is setting criteria for field compatibility. As technology increases throughout many areas of construction, researchers may error in assuming that advanced methods for qualification of concrete workability are warranted. When new technology is used, developers must be careful not to exceed user friendliness. The VSA requires use of a laptop computer. Even with increasing knowledge of computers, a majority of construction tradesmen have little computer experience. Overall, it should be understood that a device which requires the skill of an engineer to operate will make little progress in this field.

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APPENDIX A

Table A.1 Concrete Aggregate Properties

River Gravel						
		Coarse Aggregate		*Fine Aggregate*		
Coarse		Size, in	% Passing	Sieve #	Size, in	% Passing
SG	2.57	1.25	100.00%	4	0.187	99.13%
ABS	0.82	1.00	94.76%	8	0.093	87.66%
UW	101.9 lb/ft^3	0.75	53.14%	16	0.046	67.46%
Sand		0.63	31.47%	30	0.024	41.77%
SG	2.65	0.50	15.51%	50	0.012	14.34%
ABS	0.66	0.38	7.45%	100	0.006	2.99%
		0.19	0.54%	200	0.003	0.62%

Crushed Limestone						
(Capitol Aggregates)		*Coarse Aggregate*		*Fine Aggregate*		
Coarse		Size, in	% Passing	Sieve #	Size, in	% Passing
SG	2.47	1.000	99.76%	4	0.187	100.00%
ABS	5.19	0.750	88.06%	8	0.093	91.28%
UW	90.3 lb/ft^3	0.625	66.30%	16	0.046	62.42%
Sand		0.500	30.41%	30	0.024	40.49%
SG	2.42	0.375	6.06%	50	0.012	20.13%
ABS	5.99	0.187	1.73%	100	0.006	7.38%
FM	2.78			200	0.003	4.03%

APPENDIX B

Table B.1 Mixture Components and Data for VSA Re-Evaluation.

ICAR 105: Measuring the Workability of High Fines Concrete

Aggregates Key

LS= Limestone
RG= River Gravel
MS= Manufactured Sand (Limestone)
NS= Natural Sand

Notes

(1) based on second order curve, at start of flow
(2) average of first second
(3) Energy using only concrete mass
Energy generated with empty container = 195 mJ
Mass of Chute = 156 lb = 70.76 kg
Mass of UW bucket = 7.94 lb

								Flow Initiation							
Date	**No**	**Mix**	**Coarse Agg**	**Fine Agg**	**Slump**	**Air**	**UW**	**Dial Setting**	**Freq**	**Displ Amp**	**Mass**	**Total Energy**	**Conc (3) Energy**	**Initial Mass**	**Initial Flow Rate (1)**
					in.	*%*	*lb/ft^3*		*Hz*	*mm*	*kg*	*mJ*	*mJ*	*kg*	*kg/s*
7/2/2003	1	Base	LS	MS	0.5	2.2	142.88	54	29.66	0.108	118.783	24.062	9.728	47.900	0.085
	2	WRA	LS	MS	1.5	2.4	142.84	50	28.51	0.108	121.065	22.571	9.379	50.265	0.219
	3	+ H2O	LS	MS	2.5	2	141.96	47	24.67	0.127	126.052	24.394	10.700	55.047	0.263
	4	- H2O	LS	MS	0	2.2	143.48	57	32.62	0.155	119.702	60.071	24.561	48.912	0.036
	5	Fly Ash	LS	MS	2.5	1.9	141.56	47	24.76	0.131	122.026	25.441	10.689	51.072	0.218
	6	Silica Fume	LS	MS	0	1.8	141.40	58	33.66	0.164	120.451	72.539	29.925	49.318	0.068
	7	AEA	LS	MS	1.5	3.5	140.84	48	25.18	0.133	121.889	26.810	11.246	50.880	0.139
	8	Base repea	LS	MS	0.75	2.2	142.68	54	30.71	0.117	118.181	30.120	12.086	47.330	0.134
	9	20% sand	LS	MS	0	2.7	142.84	74	45.89	0.165	116.493	131.873	51.771	45.245	0.080
	10	30% sand	LS	MS	0.75	1.9	142.96	54	31.26	0.130	117.382	38.556	15.314	46.545	0.110
	11	50% sand	LS	MS	0.75	2.1	141.08	49	25.87	0.129	117.654	25.829	10.295	46.897	0.183
	12	60% sand	LS	MS	0.75	2.6	140.24	46	23.80	0.111	114.095	15.674	5.953	43.365	0.159
7/9/2003	1	Base	LS	MS	1	2	143.36	54	30.20	0.126	116.931	33.256	13.132	45.862	0.114
	2	WRA	LS	MS	2	2.2	142.84	48	25.06	0.131	122.759	26.057	11.037	51.981	0.252
	3	+ H2O	LS	MS	4	2	141.28	50	27.34	0.108	122.133	21.083	8.868	51.072	0.273
	4	- H2O	LS	MS	0.25	1.8	144.04	59	34.05	0.168	122.814	79.363	33.638	51.981	0.062
	5	Fly Ash	LS	MS	2.25	1.7	142.76	50	26.94	0.122	125.810	26.870	11.757	54.787	0.226
	6	Silica Fume	LS	MS	0	1.9	142.00	59	34.13	0.165	118.230	74.259	29.815	47.439	0.059
	7	AEA	LS	MS	1.25	4	141.04	54	29.96	0.116	120.244	28.651	11.791	49.277	0.178
	8	Base repea	LS	MS	1	1.9	144.00	55	32.21	0.142	119.187	49.097	19.949	48.137	0.102
	9	20% sand	LS	MS	0	1.3	144.60	64	36.08	0.181	108.449	91.097	31.659	36.967	0.090
	10	30% sand	LS	MS	1.5	1.6	143.16	63	36.10	0.177	114.251	91.839	34.960	43.040	0.133
	11	50% sand	LS	MS	0.25	2	142.92	64	37.21	0.180	112.837	99.792	37.212	42.052	0.046
	12	60% sand	LS	MS	0	2.4	141.68	65	37.96	0.176	114.033	100.314	38.067	43.177	0.083
7/14/2003	1	Base	RG	NS	1.5	1.6	148.64	48	24.78	0.130	120.001	24.709	10.139	49.109	0.200
	2	WRA	RG	NS	2.25	1.7	148.76	47	24.87	0.131	115.951	24.365	9.496	44.771	0.242
	3	+ H2O	RG	NS	2	1.74	148.44	50	26.79	0.123	117.957	25.121	10.052	46.971	0.271
	4	- H2O	RG	NS	1.25	1.6	148.52	52	28.18	0.107	117.300	21.167	8.398	46.359	0.200
	5	Fly Ash	RG	NS	3.5	1.8	148.08	49	25.39	0.130	116.592	24.918	9.795	45.475	0.366
	6	Silica Fume	RG	NS	0.25	2.5	145.52	57	33.45	0.148	113.302	54.848	20.594	42.486	0.088
	7	AEA	RG	NS	2	5	143.48	49	25.84	0.135	116.173	27.841	10.883	45.273	0.293
	8	Base repea	RG	NS	2.25	1.4	147.56	48	22.66	0.098	117.628	11.427	4.553	46.841	0.281
	9	20% sand	RG	NS	0.5	1.1	148.68	60	35.22	0.168	113.360	78.555	29.520	41.698	0.170
	10	30% sand	RG	NS	1.5	1.3	148.52	56	23.16	0.107	116.516	13.998	5.497	45.642	0.176
	11	50% sand	RG	NS	0.5	2.4	147.20	50	25.33	0.133	115.007	25.803	9.927	44.230	0.122
	12	60% sand	RG	NS	0	3.8	145.64	46	31.76	0.138	112.976	42.900	16.030	42.040	0.086
7/18/2003	1	Base	RG	NS	1.5	1.7	148.24	48	25.12	0.119	121.988	21.632	9.084	51.110	0.298
	2	WRA	RG	NS	3.5	1.8	148.84	44	21.49	0.118	114.909	14.643	5.626	43.963	0.443
	3	+ H2O	RG	NS	3	1.5	148.60	46	23.48	0.104	115.327	13.454	5.199	44.256	0.372
	4	- H2O	RG	NS	0.25	1.8	149.40	54	28.26	0.124	114.949	27.846	10.705	43.914	0.095
	5	Fly Ash	RG	NS	3.75	1.2	148.24	45	22.84	0.112	117.634	15.299	6.096	46.772	0.466
	6	Silica Fume	RG	NS	0.25	1.9	148.44	52	25.97	0.127	114.628	24.729	9.464	43.795	0.095
	7	AEA	RG	NS	2.5	6	142.96	52	28.46	0.116	113.096	24.378	9.126	42.052	0.395
	8	Base repea	RG	NS	1.75	1.8	148.72	48	23.97	0.101	118.494	13.687	5.514	47.530	0.304
	9	20% sand	RG	NS	1.5	1.6	151.20	53	28.39	0.116	116.473	25.156	9.873	45.690	0.277
	10	30% sand	RG	NS	4.5	0.8	149.76	49	24.56	0.106	119.401	16.057	6.541	48.474	0.351
	11	50% sand	RG	NS	0.5	2.2	147.84	54	30.14	0.103	111.953	21.425	7.883	41.097	0.183
	12	60% sand	RG	NS	0	2.9	145.92	68	42.89	0.167	112.267	113.309	41.892	41.431	0.086
7/23/2003	1	Base	RG	NS	4.5	1.2	148.56	45	22.81	0.100	116.632	11.952	4.701	45.642	0.448
(7/14+H2O)	2	WRA	RG	NS	8	1.2	149.08	42	20.80	0.104	119.362	10.934	4.452	48.323	0.520
	3	+H20	RG	NS	8	0.8	149.16	42	20.56	0.115	120.834	13.281	5.504	49.946	0.766
	4	Fly Ash	RG	NS	8	0.7	149.24	43	20.41	0.116	119.740	13.223	5.409	39.138	0.585
	5	Silica Fume	RG	NS	2.5	1.3	148.36	47	23.53	0.115	115.980	16.742	6.528	45.092	0.297
	6	AEA	RG	NS	6.25	9	137.28	45	21.41	0.104	117.049	11.487	4.543	46.294	0.877
(7/2+H2O)	7	Base	LS	MS	4.25	2.3	142.00	45	21.73	0.103	124.251	12.394	5.336	53.180	0.345
	8	WRA	LS	MS	8.25	1.7	141.96	42	20.67	0.111	118.136	12.312	4.937	46.408	0.704
	9	+H20	LS	MS	7.75	1.4	142.08	41	18.43	0.124	117.375	12.135	4.819	46.329	0.551
	10	Fly Ash	LS	MS	7	1.5	141.20	46	24.57	0.115	116.436	18.300	7.179	45.421	0.528
	11	Silica Fume	LS	MS	3	1.9	141.40	45	21.38	0.098	116.239	10.077	3.943	45.133	0.269
	12	AEA	LS	MS	7.25	10	131.92	43	20.27	0.105	113.214	10.068	3.775	42.040	0.447

Table B.2 Mixture Components and Data for VSA Re-Evaluation.

ICAR 105: Measuring the Workability of High Fines Concrete

Aggregates Key
LS= Limestone
RG= River Gravel
MS= Manufactured Sand (Limestone)
NS= Natural Sand

Notes
(1) based on second order curve, at start of flow
(2) average of first second
(3) Energy using only concrete mass
Energy generated with empty container = 195 mJ
Mass of Chute = 156 lb = 70.76 kg
Mass of UW bucket = 7.94 lb

												Mixture Proportions, SSD (lb/yd^3)								Mixture Indices		
Date	No	Mix	Coarse Agg	Fine Agg	4-sec Slump	4-sec Slump Slope	4-sec Slope/ Ini Slmp	4-sec Slope/ 4Slump	20-sec Slump	10-sec Spread	20-sec Spread	Coarse Agg	Fine Agg	PC	Free Water	Fly Ash	Silica Fume	AEA	WRA	w/c	CA/ (CA+FA)	Mortar Factor
					in.				in.	in.	in.							oz/cwt	oz/cwt			
7/2/2003	1	Base	LS	MS	4.25	0.94	1.88	0.22	10.25	13.50	18.00	1719.8	1194.1	636.8	274.2	0	0	0	0	0.43	0.59	0.84
	2	WRA	LS	MS	6.00	1.13	0.75	0.19	11.25	18.00		1719.8	1194.1	636.8	274.2	0	0	0	3	0.43	0.59	0.84
	3	+ H20	LS	MS	7.75	1.31	0.53	0.17	11.00	19.50	23.50	1694.3	1176.4	627.4	295.1	0	0	0	0	0.47	0.59	0.86
	4	- H20	LS	MS	2.50	0.63		0.25	8.00	10.50	14.50	1747.2	1213.1	647.0	251.7	0	0	0	0	0.39	0.59	0.81
	5	Fly Ash	LS	MS	8.00	1.38	0.55	0.17	10.75	18.50	24.00	1707.8	1185.7	505.9	272.3	126.5	0	0	0	0.43	0.59	0.84
	6	Silica Fum	LS	MS	3.00	0.75		0.25	9.25	10.50	13.50	1712.5	1189.0	583.4	273.1	0	50.7	0	0	0.43	0.59	0.84
	7	AEA	LS	MS	5.75	1.06	0.71	0.18	10.75	17.50	22.50	1719.8	1194.1	636.8	274.2	0	0	1.5	0	0.43	0.59	0.84
	8	Base repea	LS	MS	4.00	0.81	1.08	0.20	9.50	11.50	17.00	1719.8	1194.1	636.8	274.2	0	0	0	0	0.43	0.59	0.84
	9	20% sand	LS	MS	8.00	2.00		0.25	10.00	17.00	19.00	2334.4	583.5	636.5	274.8	0	0	0	0	0.43	0.80	0.46
	10	30% sand	LS	MS	4.75	1.00	1.33	0.21	9.75	14.50	18.50	2041.8	875.0	636.7	274.1	0	0	0	0	0.43	0.70	0.61
	11	50% sand	LS	MS	4.75	1.00	1.33	0.21	10.00	14.00	18.50	1456.3	1456.3	636.5	274.1	0	0	0	0	0.43	0.50	1.09
	12	60% sand	LS	MS	5.00	1.06	1.42	0.21	10.25	14.00	20.50	1166.3	1743.7	636.6	274.1	0	0	0	0	0.43	0.40	1.51
7/9/2003	1	Base	LS	MS	3.00	0.50	0.50	0.17	8.00	9.00	12.50	1818.4	1204.4	549.9	257.5	0	0	0	0	0.47	0.60	0.76
	2	WRA	LS	MS	5.00	0.75	0.38	0.15	9.50	13.00	18.00	1818.4	1204.4	549.9	257.5	0	0	0	3	0.47	0.60	0.76
	3	+ H20	LS	MS	7.00	0.75	0.19	0.11	9.75	16.50	19.25	1788.3	1184.5	540.8	281.1	0	0	0	0	0.52	0.60	0.78
	4	- H20	LS	MS	1.75	0.38	1.50	0.21	6.00	9.00	10.00	1832.9	1214.0	554.3	246.2	0	0	0	0	0.44	0.60	0.75
	5	Fly Ash	LS	MS	5.25	0.75	0.33	0.14	9.00	12.00	16.00	1807.5	1197.2	437.3	256.0	109.3	0	0	0	0.47	0.60	0.77
	6	Silica Fum	LS	MS	1.75	0.44		0.25	6.25	8.00	10.00	1811.8	1200.0	504.1	256.6	0	43.8	0	0	0.47	0.60	0.76
	7	AEA	LS	MS	3.50	0.56	0.45	0.16	8.25	10.50	14.00	1818.4	1204.4	549.9	257.5	0	0	2	0	0.47	0.60	0.76
	8	Base repea	LS	MS	3.50	0.63	0.63	0.18	8.00	10.00	13.00	1818.4	1204.4	549.9	257.5	0	0	0	0	0.47	0.60	0.76
	9	20% sand	LS	MS	2.75	0.69		0.25	8.25	12.00	14.00	2422.2	605.5	549.9	257.5	0	0	0	0	0.47	0.80	0.43
	10	30% sand	LS	MS	5.00	0.88	0.58	0.18	9.00	16.00	17.50	2117.7	907.7	549.9	257.5	0	0	0	0	0.47	0.70	0.57
	11	50% sand	LS	MS	1.50	0.31	1.25	0.21	6.00	8.50	10.00	1504.0	1513.9	551.2	258.1	0	0	0	0	0.47	0.50	1.04
	12	60% sand	LS	MS	1.50	0.38		0.25		8.00	8.00	1207.3	1810.9	549.8	257.5	0	0	0	0	0.47	0.40	1.44
7/14/2003	1	Base	RG	NS	5.50	1.00	0.67	0.18	9.25	13.00	16.00	1919.5	1184.6	628.8	261.6	0	0	0	0	0.42	0.62	0.81
	2	WRA	RG	NS	6.50	1.06	0.47	0.16	9.75	13.50	16.25	1919.5	1184.6	628.8	261.6	0	0	0	3	0.42	0.62	0.81
	3	+ H20	RG	NS	5.75	0.94	0.47	0.16	9.50	12.50	16.50	1909.5	1178.4	625.5	269.2	0	0	0	0	0.43	0.62	0.82
	4	- H20	RG	NS	4.25	0.75	0.60	0.18	8.75	12.00	15.00	1930.0	1191.1	632.2	253.9	0	0	0	0	0.40	0.62	0.80
	5	Fly Ash	RG	NS	7.75	1.06	0.30	0.14	10.00	14.50	19.50	1907.0	1176.9	499.7	259.9	124.9	0	0	0	0.42	0.62	0.82
	6	Silica Fum	RG	NS	2.00	0.44	1.75	0.22	6.00	10.00	11.00	1912.2	1180.1	576.3	260.6	0	50.1	0	0	0.42	0.62	0.82
	7	AEA	RG	NS	5.50	0.88	0.44	0.16	10.25	13.50	10.00	1919.5	1184.6	628.8	261.6	0	0	2	0	0.42	0.62	0.81
	8	Base repea	RG	NS	6.00	0.94	0.42	0.16	9.50	14.00	17.00	1919.5	1184.6	628.8	261.6	0	0	0	0	0.42	0.62	0.81
	9	20% sand	RG	NS			0.00				20.00	2492.1	623.0	628.8	261.6	0	0	0	0	0.42	0.80	0.48
	10	30% sand	RG	NS	4.00	0.63	0.42	0.16	8.50	11.00	15.25	2176.3	932.7	628.8	261.6	0	0	0	0	0.42	0.70	0.64
	11	50% sand	RG	NS	3.00	0.63	1.25	0.21	7.25	9.50	11.50	1548.5	1548.5	628.8	261.6	0	0	0	0	0.42	0.50	1.16
	12	60% sand	RG	NS	1.75	0.44		0.25				1236.4	1854.6	628.8	261.6	0	0	0	0	0.42	0.40	1.61
7/18/2003	1	Base	RG	NS	5.50	1.00	0.67	0.18	10.00	14.50	18.50	1843.7	1327.3	550.0	260.0	0	0	0	0	0.47	0.58	0.87
	2	WRA	RG	NS	8.50	1.25	0.36	0.15	11.00	20.00	22.75	1843.7	1327.3	550.0	260.0	0	0	0	3	0.47	0.58	0.87
	3	+ H20	RG	NS	7.75	1.19	0.40	0.15	10.00	16.75	20.50	1829.1	1316.8	545.7	271.3	0	0	0	0	0.50	0.58	0.88
	4	- H20	RG	NS	3.00	0.69	2.75	0.23	7.50	10.00	12.50	1853.6	1334.5	553.0	252.4	0	0	0	0	0.46	0.58	0.86
	5	Fly Ash	RG	NS	7.75	1.00	0.27	0.13	10.25	16.75	20.50	1833.1	1319.7	437.5	258.5	109.4	0	0	0	0.47	0.58	0.88
	6	Silica Fum	RG	NS	2.50	0.56	2.25	0.23	6.25	9.50	11.50	1837.4	1322.8	504.3	259.1	0	43.85	0	0	0.47	0.58	0.88
	7	AEA	RG	NS	7.25	1.19	0.48	0.16	11.00	16.00	20.00	1843.7	1327.3	550.0	260.0	0	0	2	0	0.47	0.58	0.87
	8	Base repea	RG	NS	6.25	1.13	0.64	0.18	9.50	15.50	18.75	1843.7	1327.3	550.0	260.0	0	0	0	0	0.47	0.58	0.87
	9	20% sand	RG	NS	8.00	1.63	1.08	0.20	10.00	19.00	21.00	2547.6	636.9	550.0	260.0	0	0	0	0	0.47	0.80	0.46
	10	30% sand	RG	NS	7.75	0.81	0.18	0.10	9.50	18.50	21.25	2224.8	953.5	550.0	260.0	0	0	0	0	0.47	0.70	0.61
	11	50% sand	RG	NS	2.50	0.50	1.00	0.20	7.50	10.00	12.50	1583.0	1583.0	550.0	260.0	0	0	0	0	0.47	0.50	1.12
	12	60% sand	RG	NS	2.00	0.50		0.25				1264.0	1895.9	550.0	260.0	0	0	0	0	0.47	0.40	1.56
7/23/2003	1	Base	RG	NS	8.00	0.88	0.19	0.11	10.50	17.75	21.25	1879.5	1159.9	615.7	291.4	0	0	0	0	0.47	0.62	0.84
(7/14+H2O)	2	WRA	RG	NS	9.75	0.44	0.05	0.04	10.75	20.75	23.25	1879.5	1159.9	615.7	291.4	0	0	0	3	0.47	0.62	0.84
	3	+H20	RG	NS	9.50	0.38	0.05	0.04	11.25	21.50	25.00	1845.8	1139.1	604.6	316.4	0	0	0	0	0.52	0.62	0.87
	4	Fly Ash	RG	NS	10.00	0.50	0.06	0.05	11.25	21.50	23.50	1866.8	1152.1	489.2	289.4	122.3	0	0	0	0.47	0.62	0.85
	5	Silica Fum	RG	NS	6.75	1.06	0.43	0.16	10.00	14.50	17.75	1872.4	1155.5	564.3	290.3	0	49.1	0	0	0.47	0.62	0.85
	6	AEA	RG	NS	10.00	0.94	0.15	0.09	11.25	20.50	23.00	1879.5	1159.9	615.7	291.4	0	0	2	0	0.47	0.62	0.84
(7/2+H2O)	7	Base	LS	MS	8.00	0.94	0.22	0.12	10.00	17.00	21.00	1655.6	1149.5	613.1	326.4	0	0	0	0	0.53	0.59	0.89
	8	WRA	LS	MS	9.50	0.31	0.04	0.03	10.25	21.50	24.50	1655.6	1149.5	613.1	326.4	0	0	0	3	0.53	0.59	0.89
	9	+H20	LS	MS	9.25	0.38	0.05	0.04	10.50	21.50	24.50	1631.5	1132.8	604.1	345.2	0	0	0	0	0.57	0.59	0.91
	10	Fly Ash	LS	MS	9.00	0.50	0.07	0.06	10.50	19.50	22.50	1644.0	1141.5	487.0	324.1	121.8	0	0	0	0.53	0.59	0.90
	11	Silica Fum	LS	MS	7.00	1.00	0.33	0.14	10.00	16.00	19.50	1648.4	1144.5	561.6	324.9	0	49	0	0	0.53	0.59	0.90
	12	AEA	LS	MS	10.25	0.75	0.10	0.07	11.00	20.00	23.00	1655.6	1149.5	613.1	326.4	0	0	3	0	0.53	0.59	0.89