

# Portland-Cement Concrete Rheology and Workability: Final Report

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## **FOREWORD**

This report was prepared at the U.S. Army Engineer Research and Development Center (ERDC) for the Federal Highway Administration under Funding Document DTFH61-96-Y-30076. The objective of the project undertaken by ERDC was to develop and validate a simple, practical test for determining the workability of freshly mixed concrete. This report covers the collection of information on existing test methods for which the procedures are standardized, techniques or approaches for which certain technologies can be employed that were possible candidates for inclusion into the workability test program, information on factors influencing the workability of freshly mixed concrete, selection of possible candidate procedures, and the test and verification of the selected procedures. This report was prepared to provide information to the sponsor on work accomplished during the period of the program. The ERDC Team performed a literature search and evaluated methods for determining the rheological properties of freshly mixed portland-cement concrete. Different techniques have been evaluated and four candidate methods and two types of commercial-off-the-shelf (COTS) pieces of equipment have been nominated for further development and evaluation. The evaluation and development of a procedure to measure the workability of freshly mixed low-slump concrete is described in this report. We were unable to develop a test method that covered the full range of concrete mixtures, including high performance concrete (HPC). The method developed is suitable to determine rheological properties of low-slump concrete.

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16. Abstract Methods for determining the workability of freshly mixed portland-cement concrete with slumps less than 51 mm (2 in) were investigated. Four potential methods to determine the workability of concrete were proposed for evaluation and development. The methods included two moving-object methods, one free-orifice method, and a vibrating-slope method. The report outlines modifications to these existing techniques and equipment to permit the measurement of rheological properties at two or more shear rates. The vibrating-slope apparatus (VSA) was selected for further development. (Questions about this report should be addressed to Dr. Paul F. Mlakar, Sr., Chief, Concrete and Materials Division, or Mr. G. Sam Wong, Research Geologist, ERDC, Structures Laboratory.)			
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## SI\* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>								
in	inches	25.4	millimeters	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	kilometers	0.621	miles	mi
<b>AREA</b>								
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ac	acres	0.405	hectares	ha	hectares	2.47	acres	ac
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>								
fl oz	fluid ounces	29.57	milliliters	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	liters	0.264	gallons	gal
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
NOTE: Volumes greater than 1000 l shall be shown in m <sup>3</sup> .								
<b>MASS</b>								
oz	ounces	28.35	grams	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact)</b>								
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
<b>ILLUMINATION</b>								
fc	foot-candles	10.76	lux	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candelas/m <sup>2</sup>	cd/m <sup>2</sup>	candelas/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>								
lbf	poundforce	4.45	newtons	N	newtons	0.225	poundforce	lbf
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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## CHAPTER 1: INTRODUCTION

The ease with which portland-cement concrete is mixed, transported, placed, and compacted is extremely important in executing successful concrete construction. Slump (American Society for Testing Materials (ASTM) C 143) (ASTM 1994c) and correlates of slump traditionally have been the measures of the flow properties (rheology) of freshly mixed portland-cement concrete. Slump is deficient in that it does not represent the full range of workability properties. Research in recent years has sought to develop or improve other measurements of fresh concrete properties to improve on this condition. Progress has been made in many laboratory tests and approaches. However, as yet, there is no test method that will allow this progress to be applied routinely in field practice. The purpose of this project was to develop and verify such a method. Since the advent of high-performance concrete (HPC), mixtures contain a variety of admixtures that alter the properties of traditional portland-cement concrete. The initial research objective was to develop a procedure that encompasses the full range of rheological properties encountered in the various concrete mixtures needed in a highway construction project. However, it became evident early on that, because of the drastically different properties of low- and high-slump concretes, a single procedure would not be sufficient. Therefore, this project concentrated on determining methods that could be used to estimate the properties of low-slump pavement concretes.

The first step taken by the research team in pursuit of a field-usable approach to measuring concrete workability was to gather information on factors affecting concrete workability and on test methods and equipment that have existed, been described in the past, or are currently in use. Criteria were developed, and methods were screened with regard to their potential for being promoted into use in the field and how well they reflect current knowledge of concrete workability principles. A few small candidate methods were chosen from this screening and reviewed for current applicability and for projected or probable modifications. A plan was written from which prototype instrument and test protocols were developed. All of these steps were completed and are described in this final report.

This work modified an existing concept adapting current technology to develop equipment and procedures used to determine the workability of low slump plastic concrete.

### Task A. Collect Current Information

1. Form a technical advisory panel consisting of representatives of State Highway Agencies (SHAs) and the concrete industry. The purpose of this panel will be to provide input to the contractor on current tests and the practicality and useability of any tests and techniques considered during the study, as well as provide suggestions for possible projects for the field testing portion of the study.
2. Conduct an information search to collect available information on:
  - a. Factors influencing the workability of plastic concrete and how these factors influence workability.

- b. Tests and potential techniques for measuring workability which reveal the influence on workability of the factors which are sensitive to changes in materials and mix design as these changes influence workability.
3. Synthesize the available information on each of the areas and develop recommendations for those tests and techniques for measuring workability. The recommendations shall be based on a number of considerations, including:
  - a. Practicality
  - b. Costs, including initial equipment costs and cost per test
  - c. Ability to predict workability for a variety of concrete mixes, including the factors discussed in A.1.
  - d. User-friendliness/simplicity
  - e. Ruggedness of the proposed equipment
4. Prepare an interim report documenting the results of the information search and presenting and discussing the tests and techniques considered.
5. Revise the interim report in accordance with comments received from the COTR. Make final selection of the approaches to be evaluated in the laboratory evaluation.

#### Task B. Evaluation of Candidate Approaches to Measure Workability

1. Conduct any modification and development work required for the approaches selected in A.5, so that all candidate approaches are sufficiently developed to conduct the evaluations.
2. Evaluate the selected approaches.
3. After evaluating the selected approaches hold a meeting of the Advisory Panel and the COTR to present the findings of the laboratory evaluation, including the rationale for the selection of the approach recommended to measure workability.

#### Task C. Preparation of the Final Report

1. Prepare an annotated outline of the final report and submit five copies to the COTR and one copy to the CO for review. Solicit review comments on this outline from the advisory panel.
2. Prepare a draft final report based on the annotated outline and detailing the work carried

out, and including the interim report. The draft final report shall include a discussion of the conclusions and recommendations derived from the performance of the contract.

Accompanying the draft final report shall be a set of slides and narrative to be used in presentations to transfer the results of this study to the industry and field practitioners. This technology transfer package shall convey the steps involved in the conduct of the workability test and the benefits to be derived from using the test.

3. Revise the draft final report, technical summary and technology transfer package in accordance with comments received from the COTR and resubmit for approval.

## **CHAPTER 2: INFORMATION SEARCH**

### **OBJECTIVE**

Workability of concrete shares with durability the distinction of being a property that every concrete should have but that cannot be measured directly. That is, there is no direct test method, standard or otherwise, for durability or workability of concrete. Instead, each of these properties is indicated by measurements of other properties that are considered to be correlated somehow to the behavior that must be controlled and that can be quantified by standardized methods.

The objective of this project was to develop a test method for concrete workability that can measure workability directly or is an improved indicator of workability through measurements of correlated properties. Further, this method must be usable in field practice and capable of becoming a standard method. When this project was undertaken, it was unclear whether such a method already existed in another form and needed only to be modified to become widely used in the field, or if it would be necessary to develop a new method, possibly beginning with extensive modification of some older technology. Thus, the first task of this project was a review of historical and current test methods for correlates of workability, an essential step toward the project objective.

### **DEFINITION OF WORKABILITY**

American Concrete Institute (ACI) Standard 116R-90 (ACI 1990b) defines workability as “that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished.” For this study, workability is considered to increase or improve as the ease of placement, consolidation, and finishing of a concrete increase. In common practice, an assumption is made that the standard test for slump of concrete (ASTM C 143) (ASTM 1994c) indicates workability. In fact, it correlates well with one component of workability: the yield stress of the concrete. Plastic viscosity also is an essential component of concrete workability but is not indicated by slump. The standard slump test is a static test and is not a measurement of workability. However, it might be used along with some dynamic test to define the essential components of workability. This possibility was considered in the review phase of the project, described in the following pages.

### **INFORMATION SEARCH APPROACH**

The principal tool used in the literature review was the search of electronic databases. Keywords used in the search were “concrete,” “workability,” and “rheology.” Databases searched are listed in table 1. Other references were identified from a review of monographs on the subject and from other documents available at the U.S. Army Engineer Research and Development Center (ERDC). The complete list of reference sources is provided in the reference and bibliography sections of this report.

Table 1. Databases searched

Database	Positive Result <sup>1</sup>
NTIS	*
EI Compendex	*
Mechanical Engineering Abstracts	
SciSearch	*
Dissertation Abstracts	*
SPIN	*
TRIS	*
GPO Monthly	
Conference Papers Index	
Engineered Materials Abstracts	
Chemical Abstracts	*
LCMARC Books	
Books in Print	
British Books in Print	
<sup>1</sup> Databases were searched in sequence as listed.	
* Asterisk indicates a positive result.	

Patents on equipment and methods to measure concrete workability were identified by searching the U.S. Patent Database using a search program provided by the Center for Networked Information Discovery and Retrieval. This database covers patents issued from 1976 through February 1997. Keywords used in the search were concrete and slump, concrete and rheology, and concrete and workability. Seventeen patents were identified and are listed in appendix A.

A number of books and major reviews that have been published in the last 30 years address the issue of measuring workability in a general way. These issues are addressed by Ferraris (1996), Scanlon (1994), Dewar and Anderson (1992), Banfill (1991), Tattersall (1991), Tattersall and Banfill (1983), and Powers (1968). Symposia on the subject are presented by Bartos (1993b), Dhir (1975), and Bomble et al. (1973).

## **FACTORS INFLUENCING WORKABILITY**

Workability is affected by every component of concrete and essentially every condition under which concrete is made. A list of factors includes the properties and the amount of the cement; grading, shape, angularity and surface texture of fine and coarse aggregates; proportion of aggregates; amount of air entrained; type and amount of pozzolan; types and amounts of chemical admixtures; temperature of the concrete; mixing time and method; and time since water and cement made contact. These factors interact so that changing the proportion of one component to produce a specific characteristic requires that other factors be adjusted to maintain workability. These interactions are discussed extensively in

texts and reviews on the subject (see Scanlon 1994, Bartos 1993a and b, Bartos 1992, Neville and Brooks 1987, and Mindess and Young 1981). Individual factors are discussed in the following text. In most mixture-proportioning procedures, the water content is assumed to be a factor directly related to the consistency of the concrete for a given maximum size of coarse aggregate (Falade 1994, Hobbs 1993, and Popovics 1962). If the water content and the content of cementitious materials are fixed, workability is largely governed by the maximum coarse aggregate size, aggregate shape angularity, texture, and grading. The coarse-aggregate grading that produces the most workable concrete for one water-cement ratio (w/c) may not produce the most workable concrete for another w/c. As a general rule, the higher the w/c, the finer the aggregate grading required to produce appropriate flow without segregation.

Three factors in concrete are involved in determining the consistency of the concrete: water-cement ratio, aggregate-cement ratio, and water content. Only two of the three factors are independent. If the aggregate-cement ratio is reduced, the water content must increase for the w/c to remain constant. The water required to maintain a constant consistency will increase as the w/c is increased or decreased.

The increase in fine aggregate/coarse aggregate ratio generally increases the water content required to produce a given workability. If finer aggregate is substituted in a mixture, the water content typically must be increased to maintain the same workability (Glanville, Collins, and Mathews 1947). Similarly, water content must be increased to maintain workability if angular aggregate is substituted for rounded aggregate. Crushed aggregates having numerous flat or elongated particles will produce less workable concrete that requires a higher mortar content and possibly a higher paste content. Aggregates with high absorption present a special case because, if they are batched with a large unsatisfied absorption, they can remove water from the final concrete mixture and, hence, reduce workability.

The size and shape of particles in the fine aggregate affect the workability. For example, the use of very fine sand requires that more water be added to achieve the workability that a coarser sand would provide. Angular fine aggregate particles interlock and reduce the freedom of movement of particles in the fresh concrete. Using angular fine aggregate (e.g., manufactured sand) increases the amount of fine aggregate that must be used for a given amount of coarse aggregate and generally requires that more water be added to achieve the workability obtained with a rounded sand (Scanlon 1994).

Lowering the cement content of concrete with a given water content typically will lower workability. A high proportion of cement will produce excellent cohesiveness but may be too sticky to be finished conveniently. An increase in cement fineness decreases workability and produces excessive bleeding, especially when the surface area (Blaine) is less than 280 m<sup>2</sup>/kg. A cement with a high fineness will cause a concrete mixture to lose workability more rapidly because of its rapid hydration (U.S. Department of the Interior 1975).

The workability of concrete mixtures commonly is improved by using air-entraining and water-reducing admixtures (Malek and Roy 1992, Cordon 1955). Air entrainment typically increases paste volume and improves the consistency of the concrete while reducing bleeding and segregation. Water-reducing admixtures disperse cement particles and improve workability, increasing the consistency and reducing

segregation (Scanlon 1994, Mehta 1986). Small changes in the amounts of chemical admixtures used in a concrete can profoundly affect workability. Some chemical admixtures interact in adverse ways with some portland cements, resulting in accelerated hydration of the portland cement.

Mineral admixtures or pozzolans are used to improve strength, durability, and workability in concrete (Paya, Monzo, and Gonzalez-Lopez 1996; Punkki, Golaszewski, and Gprv 1996; Krstulovic 1994; Mora, Paya, and Manzo 1993; Bayasi 1992; Ikpong 1992; Naik and Ramme 1990). Freshly mixed concretes are generally more workable when a portion of the cementitious material is fly ash, in part because of the spherical shape of fly ash particles. Smoother mixtures are typically produced if the mineral admixture is substituted for sand rather than cement, but highly reactive or cementitious pozzolans can cause loss of workability through early hydration (Scanlon 1994, Mehta 1986). Very finely divided mineral admixtures, such as silica fume, can have a very strong negative effect on water demand and hence workability, unless high-range water-reducing admixtures are used (Kucharska and Moczko 1994, Male 1993).

Freshly mixed concrete loses workability with time. The reduction in workability is generally attributed to loss of water absorbed into aggregate or by evaporation, or from chemical reaction with the cementitious materials in early hydration reactions. Elevated temperatures increase the rate of water loss in all of the modes mentioned above. The workability of air-entrained concretes is reported to be more easily reduced by elevated temperature than workability in similarly proportioned nonair-entrained concretes (U.S. Department of the Interior 1981).

## **CONSIDERATIONS FOR WORK PLAN**

The factors summarized here were confirmed in many other published studies and in Corps of Engineers experience. They were considered in devising a work plan for the candidate workability approaches, as presented in chapter 6 of this report. In particular, the work plan includes consideration of water content, aggregate size, and one common mineral admixture used in concretes for pavements.

## **TRENDS IN CONCRETE WORKABILITY MEASUREMENTS**

Hydraulic-cement concrete has been used in the United States since the mid-1800's. Apparently, in these early years, it was common practice to proportion concrete with just enough water to allow it to be rammed into place (Powers 1968). No references were found for test methods used to measure this property. Trautwine (1904) described mixture proportioning which resulted in sufficient mortar of appropriate consistency ("just sufficient to make a plastic paste") to fill voids in compacted coarse aggregate and noted "Ramming adds about 50 percent to the strength." The rammers are like those used in street paving world, 152 to 203 mm (6 to 8 in) in diameter, 1.2 m (4 ft) long, shod with iron, weight about 15.9 kg (35 lb), and let fall 152 or 203 mm (6 or 8 in). The earliest published test method found is for the slump-cone method. This was first published by the ASTM in 1922 as ASTM D 138-22T (currently ASTM C 143 (1994c)).



Powers (1932) recognized some of the deficiencies of the slump test and developed the “remolding test.” Unlike the slump test, which is based largely on static forces, the remolding test allows for measuring the dynamic component of workability. Comparative work indicated that the remolding test better represented important features of the workability of air-entrained concrete than did the slump test (Cordon 1955).

Other test methods were developed based on the basic principle of the remolding test. These included the Vebe consistometer (Bahner 1940), the Wigmore consistometer (Wigmore 1948), and the Thaulow tester (Thaulow 1952). The Vebe consistometer was developed into standard test methods by ASTM C 1170 (ASTM 1994h) and by the U.S. Army Corps of Engineers (USACE) (CRD C-53) (U.S. Army Engineer Waterways Experiment Station 1949). The compaction factor test, which is currently a standard test method in British Standard 1881 (BSA 1984, 1993), also includes a dynamic component, but in the configuration of a falling mass of concrete (Mather 1962).

In another approach to developing a technology that would measure the dynamic component of workability, Powers and Wiler (1941) published a description of a coaxial-cylinder rotational viscometer. Concrete was placed between the two cylinders. The outer cylinder was rotated, and the amount of force necessary to prevent the rotation of the inner cylinder was measured. This device was never developed into a standard test apparatus (Powers 1968), but it does represent the first effort to apply a rotational viscometer to concrete.

Other test methods were developed that used vibration as a means of imparting the dynamic component of the test. These include a vibrating slope method (Saucier 1966), and the Angles flow box (Angles 1974). Two recent (1994 and 1995) references were found in the Japanese literature to vibrating flow-type devices (Kurokawa et al. 1994 and 1995). The DIN flow table is a similar device used in Germany.

In spite of the limitations inherent in trying to characterize workability by measuring slump, several devices and test methods have been developed to facilitate the determination of slump by measuring some correlate of that property. These include the Kelly-Ball method, ASTM C 360 (ASTM 1994f) (originally published in 1955), and the K-slump tester (Nasser and Biswas 1996) patented in 1995.

Three patents were found for devices with valves that are regarded as indicative of slump as test results obtained from a ready-mix truck or from data collected during discharge of a ready-mix truck. One such device is a meter that measures the hydraulic pressure required to turn the drum of a ready-mix truck (patent 4,356,723 (1982)). This device apparently is commercially available and in use by some ready-mix operations. Patents 4,332,158 (1982) and 4,578,989 (1986) describe devices that mount in the delivery chute of a ready-mix truck and measure a slump correlate during delivery. Because these devices are correlates of slump, they still do not measure or indicate the dynamic component of workability.

Tattersall and Banfill (1983) analyzed the state of the art for workability of concrete test methods. They classified the technologies into two groups: empirical and rigorously defined. Most of the test methods

existing then were empirical, giving results that were interpretable only in the context of the test method. Consequently, results obtained by different test methods could not be compared. Another deficiency of most empirical tests is that they are single-point tests, i.e., they represent only a single operating condition. Rigorously defined methods are those that give results in fundamental units of measure. Tattersall and Banfill (1983) argue strongly that workability should be measured by rigorously defined methods. The focus of their considerable body of literature is to develop the application of standard rheological principles to the measure of workability of concrete (Tattersall 1982, 1983, 1991; Tattersall and Baker 1989; Tattersall and Bloomer 1979; Tattersall and Banfill 1983; Banfill 1990, 1991, 1994; British Society of Rheology 1991). The approach of Tattersall and Banfill has been to use the Bingham model for fluid flow to represent the rheological behavior of fresh concrete. This is a relatively simple linear mathematical model that relates shear rate and stress applied to fresh concrete. This model is characterized by two constants: the yield stress and the plastic viscosity. Application of this model to concrete rheology is an approximation, but it appears to work reasonably well at relatively low shear rates. The objective of state-of-the-art technology in recent years is to estimate Bingham constants and to correlate changes in these values to changes in concrete workability.

Tattersall developed the “Two-Point Workability Apparatus” (Tattersall 1971) for estimating Bingham constants. This instrument is a large version of the rotational viscometers used to measure the viscosity of Newtonian fluids but modified to accommodate the heterogeneous nature of concrete. It is similar in concept to the instrument designed by Powers and Wiler (1941). The instrument has been revised over the years (Tattersall 1991) and is commercially available. Other forms of rotational viscometers have been developed in recent years for application to concrete and are commercially available.

Other types of viscometers have been investigated but have not received as much research effort as have the rotational viscometers. Therefore, they are relatively unknown in concrete technology.

These include a moving ball viscometer, described by Powers (1968) and a free-orifice viscometer, described by Bartos (1978). In principle, these instruments can also yield estimates of the Bingham constants.

The information search identified a total of 21 methods related to measuring workability. Most of these methods do not actually measure workability, because they measure only the static component or are otherwise limited. Most of them correlate with slump at low shear rates. The key to characterizing workability may be to impart a shear rate high enough that it could be used in combination with another test, and the results of the combination might define both the static and dynamic components of workability.

To organize the discussion, methods are grouped according to how they impart energy to the concrete: by rotation, flow, vibration, penetration, drop, or linear movement. There is some overlap among these groups, and some methods arguably could be in a category different from the one in which they have been placed. Each method is described in the following text.

## **Powers and Wiler Apparatus**

The Powers and Wiler apparatus (Powers and Wiler 1941, Orchard 1979) uses the principle of the Couette or McMichael viscometer (coaxial cylinder). A closed inner drum is suspended in the center of a larger drum containing fresh concrete. The outer drum rotates back and forth through a small preset angle. The torque exerted on the inner drum is measured.

The Powers and Wiler apparatus only measures through small fractions of a revolution because, after shear failure of the fresh concrete, slippage occurs within about 3.175 mm (1/8 in) of the inner drum. This device, called a “plastometer” by Powers, is capable of generating stress-strain curves. However, varying the strain rate produces negligible output changes in the torque readings. Development of this device is said to have stopped around the time of World War II. A coaxial-cylinder viscometer that does not suffer from the slippage problem is better developed in the BML device which is discussed below.

## **Two-Point Workability Device**

The two-point workability device, also known as the Tattersall device, measures the torque required to turn an impeller submerged in a sample container at various speeds. The use of a planetary mixer is said to increase testing capability in the low-slump range. The planetary system also uses a different form of impeller blades (Tattersall 1971, 1983; Tattersall and Bloomer 1979).

## **Ready-Mix Truck Hydraulic Device**

The patented ready-mix truck hydraulic approach (patent 4,356,723 (1982)) allows an operator to monitor the torque required to turn the mixer on a truck. The inventor claims that the required torque can be correlated to the slump of the mixture.

Turning the mixer at different rates would generate varying shear rates in the concrete. The influence of factors such as concrete slippage, density of the mixture, fullness of the truck, and incline of the tank are not addressed in the patent documentation. Additionally, slippage, flow effects from the mixing vanes, and variations in mixer-truck characteristics make the system rheologically complex. Polatty (1949) described a device called “Plastograph,” invented by Glenway Maxon and used by the U.S. Army Corps of Engineers at Allatoona Dam, that measures flow of concrete in the mixer on a meter. According to the Plastograph, 3.9 was a “good dry” 25.4-mm (1-in) slump; 5.3 was a “good” 63.5 mm (2-1/2-in) slump; and 6.1 was a “wet” 107.95-mm (4-1/4-in) slump.

## **Colebrand Tester**

The Colebrand tester is a small portable mechanism similar to a drill that rotates an impeller with two small hemispheres in the concrete under test. The analyzing and control electronics are contained within the device housing. This device is similar in concept to the two-point workability (Tattersall) test. The product literature gives information on slump measurement only. The embedded design of this device

may complicate the modifications that would be needed to make viscosity measurements. It appears that measurement averaging is used to reduce error effects created by relatively large aggregate to sensor size ratios.

### **BML Viscometer**

The BML viscometer (Wallevik 1996) is based on the coaxial-cylinder viscometer. Blades are used instead of smooth cylinders to prevent concrete slippage. Four sets of inner and outer blades allow aggregates of different sizes to be tested. A computer is used to automate control, measurement, and data reduction. The output can be presented in Tattersall or rheological units. This is one of the more developed instruments available for measuring concrete viscosity. The manufacturer's field system is a slightly smaller device mounted to a frame resembling a large wheelbarrow.

### **BTRHEOM Rheometer**

The BTRHEOM rheometer is a rotational viscometer similar to the Tattersall. Instead of bladed impeller, the device rotates a bladed disc. A second bladed disc in the bottom of device also helps prevent concrete slippage. The torque required for rotation is measured. A computer is used to automate control, measurement, and data reduction. A commercial unit is available from France (de Larrard et al. 1993; Hu et al. 1995, 1996; and Hu and de Larrard 1996).

### **Free-Orifice Rheometer**

The free-orifice rheometer (Tattersall and Baker 1989, Bartos 1978) consists of a simple tube that is beveled at the bottom to create a slightly smaller diameter than the rest of the tube. The purpose of the bevel is to force the concrete to flow and not just slide out of the tube. A vibrator is required to sustain movement of a low-slump concrete. The flow rate out of the tube is measured and correlated to the concrete slump.

In its stated form, the free-orifice rheometer operates at only one shear rate. A forcing mechanism, such as a mass on the concrete column, could be used to generate additional shear rates for viscosity determination. Another likely problem with this technique is that different size tubes would be needed for varying aggregate size and concrete slump. The use of vibrators, as required when testing low-slump concrete with this device, distorts the shape of the viscosity curve at low to medium shear rates as well as offsetting the curve across all shear rates.

### **K-slump Tester**

The K-slump tester is composed of a perforated tube and a float-level measuring rod. The perforated tube is inserted into the concrete and paste flows in through the perforations. The amount of paste that flows in is indicated on the float level. This device measures to some degree the static yield of the paste. Test results have shown a high degree of scatter when correlated to slump readings. Because the tube perforations are small, aggregate influence is not assessed by this test. Application is also

limited to high-slump concrete, unless the probe insertion depth is increased significantly. (Scanlon 1994; Nasser and Biswas 1996; and patent 5,437,181 (1995)).

### **Delivery-Chute Torque Meter**

The delivery-chute torque meter (patent 4,332,158 (1982)) is designed to test the concrete as it is being removed from a mixer. Two spring-loaded torque sensors are held in the flowing concrete and measure the resulting torque, which is then correlated to slump. No information was found on measuring viscosity with this device. It should be possible to generate multiple shear rates by changing the incline angle of the chute. Additional difficulties may result from level variations in the chute. A statement was made in the patent that this device compensates for different flow rates. It is not clear how this is being achieved, but it could be an obstacle for viscosity measurement.

### **Delivery-Chute Vane**

The delivery-chute vane (patent 4,578,989 (1986)) is a simple slump-measuring device. Concrete flows down the chute, which is set at a predefined angle. The flow is then stopped, and the vane is inserted into the concrete in the chute. The slump measurement is made from a scale on the side of the vane. There does not appear to be a way to obtain multiple shear rates; therefore, it could be an obstacle for viscosity measurement.

### **Angles Flow Box**

The Angles flow box (Angles 1974, Scanlon 1994) is a box that has two removable partitions in the center. The first partition is simply to hold the fresh concrete on one side of the box until the test is started. The second partition is a grate of cylindrical bars spaced so that the aggregate can flow between them. Testing is performed by vibrating the box on a table vibrator, or possibly with a hand vibrator, and measuring the time it takes for the concrete to level itself on both sides of the box. Details for determining the cylindrical bar size and spacing as well as the details for using a hand vibrator were not included in the description of this device. Test data or technical discussion of this approach were not found during the literature search. No method of generating different shear rates (except perhaps changing the incline angle) is apparent.

### **DIN Flow Table**

The DIN flow table (Scanlon 1994, Mor and Ravina 1986, Orchard 1979, Dimond and Bloomer 1977) technique is similar to many of the remolding techniques. A mass of molded concrete is placed on a hinged drop board or a cam-operated drop table and jolted a specific number of times. The average radius of the reshaped concrete is then measured as an indicator of workability. This technique is applicable only for high-slump concrete. Additionally, it is a single-point measurement and therefore not suited to measuring flow at different shear rates.

### **Vebe (also V-B) Consistometer**

The V-B consistometer (Scanlon 1994, Orchard 1979, Balaguru and Ramakrishnan 1987) is a vibrator-based remolding test. A sample of concrete is molded with the slump cone, inside a larger cylinder. A large clear disc rests on top of the molded concrete. The vibration time required for the slump mold to remold into the larger cylinder is measured. This test is suitable only for dry concrete (50.8-mm (<2-in) slump). While the results of this test are related to viscosity, the relationship is not direct, and multiple shear rates are not easily obtained. The influence of vibration would also distort the viscosity curve if it were obtainable.

### **Remolding Test (Powers)**

The remolding test (Scanlon 1994, Powers 1932, Orchard 1979) developed by Powers is very similar to the V-B consistometer. The primary difference is the use of a drop table instead of an electric vibrator. The number of drops required to remold the slump cone mold into a large-diameter cylinder is the measured quantity. This is a single-point test. The drop table creates an initial high shear rate that decreases quickly to zero. Rheologically, this technique suffers from combining a range of shear rates along with the static yield into the measurement. Ideally, a single constant shear rate is desired either from terminal conditions or control.

### **Thaulow Tester**

The Thaulow tester (Scanlon 1994, Orchard 1979) is very similar to the remolding test and the V-B consistometer. For high-slump concrete, a handle on the container is dropped as the vibration source. For a lower-slump concrete, a drop table is used. This device suffers from the same problems as the other vibration-based remolding methods, and vibration would distort the viscosity curve.

### **Vibrating-Slope Device**

Use of the vibrating-slope device is described by Saucier (1966). A known mass of concrete is placed in an inclined trough on a vibrating table. The vibrating table is switched on, and the time required for half of the concrete to flow into the catch container is measured. The catch container can be placed on a large scale to allow determination of the stop point. While the testing of this technique has focused on slump cone correlation, it may be possible to use different incline angles and produce a series of shear rate measurements suitable for viscosity determination.

### **Wigmore Consistometer**

The Wigmore consistometer (Scanlon 1994, Orchard 1979, Wigmore 1948, Anonymous 1949) consists of a concrete container, a drop table, and a small metal sphere attached to a graduated rod. The sample of concrete is vibrated with the drop table, and the number of drops required for the sphere to fall a specific distance is measured. In its defined state, this is a single-point measurement. It may be possible to use spheres of different mass to produce different maximum shear rates.

## **Kelly Ball**

The Kelly ball is a large, heavy, ball-shaped steel probe that is gently set on the concrete surface. A graduated scale allows the operator to measure how deep the ball settles into the concrete. (See ASTM 1994f, Scanlon 1994, Kelly and Polivka 1955, Howard and Leavitt 1952, and Orchard 1979).

## **Ring Penetration Test**

This method consists of a steel ring that is allowed to sink into fresh concrete under its own mass and the sinking velocity is measured (Kurokawa et al. 1995, Teranishs et al. 1994). When used to measure concrete, masses are added to the apparatus, and the minimum load needed for penetration is closely related to the yield value. The method is applicable to grouts and may be applicable to fluid concretes. It apparently is not applicable to low-slump concretes.

## **Compacting Factor**

The compacting factor test involves dropping concrete through multiple heights and measuring the degree to which it compacts (Scanlon 1994; Orchard 1979; Mather 1962, 1965; Mather and Saucier 1963). The density of the dropped concrete is compared to the density of vibrator-consolidated concrete. This test is a standard test method in BS 1881 (BSA 1984, 1993). This test measures the energy needed to obtain a certain degree of compaction. Results of this test cannot be related to viscosity or yield stress.

## **Moving-Ball Viscometer**

The moving-ball viscometer is based on the classical falling-sphere viscometer. A sealed linear actuator, load cell, and a small vibrator are the primary components. The actuator pushes and/or pulls an object such as a sphere through the concrete, and the load cell measures the resulting terminal forces. The vibrator is used to reconsolidate the concrete for the next run and is briefly used to initiate movement at low force levels. The physics are well defined for this approach and include correction calculations for boundary influences such as sample container. (See Odar 1967; Shepard et al. 1995; Dinsdale and Moore 1962; Gilmont 1964; Powers 1968).

## CHAPTER 3: SELECTION OF CANDIDATE TEST PROCEDURES

### EVALUATION PROCESS

#### Criteria for Selection of Workability Test Methods

The criteria for measuring performance of a workability testing apparatus as listed in Task A.3 of the prospectus are practicality, costs, applicability to wide range of concretes, user-friendliness and simplicity, and ruggedness of the equipment. This section defines these five criteria and discusses many of the questions associated with each criterion. Most of the questions could not be answered from published information during initial screening and will be addressed fully only for the candidate methods chosen for further evaluation as a result of this initial screening. Even though many of the 21 methods measured only one component of workability or were not direct measurement devices, they were included in the initial screening for completeness and because they still might have the potential to be used in combination with another method.

#### Criterion 1: Practicality

Practicality includes measures of how practical the equipment and procedure are, that is, how feasible or possible it is to use the equipment for measuring workability and how well the equipment serves its intended purpose. Some of the issues to be considered when rating practicality of each device are the following:

1. Does the method require that a sample be taken of the concrete? Or can a test be made within a batch or in the form or in the mixer?
2. If a sample of concrete must be taken, how large a sample is required? Does it lead to long sampling delays and wasted concrete?
3. What volume of concrete is needed for test?
4. How long does it take to test the concrete? Does this cause delays in placement, or delays in acceptance decisions for each batch or truck?
5. How quickly is the answer available? If data processing after testing is a lengthy step, such a method may not be practical in the field where acceptance decisions must be made quickly.
6. Is the concrete tested before, during, or after placement? Time of testing may impact the timing and sequence of placement.



7. How portable is the equipment? In situ or rapid testing during paving operations may require that the test equipment move in conjunction with the paving operations or continuously.
8. Does the equipment have special power requirements? Considerations here are availability of 120- or 220-V electrical supplies, field generators, line stabilizers, or other special sources or modifiers.
9. Size, bulk, and mass of the equipment may affect many aspects of testing.
10. Is the concrete tested directly, or is there some special pretreatment requirement? Examples of possible pretreatment are aggregate screening, temperature measurements, or filling some specialty sample container.

## **Criterion 2: Costs**

Any equipment for testing workability will have many associated costs in addition to its initial purchase price. Some of the costs to be considered are as follows:

1. Initial purchase price of equipment.
2. Availability of equipment commercially in the United States. If it is not already available, the costs of modification or equipment development are a factor.
3. Costs associated with promotion of general acceptance and widespread application of the equipment. These may include publication of manuals, training, advertising, or other promotion costs.
4. Actual per-test cost. This may vary widely depending on the practicality considerations (criterion 1), the number of people required to operate the equipment, and most of the factors listed in criterion 2.
5. Frequency of testing required. Does the test regimen defined by use of the equipment follow existing ASTM or other standard guidelines? Or does it require development of new testing guidelines or standard practices?
6. New test methods--exotic or complicated, and cost of training qualified operators.
7. Supplies needed for method or equipment. Are disposable supplies required that must be purchased frequently? Do any required materials have a shelf life, thus imposing new inventories?
8. Calibration or verification of the equipment. What costs are associated with quality assurance?

9. Equipment repair or parts replacement. What spare parts should be stocked, and what delays occur if parts are not available?
10. Need for a back-up system.
11. Value of posttest concrete sample. How much wastage is associated with the required testing?
12. Time delays as a result of testing during paving or placement operations.
13. Impact on placement operations of equipment downtime for verification, service, routine maintenance, or other required delays between tests (cool-down cycle).
14. Peripheral equipment required, in addition to the test equipment itself, for full performance of the method.

### **Criterion 3: Applicability to a Wide Range of Concretes**

The range of aggregate sizes that must be accommodated by the workability device of choice is fairly well defined by the range of aggregates in standard use in U.S. paving operations. For example, the apparatus need not accommodate the boulder-size aggregates of mass concretes. Still, aggregates will range from fine sand sizes up to almost 37.5 mm (1-1/2 in), and will cover all common aggregate shapes. The widespread use of both mineral and chemical admixtures in concrete pavements necessitates that the device must be usable over large ranges of fluidity, harshness, and ultimately, workability. Special considerations for applicability include the following:

1. Can the test be used for rapid-setting concretes? Fast-track paving, rapid-setting repair materials for minimum downtime of roadways, and many other concretes have a working time short enough to pose problems for many potential tests. If the equipment or method selected must be applicable to concretes with very short working times, that will eliminate many options.
2. Can the equipment be used for very stiff (no-slump or very-low-slump) concretes, such as those used in slip-form paving or roller compacting?
3. Is it effective for measuring workability of harsh concretes with highly angular aggregates or finely ground mineral admixtures?
4. Can it handle special aggregates for skid resistance, or unconventional materials such as ground or chipped recycled rubber?

5. Do existing ASTM or other standard testing methods or practices for stiff or harsh concretes apply to testing with this equipment, or must new standard practices be developed?

#### **Criterion 4: User-Friendliness and Simplicity**

Some of these are closely related issues that were considered with criterion 1, Practicality. However, user-friendliness or simplicity centers around the person or people required to conduct the test and produce useful test results:

1. How many people are required to handle the equipment, conduct the test, and produce useful results?
2. Is the equipment portable enough to move easily with paving operations?
3. How frequently and how much time is required for knockdown, packing, transport, unpacking, setup, verification, etc? Relative to an entire paving job, are these times acceptable?
4. Is maintenance and verification truly routine, or are additional specialists required?
5. What is the time delay between testing and output of useful results? Can the equipment provide information rapidly enough to be the basis of acceptance decisions?
6. Is the equipment output immediately useful, or does it require extensive calculation to transfer output data into useful information?
7. Are data acquired directly, or must they be transcribed or entered into software before processing?
8. Does or can the equipment provide directly readable outputs that are useful in the field; that is, does it report in real time?
9. Will operators need computer training or more training than is required for measuring slump?
10. Can the equipment be used readily by multiple operators? Truly user-friendly equipment can generate an answer within specified acceptable tolerances reliably and repeatedly when operated by a standard practice, no matter what trained person is operating it.
11. What is the reuse interval? Does the reset, cool-down, or reinitiate procedure cause a delay and waste operator time?

## **Criterion 5: Ruggedness**

Some considerations for equipment ruggedness affected criterion 4. Here, they apply to the actual physical sampling, testing equipment, and ancillary hardware, rather than to operators or job sequencing:

1. Frequency of parts replacement, spare parts inventory, back-up equipment, support materials with a short shelf life, downtime for repair, cool-down or reset time, calibration and verification requirements all are part of ruggedness.
2. Ease in maintaining the equipment and checking for compliance with equipment specifications such as those in an ASTM Test Method? Calibration and equipment tolerances must not be altered.
3. Special protection required for the equipment for long periods of time and use in field conditions? Special protection may include dust control, temperature control, power-surge control, humidity barriers, or other physical means.
4. Versatility of equipment to continue to function as needed and specified after multiple operators.

As stated previously, not all of these questions could be considered for every method screened. There was no information available on some subjects. Some questions applied to only a few methods. To create a workable matrix for the first evaluation process, based only on published information, these criteria were simplified into more specific requirements.

The practicality factor was simplified into three standards relating to implementation: sample testing, in situ testing, and testing in equipment such as pavers, hoppers, pumps, and mixers. Most of the rated approaches are focused on testing of removed samples. The techniques applicable to in situ testing can typically be applied to sample testing without modification.

The cost factor was broken down into four standards: equipment cost, testing time and labor, maintenance and serviceability, and availability. In many cases, estimates were used based on the complexity of the hardware and test procedure. Maintenance and serviceability were rated based on how likely it seemed that a component might fail, if that component was available off the shelf, and if a technician could make the repair. Some devices were considered to be available if their construction was extremely simple or if they have been standardized somewhere.

Applicability was broken down into three standards: ability to generate multiple shear rates, ability to test a wide variety of concrete mixtures, and rheological simplicity.

A complete workability test should quantify not only the static yield (or slump) but also the dynamic viscous behavior of plastic concrete. Over practical shear rates, concrete behavior is approximated by the Bingham model. An acceptable approach should be capable of producing measurements across or

at different shear rates. This allows quantification of the offset and slope of this linear model. It is beneficial for the approach instruments to test at shear rates approximating real concrete operations. It is also considered beneficial if the shear rate is constant and not transitional, allowing terminal conditions to be measured. Many of the rated workability techniques focused only on slump measurements. When apparent, simple modifications of these techniques were considered, possibly allowing them to generate or test at multiple shear rates.

A simple rheological approach increases that ability of the test method to prove that the desired parameters are being measured. Simple rheology refers to the simplicity of the physics influencing the measurement operation. The coaxial cylinder rheometer is an example of a simple rheological approach. Approaches that incorporate vibrators or drop tables into their measurements are considered more rheologically complex. An approach is also more complex if it combines a transitional range of shear rates and static yield instead of a single shear rate.

User-friendliness and simplicity were restated as automation and simplicity. Typically, a simple device is not very automated, and an automated device is not very simple. This trade-off is a function of the level of development and characteristics of the approach. If an approach was highly automated but not necessarily simple, it received a good rating. If a device was simple and could lend itself well to automation or does not require automation, it also received a good rating.

Ruggedness was broken down into the standards of vulnerable components and sensitivity to elements and handling. Consideration of these categories was based on the number and size of moving parts, vulnerability of these parts to concrete, ability of the equipment to withstand shock, and the effect rain or dust might have on the equipment. Larger devices with computer components received better ratings if the computer could easily be disconnected and removed.

### **Technical Evaluation by Scientists and Engineers**

Each approach was evaluated technically in the aforementioned categories. A rating of good, fair, or poor was given to each. Categories for which information was either not found or not published were noted. Approaches that had a poor rating and some that were rated fair were also rated on the risk of improving the device in that category through additional development and/or modifications.

The 21 candidate methods described in the previous section were evaluated by the 6 scientists and engineers listed as authors of this report. The preliminary screening was a qualitative process, drawing on the extensive research and field experience of this group. The group evaluation process included identifying whether the method measured a static or a dynamic component of workability, and considered the potential for using tests in combination to characterize workability. Thus, no test was eliminated outright on the basis of lacking completeness. Dynamic tests were considered for their potential to be combined with the familiar and standard test for concrete slump to quantify workability. Each of the methods was rated for technical merit as well as the risk of fielding the particular method, using the descriptors shown in table 2.

The following pages provide a brief description of each technique along with some details from the reviewers' comments.

Table 2. Rating descriptors.

Technical	
Good	Meets standard as reviewed or is able to meet standards with minimal modification
Fair	Can be made to meet standard with some modifications
Poor	Cannot be made to meet standard without special emphasis
Risk	
Low	Minimal effort is required to bring product to meet standard
Medium	Major effort is required to meet the standards
High	The standard cannot be met within the funding and time constraints

## EVALUATION SUMMARY AND NOMINATION

Of the 21 approaches that were evaluated, 9 received a rating of good or fair based on only simplified considerations of the 5 performance requirements. The remaining 12 were rated poor and considered of high risk with regard to development for producing meaningful results for this project. Each evaluator brought certain expertise to his evaluation of the methods considered. The evaluators met as a group to discuss their ratings and to collectively rate the methods. This collective rating is summarized in table 3.

Three of the four methods that were rated technically “good” used closely related technologies; that is, they all are rotational viscometers and are complex devices designed for laboratory use as opposed to routine field use. The evaluators considered that it was not in the best interest of the project to concentrate all future efforts on these “good” devices, given their similarity, cost, and complexity. Another factor not specifically listed in the screening is that the review group tried to select candidate methods that represented several different technical approaches to measuring workability, rather than to select methods that were different versions of the same technology. The four candidate methods with a fair to good technical rating and medium developmental risk were selected as having promise as fieldable techniques and warranting further testing represent one device each from the flow, moving object, vibration, and rotation type techniques. Thus, they are the best available candidates from several different technologies.

Many of the systems considered are poorly suited to determining workability because they focus solely on the static yield or slump measurements. Some of the reviewed techniques combine a result obtained from transitional shear rates and the yield stress. The drop-table methods and the Kelly ball are

examples of such systems. These techniques are ill suited because the shear rates or the stresses are not steady state and the results are also weighted toward the static yield measurement. Other systems incorporate vibrators to induce flow of stiff concretes.

Table 3. Summary of composite ratings.

No.	Approach	Technical	Risk
1	Powers and Wiler Apparatus	Poor	High
2	Two-Point Workability (Tatersall)	Good	Med
3	Ready-Mix Truck Hydraulic	Fair	High
4	Colebrand	Fair	Med
5	BML Viscometer	Good	Med
6	BTRHEOM Rheometer	Good	Med
7	Free Orifice	Fair	Med
8	K-Slump	Poor	High
9	Delivery-Chute Torque Meter	Fair	High
10	Delivery-Chute Vane	Poor	High
11	Angles Flow Box	Poor	High
12	DIN Flow Table	Poor	High
13	V-B consistometer	Poor	High
14	Remolding Test (Powers)	Poor	High
15	Thaulow Tester	Poor	High
16	Vibrating Slope	Fair	Med
17	Kelly Ball	Poor	High
18	Wigmore Consistometer	Poor	Med
19	Ring-Penetration Test	Poor	High
20	Compacting Factor	Poor	High
21	Moving Object	Good	Med

The approaches listed in table 4 are nominated for consideration for development and evaluation as potentially capable of measuring workability for concretes applicable to pavement construction. All of the nominated approaches have weaknesses. The major concerns for each nominated approach are described in the modification, development, and acquisition plan sections of this report (Chapters 4 and 5). This first screening involved a simplified consideration of the five performance criteria.

Evaluation of the best candidate approach required answering many of the questions given at the beginning of this chapter. The four approaches in table 4 were considered for actual field measurements. In addition to these candidates, the laboratory-grade rotational viscometer (BTHROEM) was used as a laboratory reference device.

Table 4. Nominated approaches.

1	Free-orifice rheometer
2	Moving-object rheometer
3	Vibrating slope
4	Colebrand tester

The following paragraphs summarize the technical concerns expressed during evaluation of the candidate devices. Detailed evaluation forms are provided as appendix B.

Free-orifice rheometer—This classical method for rheological measurement does not normally operate at multiple shear rates. To obtain different flow rates, different diameter orifices would be used. The method may be more useful when combining measurements made using this technique with a static measurement (such as slump) to describe the rheological properties of a concrete mixture. To prevent blockage of the orifice, the opening should be a minimum of three times the maximum-size coarse aggregate particle. Even with the large openings, the evaluators did not believe that this technique would be workable without the use of vibration. This device would be used strictly for testing of sampled concrete. It would not be useful for testing of in situ concrete or for testing of concrete while the concrete is still in the mixer or a paving machine.

Moving-object rheometer—The moving object (moving-ball viscometer) is a classical rheological technique. Theoretically, one can construct a device that will operate at multiple shear rates and will work across a broad range of concrete mixtures. It is anticipated that the device could be made portable for use in testing concrete sampled from a batch as well as in situ concrete and concrete in mixers. No such device is currently available for use in determining rheological properties of concrete. Construction of a test device should be rather simple for laboratory testing of this technology.

Vibrating slope—Since vibrating slope at one fixed angle develops a single shear rate, it is anticipated that testing the concrete mixture at several slope angles would give multiple shear rates for a concrete mixture. Vibration field adds to complexity for determination of shear and classical rheology calculation. Instead, an index number determined by the change in the discharge rate versus angle of discharge will be used as a correlation to concrete workability.



Colebrand tester—Torque is measured as two hemispheres mounted at the end of a shaft are rotated. Measured torque is correlated to slump and w/c. This device is commercially available and is designed for field use. It works with concrete mixtures with a slump greater than 70 mm and mixtures with coarse aggregates having a nominal maximum size of less than 32 mm. Portability of the device allows its use for in situ testing of concrete mixtures that have been placed, testing of concrete mixtures while still in a truck or paving machine, and also in concrete sampled from a concrete batch. This tester uses a battery that is internal to the device and rechargeable; it can be recharged using normal 120-v current with the accompanying charger. The device is lightweight and requires only a single operator. The current device does not allow for multiple shear rates. Ten data points are collected and then averaged at 1 fixed shear rate. The time to collect the data using this device is similar to the time required to perform a slump test.

## CHAPTER 4: LABORATORY EVALUATION OF CANDIDATE TEST PROCEDURES

The laboratory evaluation included selection of a commercial off-the-shelf rheometer to use as a standardization tool in testing, modifying, developing, and verifying the performance of the four potentially fieldable candidate approaches. The two rheometers that were considered as reference tools were the BML and the BTRHEOM. (The items in table 4 are workability techniques recommended for further consideration as fieldable devices.) A BTRHEOM was purchased for this program because of its size and portability. The following sections describe the status of the research rheometer and the four techniques that were considered. Topics discussed include the technical difficulties with each technique, as anticipated by the research team, and approaches and modifications to improve performance.

Low-slump concrete mixtures were used in developing and testing the candidate methods. To minimize the effects of hydration and the necessity of continuing to make new batches of concrete, the test mixture consisted only of fly ash, water, fine aggregate, and coarse aggregate. The slump changed as the water evaporated from the mixture, and water was added to maintain slump during testing. The fly ash mixture proportions were as shown in table 5.

Table 5. Test concrete mixture proportion.

Materials	Batch, m <sup>3</sup>
Cement, kg	-
Fly ash, kg	356
Water, kg	Variable
Fine aggregate, kg	534
Coarse aggregate, kg	1,424

Water was added to the test mixture adjusting the workability to obtain mixtures with slumps of near zero and 50.8 mm (2 in). Slumps was measured for each test according to ASTM C 143, "Standard Test Method for Slump of Hydraulic Cement Concrete," (ASTM 1994c) prior to using the mixture in testing the devices. Higher-slump mixtures were made by the addition of more water.

### BTRHEOM DEVICE

The laboratory version of the BTRHEOM device is shown in figure 1. This device uses rotating discs to measure viscosity. The discs are fabricated to prevent slippage of the concrete. A field system, which uses a portable computer is available for this device.

The BTRHEOM is commercially available from France. The research team was able to obtain the use of the equipment. The BTRHEOM is limited to testing concrete with a slump of more than 50 mm.

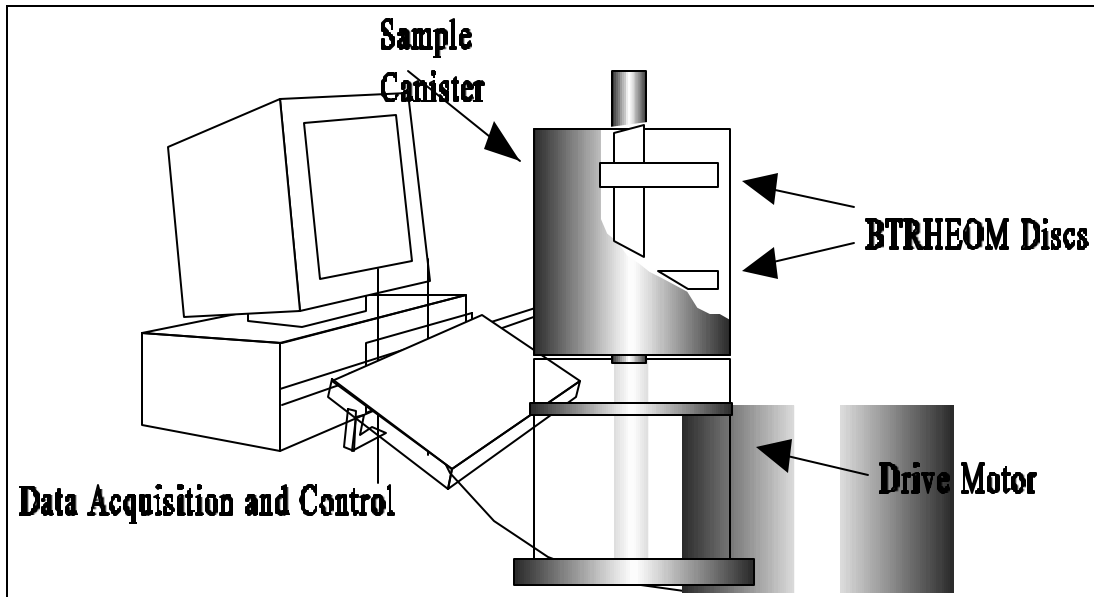


Figure 1. BTRHEOM device.

When the device was evaluated using the low-slump mixture, no steady-state measurements could be made, even when vibration was added. Either the system did not rotate or, when rotation was possible, it tended to be sporadic in rotational speed. This apparatus is not capable of handling the low-slump mixture, even with vibration.

### **FREE-ORIFICE RHEOMETER**

The free-orifice rheometer is shown in figure 2. This device measures the flow rate produced by the gravitational force of the concrete and the opposing viscous force produced at the smaller exit orifice. Modification of this approach to generate multiple shear rates involved incorporating some sort of variable external force, such as a linear actuator or external weights. A linear actuator as described in the development section of the moving object approach was used to generate high applied forces for testing low-slump mixtures without external vibration. External vibration was necessary for low-slump concrete.

One reported problem with this technique is that the orifice size is a function of the maximum aggregate size and the concrete slump. Laboratory testing with this device revealed that, even with several orifice sizes, flow through the device was not possible within the practical range of the device and concrete mixtures used in the program.

### **MOVING-OBJECT RHEOMETER**

In 1850, Sir George Stokes first developed an equation for calculating the absolute viscosity of a metal sphere falling through a fluid. Still today, falling- and drawn-object viscometers are used extensively for laboratory and field materials testing. The physical equations are well defined and include provisions for influences such as container boundary effects.

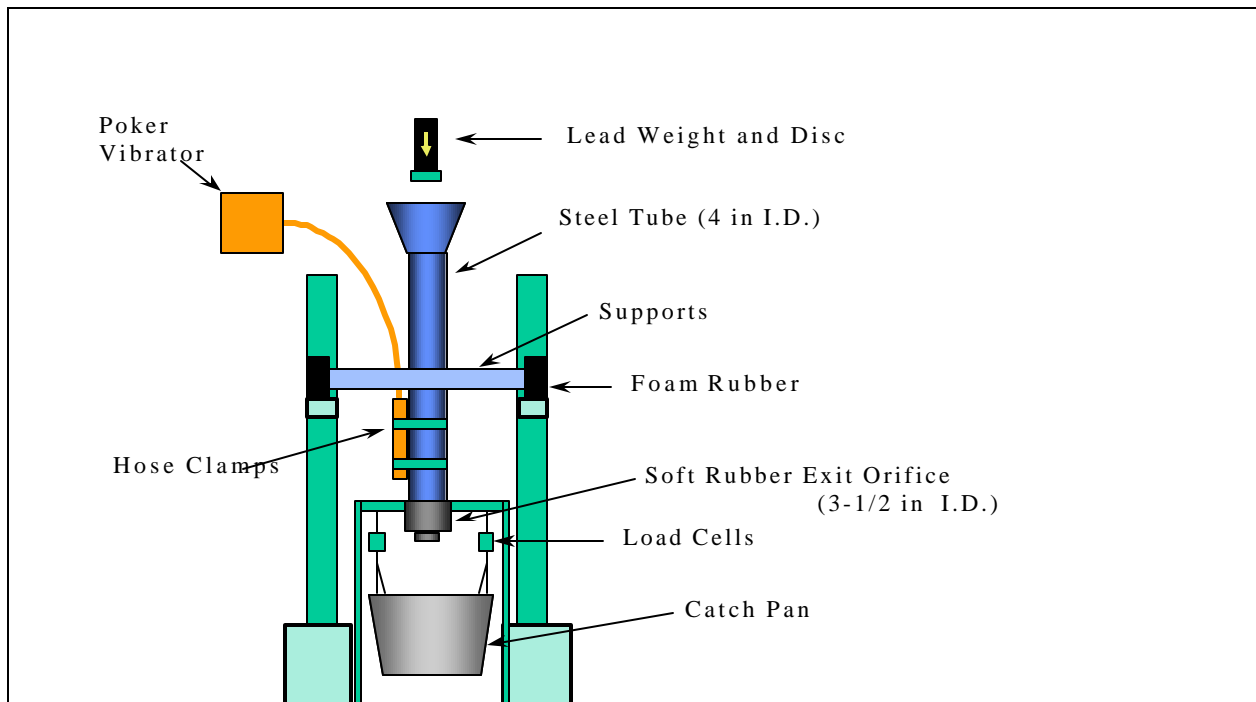


Figure 2. FREE-orifice rheometer.

L'Hermite and Tournon (1993) performed workability experiments in the late 1940's by controlling the force and measuring the rate at which a steel sphere moved through vibrated concrete. They confirmed the application of Stokes law to vibrated concrete and use of the drawn sphere.

The moving-object rheometer in a conceptual final form is shown in figure 3. The data acquisition and control operations could be performed by a notebook computer or an embedded system. A moving-object rheometer in a limited laboratory form is shown in figure 4. This laboratory system uses pulleys in various configurations to create the different shear rates needed to describe viscosity.

This procedure was evaluated using both a constant-force and a constant-velocity system. The laboratory unit for the moving-object device used an overhead crane as a constant-speed device. Pulleys were used to achieve four speeds from the two-speed crane. While the data series from these tests had consistent patterns, a steady-state force value was not always clear.

Data collected using a constant-force device were somewhat more difficult to interpret, because the maximum force required is not known prior to testing. To reduce the force required for the test to a practical level, a vibration field was applied to the concrete test sample.

Dilatation of the concrete during object movement through the concrete mass required that a large amount of concrete must be tested. Restraint imparted by the dilatation of the concrete

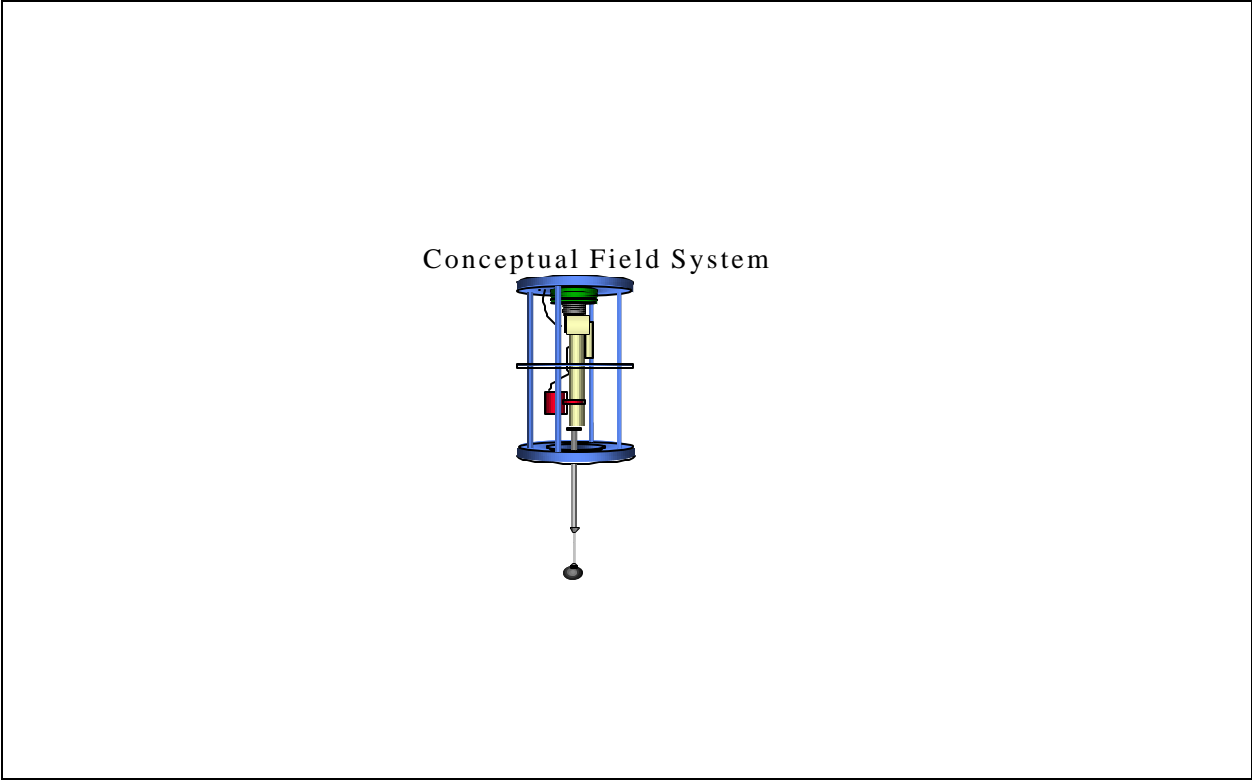


Figure 3. Field embodiment of the moving-object rheometer.

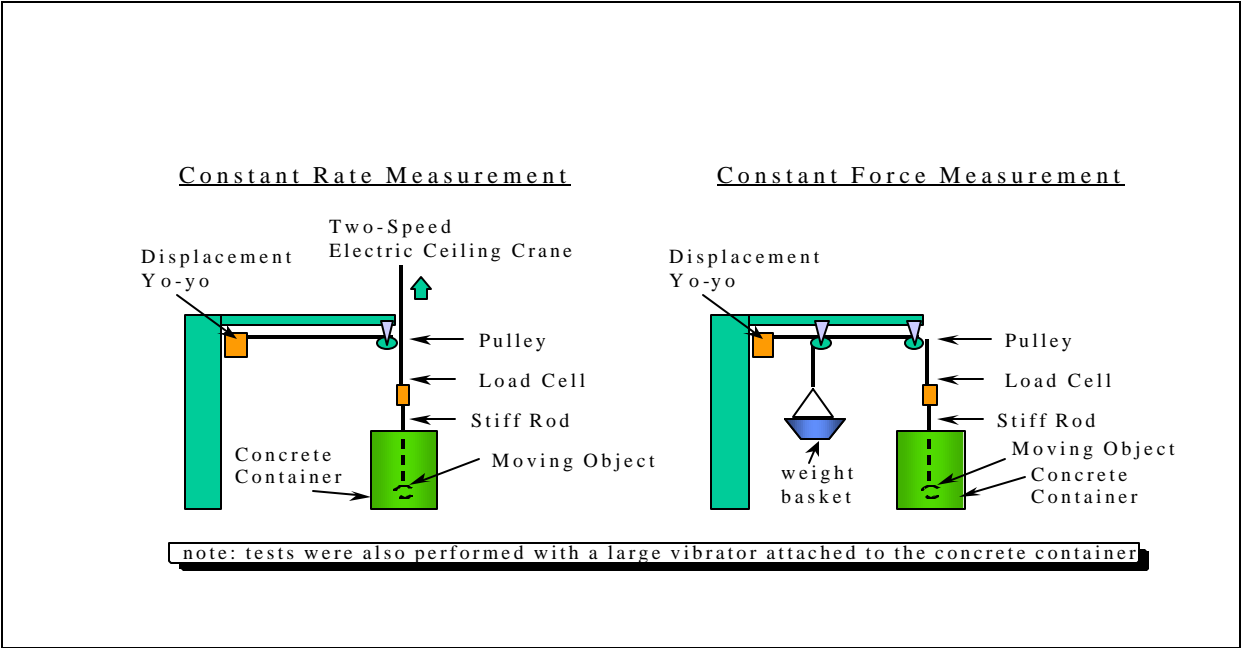


Figure 4. Laboratory configuration for testing with moving-object approach.

increased the force necessary to move the object through the concrete, as well as causing increased velocity as the object neared the free surface of the sample being tested.

## VIBRATING-SLOPE VISCOMETER

The vibrating-slope viscometer, in its laboratory form, is shown in figure 5. For this initial approach, the time required to vibrate half of the concrete out of the chute is measured as an indication of workability.

The modification for this approach involved changing the angle of incline to generate multiple shear rates and measure maximum discharge rate. This device performed well in the laboratory phase, and a more field-applicable device was developed and is recommended for further testing.

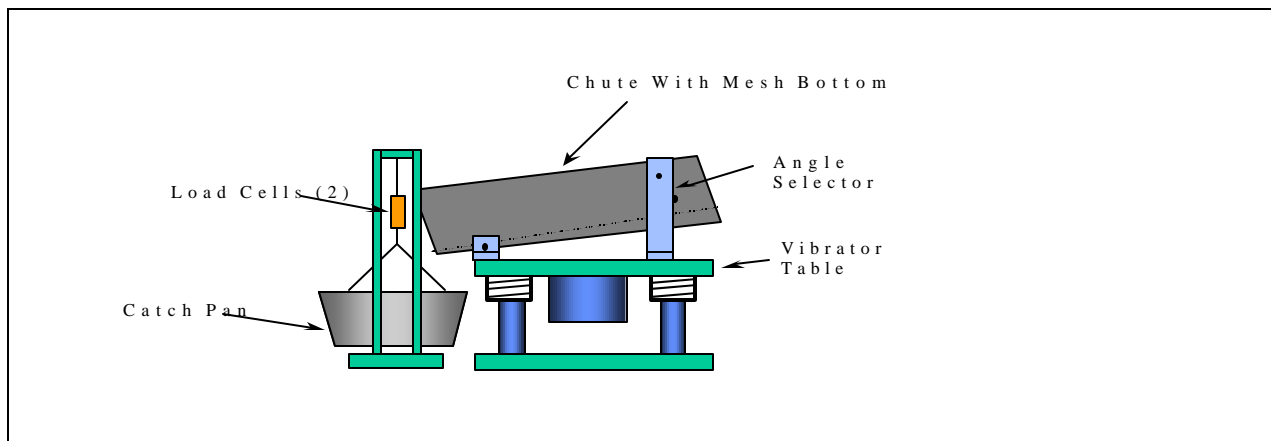


Figure 5. Laboratory version of vibrating-slope viscometer.

Discharge rate was determined for some low-slump concrete as shown in figure 6. Mixtures were tested at slopes of 10 and 15 deg. There was an increase in the discharge rate with increase in slope angle. No problems were encountered with handling of either the fluid mixture or the low-slump mixture. Fluid concrete mixtures flowed from the chute without vibration, whereas the low-slump concrete required vibration to discharge the concrete. Maximum vibration was used for all tests performed. This method does not lend itself to the measurement of fluid concrete, as the concrete begins to discharge soon after the gate to the chute is opened. Concrete mixture with a one-inch slump showed slight decrease in discharge rate with an increase in discharge angle this was due to aging of the concrete mixture during testing. Higher-slope angles may be necessary for low-slump concrete.

## COLEBRAND TESTER

A modified Colebrand tester is shown in figure 7. In its current form, the device makes a dynamic measurement that is correlated to slump. This embedded system does not display in the output information the rotational speed or resulting drag force. Hemispherical probes similar to those used in the Colebrand tester were fabricated and were used in conjunction with a two-point test device instead of the impellers normally used, and the ability of this type of device to

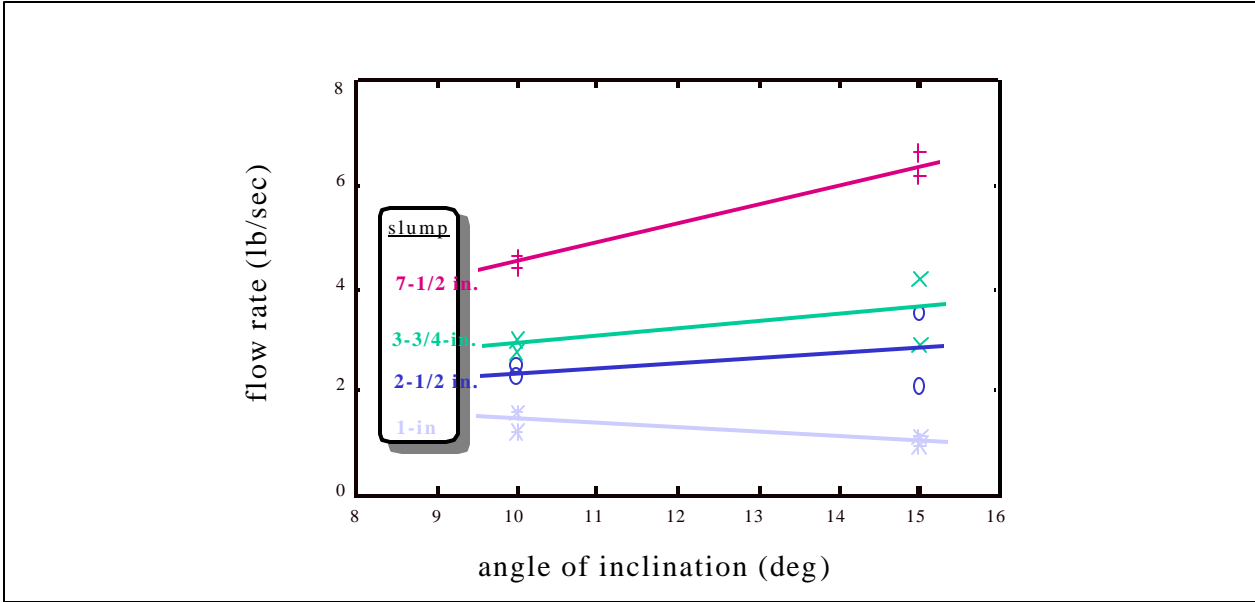


Figure 6. Relation of flow rate to angle of inclination.

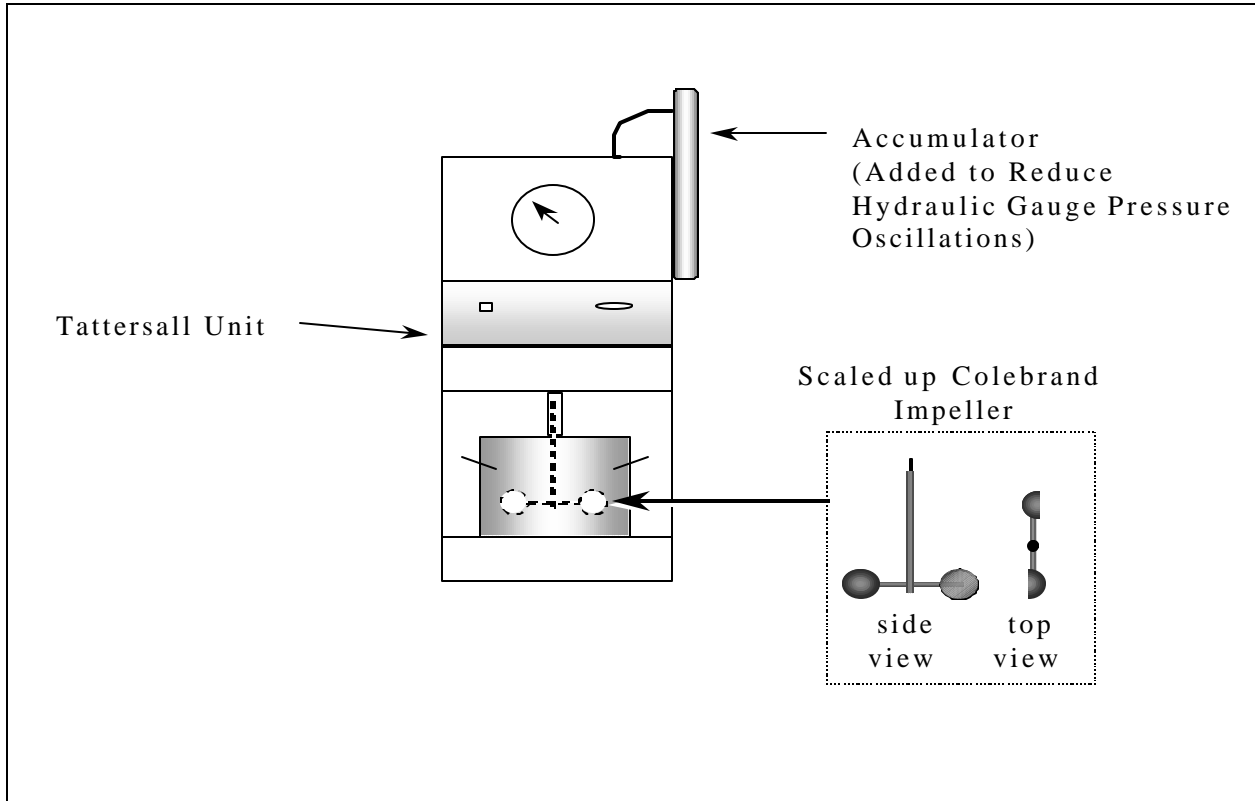


Figure 7. Modified Tattersall/Colebrand tester.

measure additional shear rate was evaluated. Low-slump concrete tested using this device showed channeling of the concrete by the probe after one revolution. The indicated viscosity of the concrete (slope of lines in figure 8) remained the same or dropped, revealing problems using this device for high-shear determination in low-slump concrete mixtures.

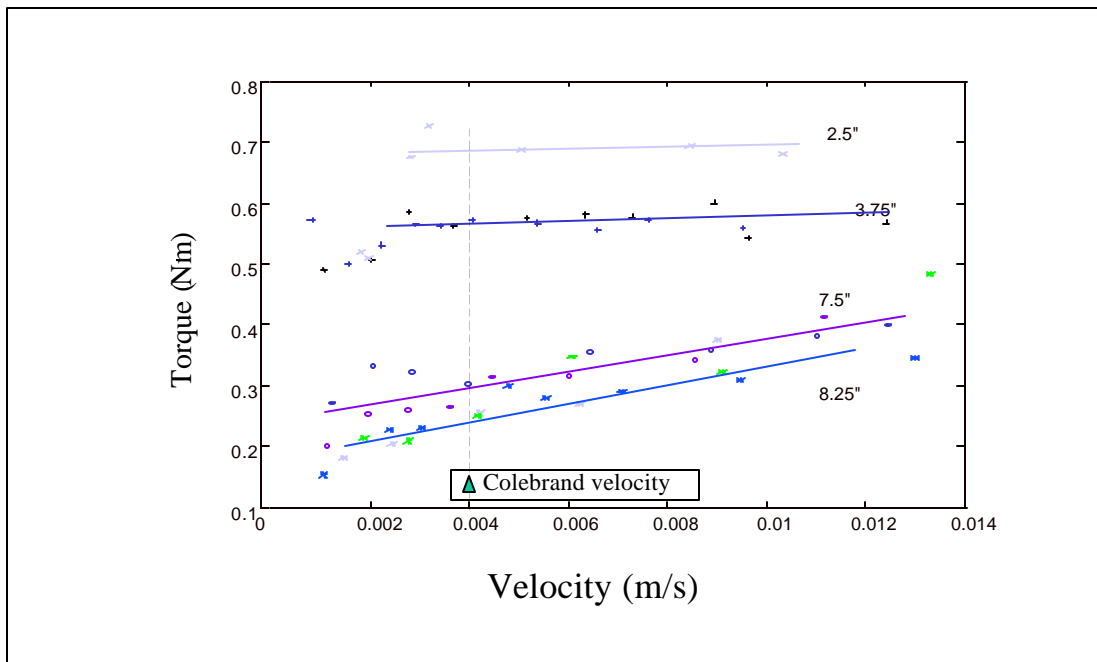


Figure 8. Viscosity (slope) of concrete based on use of Colebrand probe in Tattersall machine.

The Colebrand tester was tested separately with several concrete mixtures. These measurements correlated with slump as shown in figure 9.

Three of the candidate methods had physical limitations that were difficult to overcome. Flow through the free-orifice device was intermittent, and consistent flow measurements could not be obtained for the size of device tested. The moving-object rheometer required a large sample and container size to avoid dilation of sample and influence of container size on the measurements. The Colebrand only gave results that correlated with slump. However, when the probe was used with low-slump concrete to determine shear stress at different shear rates, the probe would make a channel through the concrete upon its first pass and subsequent passes through the concrete gave results that were not useful.

The vibrating-slope apparatus was the only method that could measure some relevant properties of low-slump concrete. It was selected for additional testing and development.



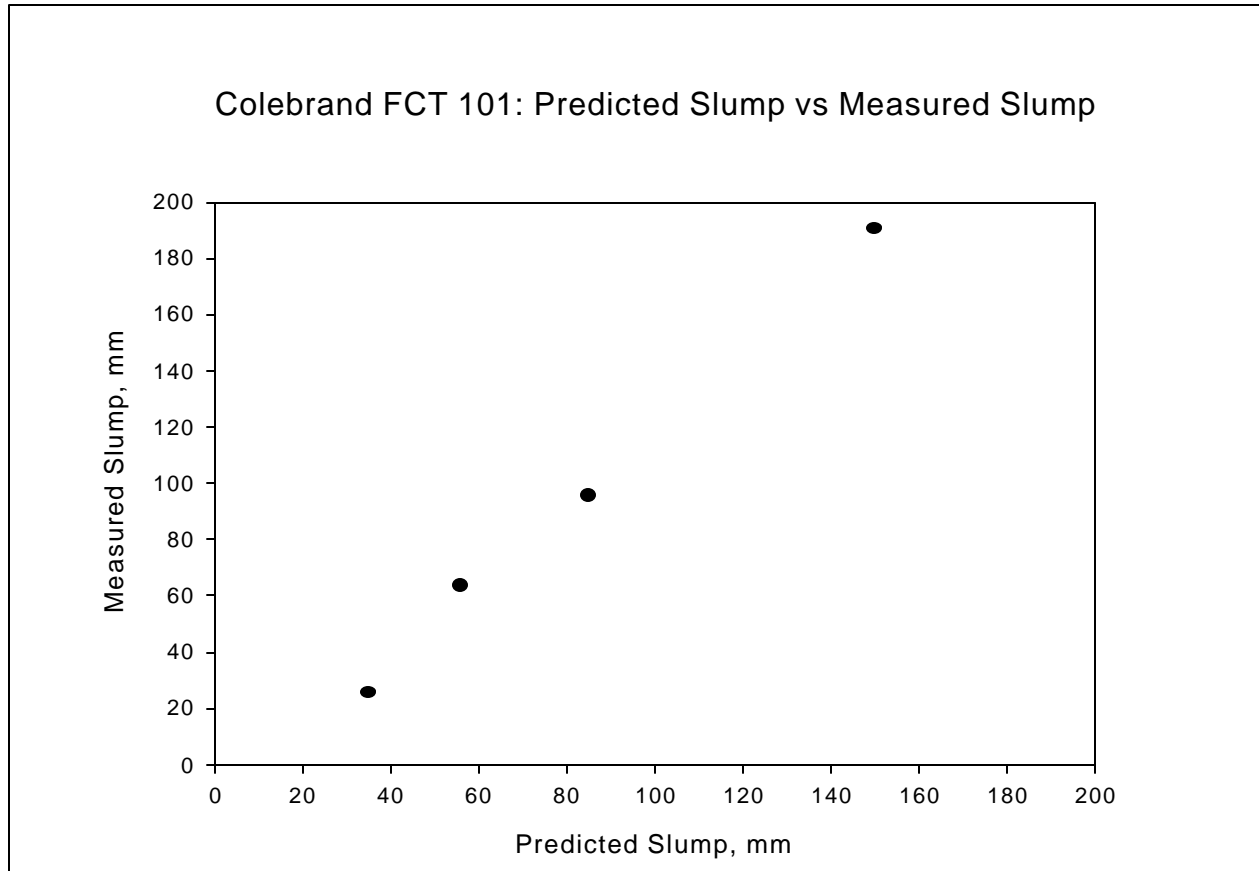


Figure 9. Relation of predicted slump using Colebrand tester (FCT 101) to measured slump.

## CHAPTER 5: VIBRATING-SLOPE APPARATUS

The initial laboratory system from which the portable vibrating-slope apparatus (VSA) (figure 10) was designed using a vibrating table, an attached chute, and an external electronic scale. The scale was used to measure the mass of the deposited concrete as a function of time. The following sections document the development of a device to meet the requirements of portability, compactness, and ruggedness for field use, as well as the software for data acquisition and data processing.

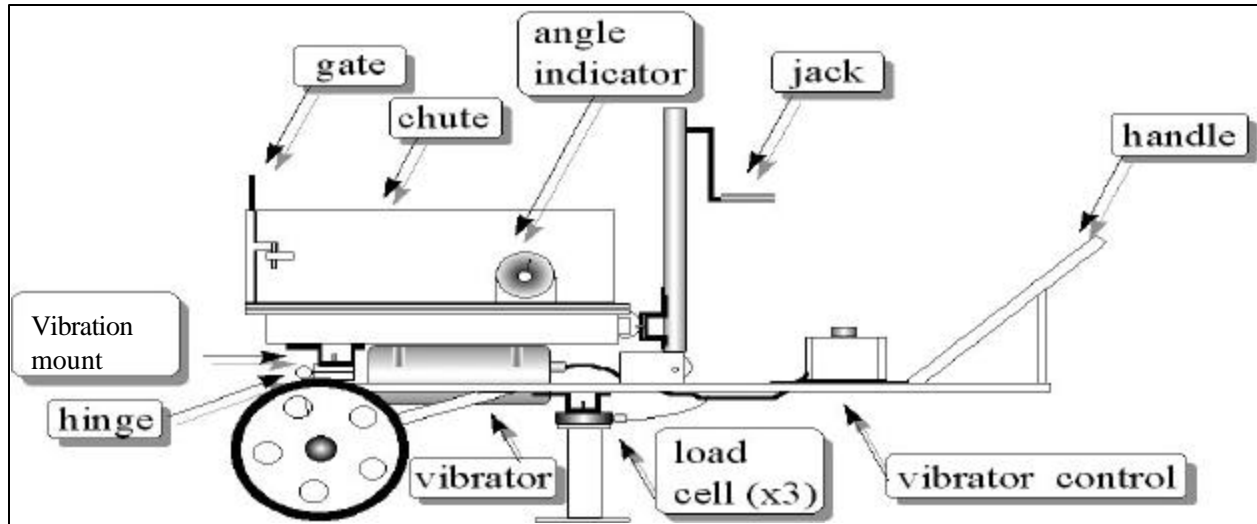


Figure 10. Portable vibrating-slope apparatus.

### VIBRATING-SLOPE APPARATUS (VSA) HARDWARE DEVELOPMENT

The VSA measures the rate at which vibrated concrete flows from a chute. One of the key modifications was the incorporation of the load-cells into the device chassis so that an external mass-determining apparatus was not needed. To accurately measure the concrete mass while under vibration, three things are done. First, vibration isolators are used between the load-cell and chassis and between the chassis and vibrating chute. Second, an analog-summing amplifier is used to combine the output from three load-cells into one signal. Since the instantaneous vibration component at each load-cell is different, summing the load-cells helps average out vibration noise. The third step used to reduce vibration noise is signal averaging. This is accomplished in the data-acquisition program. Sequential signals are averaged over a time interval small enough so that the concrete mass does not significantly change, but long enough to span several vibration cycles. Since the vibration phase varies in each signal, averaging is effective in reducing the vibration noise.

During testing of the laboratory system, the appearance of vibration nodes and antinodes in the chute was noted. As a result, the concrete was not being uniformly vibrated in the chute. Concrete at a node would undergo minimal vibration, while concrete at the antinodes would experience more vibration.

Because the concrete that was under more vibration flowed more freely than the concrete at a node, a hump would tend to form near the node (near the center of the chute). To overcome this problem in the VSA, the vibrator was mounted directly on a large stiff plate of 12.7-mm (1/2-in) steel, which forms the bottom of the chute. In addition, the walls of the chute are isolated from the bottom by rubber strips and grommet vibration mounts. This helps to minimize vibration nodes in the chute walls and reduces the overall vibration of chute walls, producing a more uniform vibration field in the concrete.

The bottom of the chute is covered with staggered transverse metal strips about 12.7 mm (1/2 in) in height. These strips prevent the concrete from sliding out of the chute. A quick lift gate is used at the front of the device to hold the concrete in the chute during filling, leveling, transport, etc. A manual screw-jack on the back of the chute allows various incline angles to be set. The incline angle is determined with an angle indicator magnetically affixed to the chute. This indicator gives the true angle of incline regardless of the ground surface incline or smoothness.

There are eight vibration dampers to isolate vibration on the VSA. Six of these are the type used on vibration tables and other heavy-vibration applications. Three of the six dampers are mounted directly to the top of the load-cells to help prevent chassis vibrations from traveling through the load-cells to the pedestal or wheels. If excessive vibration reached these supports, the system would hop on the ground, and measurement data very likely would be lost. Two additional vibration dampers are used to connect the front of the chute to two heavy-duty hinges located on the chassis.

Two custom dampers and one standard damper are used to connect between the jack, chute, and chassis. These custom dampers allow for the rotational freedom needed to connect the screw-jack between the chassis and chute while also reducing vibration transmission into the chassis. They were constructed from a hollow pipe, large, thick, rubber washers, threaded rod, nuts, and steel washers.

The VSA is moved by lifting up on the chassis handle, allowing it to roll on the front wheels, like a wheelbarrow. Large-diameter, hard, rubber wheels are used so that the device can be more easily transported over rough and uneven surfaces. The front wheels share a common axle that is braced to the rear supporting leg. This bracing helps provide the rigidity needed to compensate for the softness and flexibility of the vibration mounts.

The load-cells are fatigue-rated transducers of the pancake-type capable of measuring both tension and compression to 226.8 kgf (500 lbf). A custom electronic circuit was constructed to provide regulated and temperature-compensated load-cell excitation as well as to condition the output signals. The 120-ohm load-cells are excited with a bipolar direct current of 20 v. All of the amplifiers in the circuit are excited with a regulated bipolar direct current of 30 v. This sets the output limits to  $\pm 15$  v. In the signal-conditioning circuitry, the differential outputs from the three load-cells are converted to single-ended outputs by means of three high-performance differential operational amplifiers (op-amps). These single-ended signals are then summed and scaled with a summing op-amp network. An optional six-pole low-pass filter output is also provided by means of a specialized integrated circuit (figure 11).

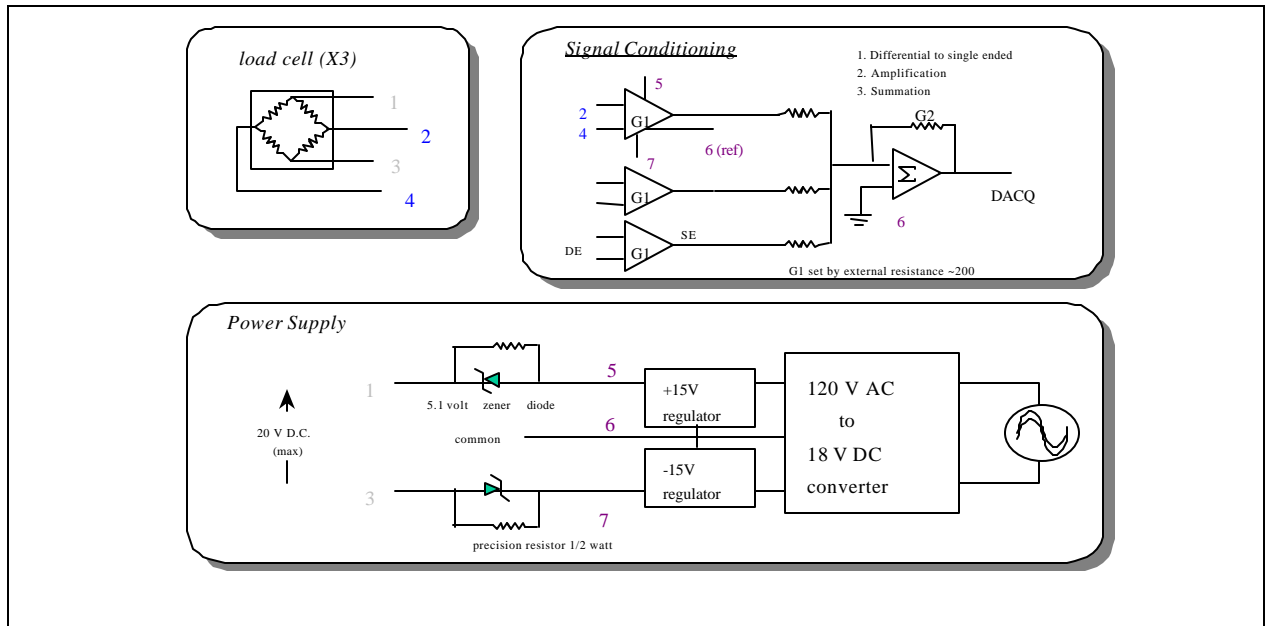


Figure 11. Circuit diagram.

The VSA is powered by a standard 120-v alternating current. Battery power of the entire system is not feasible because of the power requirements of the vibrator. This system was built with a variable-speed vibrator to allow maximum testing flexibility. Currently the system is being evaluated with the vibrator operating at maximum speed and its off-center mass set to a force level of 136.07 kgf (300 lbf).

## VIBRATING-SLOPE DATA-ACQUISITION SOFTWARE

The software that is used to perform the data collection, display, and processing for the vibrating slope device is written in Hewlett Packard's Virtual Engineering Environment (HP-VEE) (appendix C). This software interfaces a Data Translation PC Card. This card is a 12-bit 200,000-sample per second analog-to-digital converter. The software is comprised of two programs. The first program collects and averages the raw data and stores this information, as well as the incline angle and test description. This program also processes and displays the flow-rate information, although this information is not stored. The second program reads, processes, and displays the data files generated by the first program. Discharge rate decreases as the chute empties, so a maximum flow rate is calculated for that incline angle. After all test data have been read in, a linear fit is applied to the data, which relates the maximum flow rate in kilograms per second (pounds per second) to incline angle.

The data collection program allows the user to change data-acquisition parameters including angle of inclination, test description, data file, and length of test. However, for the majority of concrete mixtures, the default configuration should be used. When the user clicks the start button, the software activates a timer that keeps up with the elapsed test time. This start button also begins the data acquisition. During data acquisition, 4,096 samples are collected at a rate of 100,000 samples/s and then averaged to generate each data point. This sampling process is repeated until the stop button is pressed. A multiplier

and offset are used to apply a calibration to the data. Periodic calibration is performed using dead weights. The output data file contains test comments, incline angle, elapsed time, and the previously described data. Additional processing is performed on the data so that the user can preview the test results. These processing operations are described below. During a test, a real-time graph of the collected mass data is displayed on the screen as well as a numeric display of the instantaneous weight. After the collection of data is stopped by the user, the mass flow-rate data are calculated and displayed.

The second program, which performs the data-reduction tasks (figure 12), allows the user to load multiple data files created by the previously described program. The elapsed test time and measured amplitude data array, which are both contained in the stored data file, are used to construct a wave form that relates amplitude as a function of elapsed time. A seventh-order polynomial fit is then applied to the data as a type of low-pass filter. A first-order derivative is then applied to the data to convert them from mass to mass flow rate. The maximum mass flow rate that occurs in the first half of the data is then extracted. This value is stored in an array along with the angle at which the test was run. A composite graph is also updated with this result. This process is repeated for as many test data files (for a given mixture) as desired. Each time a test data file is loaded, the extracted angle and flow-rate information are added to the final array. When the user has loaded all of the desired test data, the “Go” button is pressed and the software calculates the best linear fit of the data as well as a correlation coefficient or quality indicator. At least two different measurement angles must be loaded to calculate a fit, but there is no restriction on loading multiple tests performed at the same angle.

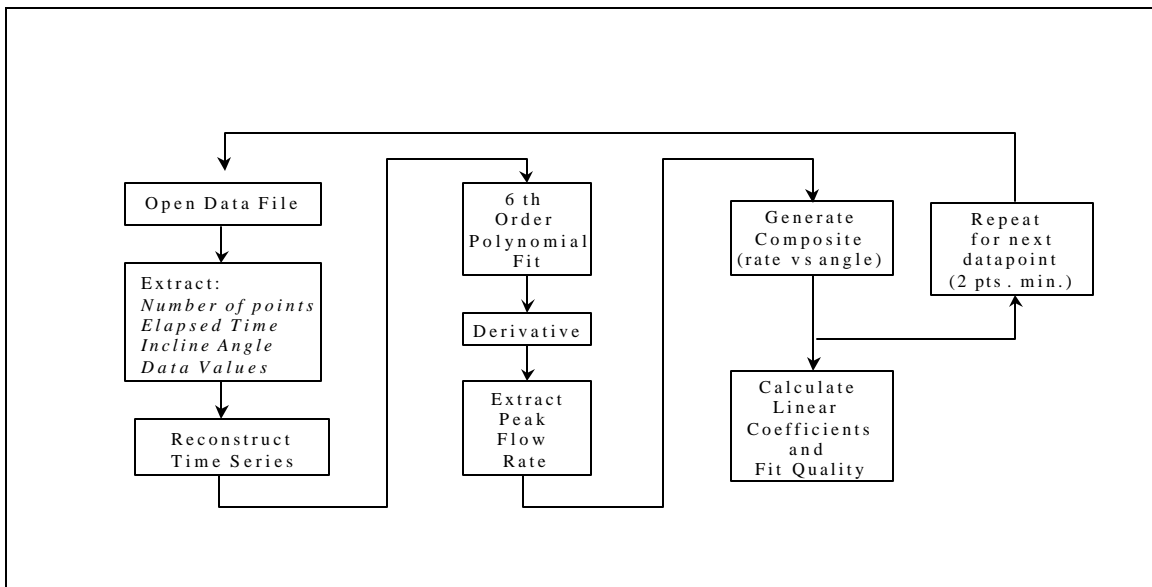


Figure 12. Data-reduction flow diagram.

## CHAPTER 6: VERIFICATION OF EQUIPMENT PERFORMANCE AND FIELD EVALUATION

### MATERIALS AND TEST METHODS

Materials Company, a Class F fly ash, natural rounded fine aggregate, and two coarse aggregates, (a washed gravel meeting ASTM C 33 (ASTM 1994a) nominal size No. 67 from Mississippi Materials Company and a limestone coarse aggregate with a 19.05 mm (3/4-in) maximum size from in-house standard stock).

The candidate technology was examined in an evaluation program that purposed to determine needed modifications to hardware and operational details. Several concrete mixtures were used in this step. Mixture 1 is the only one to contain a high-range WRA (water-reducing admixture). Air entraining admixture (AEA) was used in two mixtures. Other mixtures varied in the fly ash content and the amount of cement in the mixture. Mixtures are described in the following table:

Table 6. Concrete mixture proportions for evaluation program.

Material	Mixtures					
	990085 <sup>1</sup>	990086 <sup>1</sup>	990087 <sup>2</sup>	990088 <sup>2</sup>	990089 <sup>2</sup>	990090 <sup>2</sup>
Cement, kg (lb)	331 (729)	152 (335)	185 (406)	231 (508)	145 (319)	192 (423)
Fly ash, kg (lb)			46 (102)		47 (104)	
Fine aggregate, kg (lb)	480 (1,057)	609 (1,341)	540 (1,188)	598 (1,316)	534 (1,176)	535 (1,176)
Coarse aggregate, kg (lb)	767 (1,690)	824 (1,815)	883 (1,943)	845 (1,860)	948 (2,089)	948 (2,089)
AEA, ml (fl oz)	367 (12.4)	59 (2.0)	132 (4.5)	441 (15)		
WRA, ml (fl oz)	863 (29.2)			88 (3)		
Water, kg (lb)	116 (255)	99 (218)	110 (243)	110 (243)	83 (182)	83 (182)
<sup>1</sup> Natural chert coarse aggregate.						
<sup>2</sup> Crushed limestone coarse aggregate.						

### CONCRETE TEST

For all mixtures, the following standards were applied: for slump, ASTM C 143 (ASTM 1994c), “Standard Test Method for Slump of Hydraulic-Cement Concrete”; for air content, ASTM C 231 (ASTM 1994e), “Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method”; and for temperature, ASTM C 1064 (ASTM 1994g), “Test Method for Temperature of Freshly Mixed Portland Cement Concrete.”

A sample of freshly mixed concrete (approximately 0.1 m<sup>3</sup>) is placed and compacted by vibrating in the chute. The chute is raised to a predefined angle and vibrated to allow the concrete to flow out of the chute. The rate of discharge is measured and recorded. A second sample is prepared in the same manner and tested at a predefined angle different from that used in the first measurement. The workability is defined as the slope of the line defining the two discharge rates versus the angle of the discharge chute.

A draft method of the VSA procedure is presented in appendix D. The maximum discharge rate is determined for a minimum of two discharge angles. The discharge rate will increase relative to the discharge angle and the effort necessary to move the concrete. Concrete that is easily moved will have a higher discharge rate than those stiffer and less workable concrete. The discharge rate for concrete having a lower workability will show a smaller increase relative to the increase in the discharge angle. Figure 13 illustrates two concretes having different workability indices. The concrete represented by series 1 has a workability index of 0.20 and concrete series 2 has a workability index of 0.13. More work effort is required to move the concrete represented by series 2 than is necessary to move the concrete in series 1.

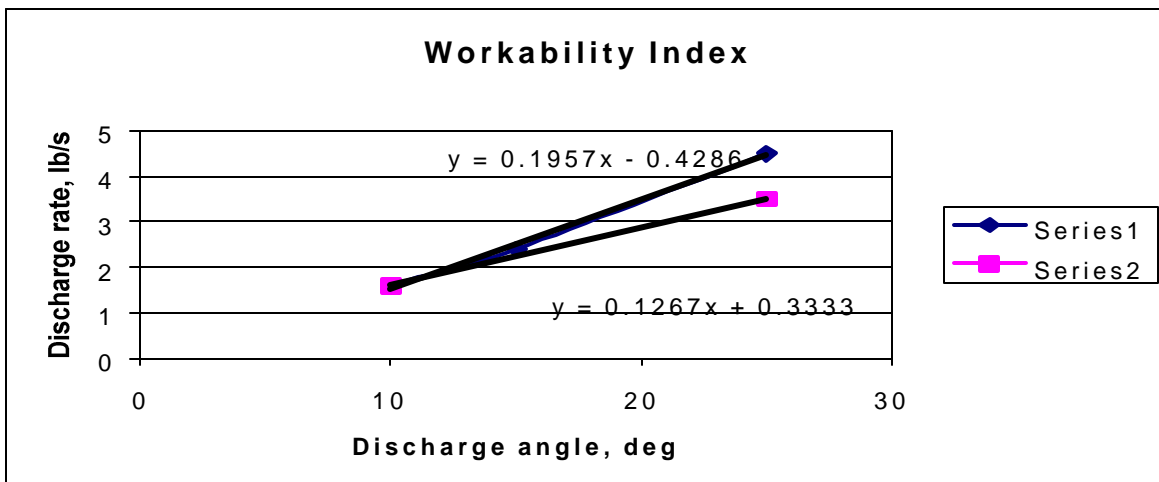
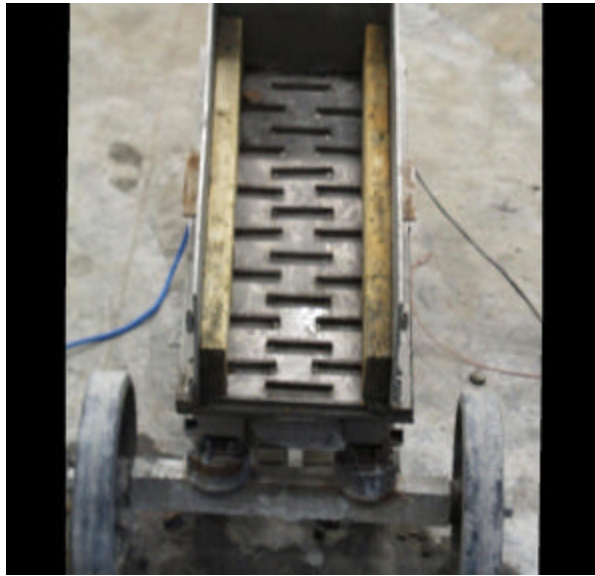


Figure 13. Two concretes with different workability indices.

The general procedure for testing using the VSA is described below. More angles were included for additional information.

The bottom of the chute was leveled and then dampened and allowed to drain so that no standing water remained in the chute. The concrete was placed into the chute in a single lift, bringing the level of the concrete 100 mm (4 in) above the bottom of the chute (figure 14). The vibrator attached to the apparatus was then used to vibrate the concrete to rid the system of “tracks” and voids. This took approximately 5 s, depending on the stiffness of the concrete.

The angle of the chute was raised to 10 deg, the gate was opened, and the data-acquisition system and the vibration were started.



a. Discharge chute is cleaned and drained prior to use.



b. Concrete remains in the chute when the gate is removed.

Following the test, residual concrete from the chute was removed and the chute was releveled. A second sample of concrete was placed into the chute to the same height and treated as in the case of sample one. After consolidation, the chute was raised to an angle of 15 deg and the test was repeated. The process was also investigated using 5-, 10-, and 25-deg angles.

Figure 14. Concrete discharge chute.



Tables 7 through 14 summarize the testing of the VSA.

Table 7. Batch 990085, 203.2-mm (8-in) slump.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	10	2.601 (5.729)	
B	10	2.054 (4.525)	
C	10	2.498 (5.503)	
D	15	2.959 (6.518)	
E	15	2.969 (6.54)	
F	15	3.556 (7.832)	
G	25	4.672 (10.29)	
H	25	5.689 (12.53)	
I	25	3.392 (7.472)	
J	15	3.578 (7.881)	
K	5	1.693 (3.728)	
L	5	1.722 (3.793)	
M	5	1.910 (4.208)	

Table 8. Batch 990085, 165.1-mm (6.5-in) slump.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
N	10	2.536 (5.585)	
O	15	6.401 (14.1)	
P	25	8.717 (19.2)	
Q	10	2.281 (5.024)	
R	15	3.597 (7.923)	
S	25	4.069 (8.962)	

Table 9. Batch 990086, 95.25-mm (3-3/4-in) slump, 7.8% air.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	15	2.432 (5.357)	
B	15	2.023 (4.455)	
C	15	2.283 (5.029)	
D	25	10.056 (22.15)	Bad data
E	25	3.196 (7.04)	
F	25	2.808 (6.186)	
G	10	1.172 (2.581)	
H	10	0.977 (2.153)	
I	10	1.286 (2.833)	

Table 10. Batch 990086, 7.8% air.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
J	10	1.738 (3.828)	101.6-mm (4-in) slump
K	15	3.213 (7.076)	
L	25	3.726 (8.207)	
M	10	1.882 (4.145)	76.2-mm (3-in) slump
N	15	2.570 (5.661)	
O	25	4.065 (8.954)	
P	10	2.119 (4.667)	63.5-mm (2.5-in) slump
Q	15	1.781 (3.922)	Bad data
R	25	3.168 (6.979)	

Table 11. Batch 990087.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	10	1.629 (3.589)	76.2-mm (3-in) slump
B	15	1.559 (3.433)	
C	25	2.606 (5.74)	
J	10	1.615 (3.557)	101.6-mm (4-in) slump
K	15	2.364 (5.207)	
L	25	4.465 (9.835)	
M	10	1.846 (4.067)	101.6-mm (4-in) slump
N	15	2.684 (5.912)	
O	25	3.631 (7.998)	

Table 12. Batch 990088.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	10	1.491 (3.284)	127-mm (5-in) slump
B	15	2.517 (5.543)	
C	25	3.441 (7.58)	
D	10	1.915 (4.219)	101.6-mm (4-in) slump
E	15	2.07 (4.559)	
F	25	3.802 (8.374)	
G	10	1.622 (3.573)	57.2-mm (2-1/4-in) slump
H	15	2.10 (4.625)	
I	25	2.783 (6.131)	
J	10	1.286 (2.833)	44.5-mm (1-3/4-in) slump
K	15	1.611 (3.549)	
L	25	3.410 (7.512)	

Table 13. Batch 990089.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	10	0.565 (1.245)	31.8-mm (1-1/4-in) slump
B	15	1.168 (2.572)	
C	25	1.658 (3.651)	
D	10	0.716 (1.577)	6.4-mm (1/4-in) slump
E	15	0.841 (1.852)	
F	25	1.446 (3.186)	

Table 14. Batch 990090.

Measurement	Angle, deg	Max Discharge rate, kg/s (lb/s)	Comments
A	10	1.307 (2.879)	50.80 mm (2-in) slump
B	15	2.041 (4.496)	
C	25	2.339 (5.151)	
D	10	1.183 (2.605)	31.8 mm (1-1/4-in) slump
E	15	1.145 (2.523)	
F	25	1.884 (4.149)	

## RESULTS AND DISCUSSION

Since each construction operation using concrete operates under a specific shear rate, it requires a different amount of force to work the concrete for a given mixture for a given operation. There is only one shear rate for the static case, and that is zero. However, there is an infinite number of shear rates for the dynamic case, and hence there is an infinite number of required stresses or work values. Since the work function is a straight line, at least for low shear rates, we do not have to measure an infinite number of points. Only two sets of coordinates are measured to develop the linear function for the work curve. Only two parameters are necessary to define the curve—the yield stress and viscosity. The yield stress is the y-intercept, and the dynamic viscosity is the slope. By plotting the data with the angle on the x-axis and the discharge rate on the y-axis, we can use the equation of a straight line to describe the workability of the concrete.

The workability index “W” is calculated as the slope of the line between two points determined using the discharge rate at two discharge angles. The following equation was used to make the calculations:

$$R = WA + C$$

R = rate of discharge, mass/unit time

A = angle of discharge, degrees

W = workability index

C = calculated yield offset

$$W = (R_2 - R_1)/(A_2 - A_1)$$

$$C = R - WA$$

Workability index trends were calculated for the two mixtures having similar slumps but differing compositions. Mixtures 990089 and 990090 were mixtures having the same ingredients, varying only that in Mixture 990089 some of the cement was replaced by fly ash. Mixture 990089 shows lower slumps and discharge rates for both fly ash mixtures than those of 990090 without fly ash (figure 15). Where the slumps of 990089 and 990090 were the same, the mixture with fly ash had a larger workability index, i.e., a steeper slope.

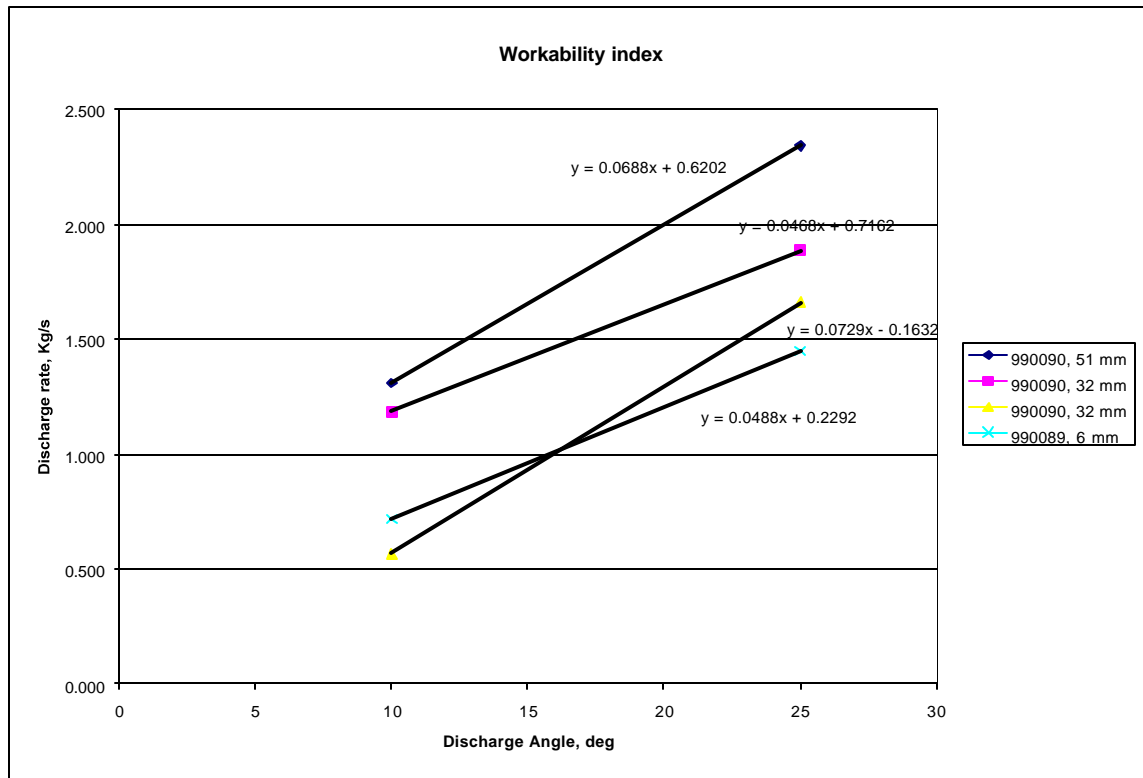


Figure 15. Workability index.

The workability index was calculated using averages of three points at three angles (10-, 15-, and 25-deg) and was also calculated using the averages of two points at 10- and 25-deg angles. The results showed that there is little difference in developing the third point. The workability index calculated based on the averages of three data points for Mixture 990085 was  $y = 0.322x + 2.07$  and, when calculated using two angles, was  $y = 0.3233x + 2.01$ .

The data are sometimes scattered, as shown in figure 16. This sample was tested three times. As the sample aged, changes in its workability were observed. The slope of the regression curve ranged from 0.1211 for the initial sample (line a) to 0.0799 in sample c (with sample b at 0.1314).

The VSA was rolled onto the ramp of a small utility trailer and was taken to a local ready-mixed concrete plant for evaluation and test. The plant provided an area normally used for testing, which contained a source of both water and 110-v electric current. Although the notebook computer is capable of operating on batteries, it was operated using a common AC supply used by the vibrator on the VSA.

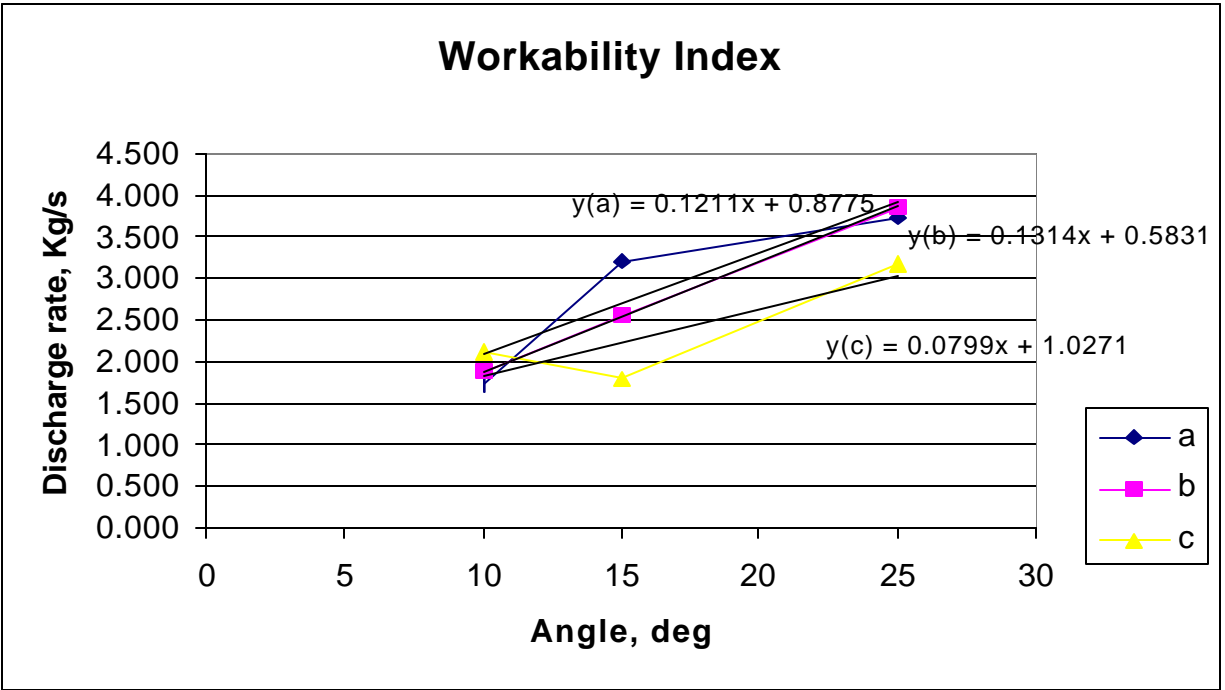


Figure 16. Three-point data.

The plant adjusted its mixture proportion and produced concrete with three slumps by adjusting the w/c. Mixtures had slumps of 222.3, 12.7, and 165.1 mm (8-3/4, 1/2, and 6-1/2 in). The truck discharged the sample into a wheelbarrow from which concrete samples for the slump and VSA tests were obtained. The amount of concrete in the wheelbarrow was no more than the amount taken normally during quality testing in the field.

Time required to set up was reasonable. Power necessary for the operation is generally available at concrete-batching facilities. Once the VSA was set up, numerous measurements could be made with relative ease.

Measurements were made automatically with no data collection or calculations made by the technicians running the test. The maximum rate of discharge was determined by the data-reduction program. (See appendix D for details of the data acquisition and reduction program.)

Cleanup can be done with a scrub brush and a 19-L (5-gal) pail of water. This was aided somewhat by presence of an available external water source, also readily available at batching facilities.

Initial setup problems included the need for a place to put the notebook computer, glare from sunlight which made it difficult to read the computer screen, and inability to obtain a signal from the load-cells to the data-acquisition program. The working surface problem was solved by turning over a 19-L (5-gal) plastic bucket and using the bottom surface to hold the computer. Glare on the computer screens continued to be a problem during the course of the field test. The connection between the cables and a

data-translation PC card is not rugged and tends to come loose when moved. Care was taken to make sure there was good connection to the PC card prior to running each test.

An 222.3-mm (8-3/4-in) slump concrete was tested using the VSA. During the testing, vibration caused the concrete to splatter from the chute. Items not cleaned with water should be covered (i.e., the notebook computer and controllers on the VSA.)

Miscellaneous apparatus items needed for the VSA test are similar to those needed the determination of slump (ASTM C 143 (ASTM 1994c)) or for air content determination (ASTM C 231 (ASTM 1994e)). Items include a scoop or shovel to load concrete into the VSA, a trowel or other device such as a square-nose shovel to level the concrete, a scrub brush to aid in cleaning the unit after testing, a 19-L (5-gal) plastic bucket to carry water, waste concrete, and gloves.

## **CHAPTER 7: FUTURE DEVELOPMENT**

The current program was limited to the development of a method for determining the workability of concrete. Several concrete mixtures were tested during this program to verify the ability of the system to obtain these measurements. The limits of resolution or the ability of the VSA to resolve the effort necessary to move certain concrete was not determined. Continued effort is necessary to correlate the information gained from the VSA and how to use the information in specifications and in proportioning mixtures. Future research and development should include the development of correlation of concrete properties with VSA index numbers in addition to increasing the portability of the VSA software and hardware. Currently, our testing has shown that using vibrating slopes with angles of 10 and 25 deg can resolve differences in concrete having similar slumps. It is assumed that the workability index decreases as the effort required to move the concrete increases. If the calculated workability index of 0.2 goes to 0.1, more effort is required to move the concrete with the workability index of 0.1.

The VSA was configured with flexibility in mind so that tests could be run at different slope angles, using varying amounts of material, collecting data at different rates and displaying data for analysis. The unit currently has a mass of about 158 kg (350 lb) and consists of the test device and a notebook computer for data acquisition. Detailed drawings of the VSA device are presented in appendix E. The computer uses HP-VEE software to perform the data collection, processing, analysis, and storage. The data-acquisition card is a PC-card that plugs into the notebook computer. This configuration is very beneficial during system development, because it provides a great deal of flexibility and signal-processing capability. This flexibility has caused the equipment to be bulky and cumbersome.

A reduction in overall mass of the device can be achieved by using components of lower mass where possible and in reducing the dimensions of the chute.

### **EMBEDDED SYSTEM**

An embedded system for data acquisition and processing can replace the notebook computer. In the sunlight, the computer screen was difficult to view. Also, it was difficult to keep the computer clean and free of debris. Additional work area was necessary for placement of the computer, and the computer is not rugged enough for everyday use in the field.

An embedded system would be compact and mounted on the vibrating slope apparatus, and depending on the desired output, it should provide the same data-acquisition and processing capability of the current system at a much-reduced production cost. The system would have limited output capabilities, providing a discharge rate from which a workability index is calculated. The embedded system would be easier to use, with fewer input options and an automatic output. The embedded system should have increased stability and reliability.

Once the signal-processing, data-acquisition, and other test-method parameters are chosen, the embedded system can be designed. Embedded systems can be built from scratch or set up using



multifunction-type kits. These kits provide a more economical solution for moderate production levels. Typically these kits contain data-acquisition components, a programmable microprocessor, ROM, RAM, and various binary and/or analog outputs on a single circuit board (figure 17).

Measurement speed and resolution, as well as computational performance, are dependent on the parameters of the embedded system.

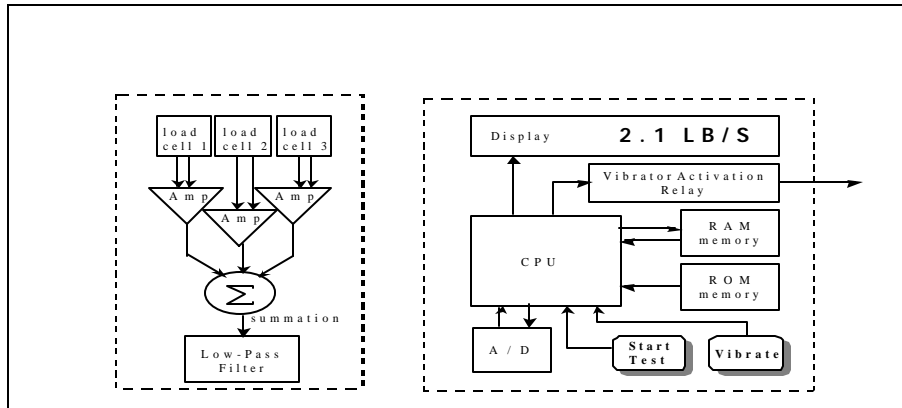


Figure 17. Schematic of embedded system.

## DEVELOPMENT PROGRAM

Several sophisticated signal-processing functions are currently implemented in the VSA. A development program should consist of additional performance studies of the parameters of these functions parameters as well as similar functions that may have implementation benefits. As an example, a polynomial curve fitted to the averaged data was found to be the most robust of several possible filtering techniques. However, there are many other filtering techniques (including adaptive and nonlinear methods) that were not explored. Because embedded systems are generally not flexible, it is important to invest a portion of the initial development effort into the research and design of what is being implemented. The goal of this phase should be to increase the reliability, accuracy, speed, and robustness of the final implementation.

Once a design has been selected, the implementation can follow many possible routes. As mentioned previously, the VSA is likely to have low-to-moderate production levels. Thus, a multifunction embedded-system kit will likely be the most economical solution.

Circuit-simulation software will be used to model the analog and, to a lesser extent, the digital portion of the embedded system. These simulators are highly developed and include such things as controlled modeling of temperature and noise effects. As an example, the existing load-cell signal-conditioning consists of a regulated power supply, differential buffer amplifiers, a summer amplifier, and an optional sixth-order low-pass filter. Simulation Program with Integrated Circuit Emphasis (SPICE) models of these components are freely available from manufacturers. The models allow designers to simulate and

test the components in a complete circuit. This modeling is important for “what-if” testing. For example, what if the power supply exceeds its output rating, or what if the ambient temperature is 40.55 °C (105 °F)? This modeling also allows optimization of passive component values (e.g., resistors, capacitors, diodes).

A processor-based embedded system will consist of some low-level programming. Most of the more developed kits use interpreted languages such as BASIC (beginners all purpose symbolic instruction code) or some form of compiler. A Motorola or Intel processor in its raw state would be programmed in 1's and 0's. At this level the programmer must specify every detail, such as where in memory to get an input value and where to put a result. The bulk of the programming effort will likely consist of implementing the signal-processing and data-handling functions.

Most embedded systems have both analog and digital components. Some of the initial design effort will focus on selecting the most appropriate form of implementation. Each type of implementation has its own benefits and drawbacks depending on what is being implemented. Noise immunity, speed, circuit complexity, design complexity, and stability are factors that should be evaluated when choosing between an analog or digital implementation.

At least one prototype should be constructed prior to constructing the final system. Various lessons and improvements from the prototype would be incorporated into the final system. End-user needs would determine the form of the final output. This could range from a scalar value displayed on a liquid crystal display (LCD) to onboard storage of data for serial or wireless downloads. The embedded system should be laid out with sufficient detail for accurate reproduction. This would include board level tuning, calibration, and evaluation procedures.

The final system would be packaged in a hand-held pendant form (figure 18). This pendant would have (as a minimum) membrane (waterproof) buttons for user input and an LCD for displaying test results. The pendant and internal components would be designed to resist damage from temperature, shock, and moisture.

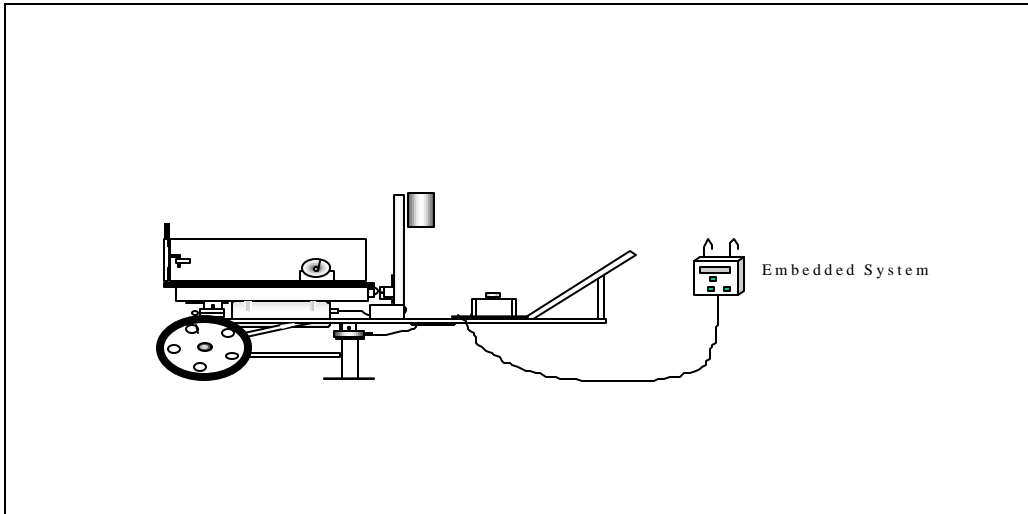


Figure 18. Hand-held pendant embedded system.

## CHAPTER 8: CONCLUSIONS

The development of the VSA was intended to provide additional information on workability of low-slump fresh concrete. Where the slump measures as static yield stress, workability is a function of effort required to move the concrete under applied force especially required in the placement of low-slump concrete. It was concluded that the VSA test could be used as a measure of workability of concrete having low slump. The use of vibration to impart energy to the concrete makes the calculation for determining basic rheological values challenging. In practice, vibration is used to consolidate concrete, so that values derived in this manner actually simulate field practices.

The following conclusions were made during this investigation:

1. Low-slump concrete acts more like a plastic than a fluid. Vibration is necessary to make the concrete fluid for the measurements made using the VSA. The design of the VSA encompasses the use of vibration in its design.
2. The VSA is capable of determining the workability of low-slump concrete. Due to some scatter in the data, and the lack of a method that currently can measure fundamental parameters of rheological properties of low-slump concrete, additional testing of all concrete mixtures that might be used by the highway department are needed to refine the limits of the device for distinguishing small differences in mixture proportions.
3. The workability of a concrete mixture can be described using two points. For mixtures there is a straight-line relationship between the discharge rate and the angle of the chute.
4. The VSA can be handled easily by a single operator. The device as constructed has a mass of about 136.1 kg (300 lb). The effect of mass of the VSA was minimized by mounting the unit on wheels and using mechanical advantage offered by extended handles. Some reduction in mass may be feasible, but much of the mass is in the vibrator and the support needed to evenly distribute the energy of the vibrator throughout the sample.

**APPENDIX A: PATENTS PERTINENT TO  
CONCRETE WORKABILITY**

<i>Patent No.</i>	<i>Year</i>	<i>Name</i>	<i>Inventor</i>
3935726	1976	Apparatus for measuring viscosity of liquids	Heinz
3967934	1976	Prothrombin timer	Seitz, Bowen
4062225	1977	Rotational viscometer and plastometer	Murphy and Ortm
4148215	1979	Apparatus for making rheological measurements	Hofstetter
4299119	1981	Incremental rotary viscometer	Figzgerald, Matusik, Nelson
4332158	1982	Slump testing device	Osborne
4356723	1982	Process and apparatus for continuously measuring slump	Fay
4388823	1983	Apparatus for automatically measuring viscosity of liquids	Garnaud, Bouhier
4535621	1985	Proc. & app. for meas. rheol. props. of semi-solid bodies by harmonic shear in rotation	Gervais, Vermeire, Cerf, Toux
4578989	1986	Concrete slump measuring device	Scott
4879897	1989	Method and apparatus for determination of viscosity	Booth, Edwards, Wrigley, Orth
5203203	1993	Viscometer for in situ monitoring	Bryan, Bryan
5240225	1993	Plastic slump cone	Workman, Fitzgerald
5321974	1994	Method and device for determining rheological properties	Hemmings
5357785	1994	Method and device for determining rheological properties	Hemmings
5359881	1994	Viscometer for sanitary applications	Kalotay, Van Cleve
5437181	1995	Concrete slump testing	Nasser

APPENDIX B: SYSTEMS EVALUATION FORMS

<b>Powers and Wiler Apparatus</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	Measures shear failure
Works across a broad range of mixes	Poor	High	Small aggregate size
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Fair		
In situ testing	Poor	Med	
Equipment testing (pump, paver, etc.)	Poor	Med	
<b>Cost:</b>			
Equipment cost	Fair	Med	
Testing time and labor	Fair	Med	
Maintenance and serviceability	<sup>1</sup>		
Availability	Poor	Med	
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Poor	Med	
<b>Ruggedness:</b>			
Ruggedness of components	Fair	Low	
Immunity to elements and handling	Poor	Low	

<sup>1</sup> Unpublished or unacquired information.

<b>Two-point Workability</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Good		
Works across a broad range of mixes	Fair	High	> 1-in slump w/ planetary drive
Rheological simplicity	Fair		Poor w/ planetary drive
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	Med	
<b>Cost:</b>			
Equipment cost	Fair	High	
Testing time and labor	Fair	Med	
Maintenance and serviceability	Good		
Availability	Good		Commercialized
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Fair		
Immunity to elements and handling	Poor	Low	

<b>Ready-mix Truck Hydraulic</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Fair	High	Slippage may be a problem
Works across a broad range of mixes	Fair		
Rheological simplicity	Poor	High	Sensitive to weight, load, etc
<b>Practicality:</b>			
Sample testing	Poor	High	
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Fair	High	Only mix-truck
<b>Cost:</b>			
Equipment cost	Fair	Low	
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Good		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		



<b>Colebrand Tester</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Low	
Works across a broad range of mixes	Fair	High	>7-mm slump, <32-mm aggregate
Rheological simplicity	Fair		
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Good		
Equipment testing (pump, paver, etc.)	Fair	Med	
<b>Cost:</b>			
Equipment cost	Fair		
Testing time and labor	Good		
Maintenance and serviceability	<sup>1</sup>		
Availability	Good		Commercialized
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Good		
<b>Ruggedness:</b>			
Ruggedness of components	Fair		
Immunity to elements and handling	Good		

<sup>1</sup> Unpublished or unacquired information.

<b>BML Viscometer</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Good		0.0022-0.85 rps
Works across a broad range of mixes	Fair		>80-mm slump, <32-mm aggregate
Rheological simplicity	Good		4 config, Coaxial cylinder
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Poor	High	
Testing time and labor	Good		
Maintenance and serviceability	<sup>1</sup>		Commercialized
Availability	Good		Commercialized
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Good		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	<sup>1</sup>		

<sup>1</sup> Unpublished or unacquired information.

<u>Moving Ball Viscometer</u>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Good		
Works across a broad range of mixes	Good		Theoretically
Rheological simplicity	Good		Classic rheological technique
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Good		
Equipment testing (pump, paver, etc.)	Good		
<b>Cost:</b>			
Equipment cost	Fair	Med	
Testing time and labor	Fair	Med	
Maintenance and serviceability	<sup>1</sup>		
Availability	Poor	Low	
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Good		
<b>Ruggedness:</b>			
Ruggedness of components	<sup>1</sup>		
Immunity to elements and handling	<sup>1</sup>		

<sup>1</sup> Unpublished or unacquired information.

<b>Free Orifice Rheometer</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Med	
Works across a broad range of mixes	Fair	High	Different tubes required
Rheological simplicity	Fair	Med	Without vibration
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Fair	Med	Specialized vibrator required
Testing time and labor	Fair		
Maintenance and serviceability	Good		
Availability	<sup>1</sup>		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Poor	Med	
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<sup>1</sup> Unpublished or unacquired information.

<b>Angles Flow Box</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	High	
Rheological simplicity	Poor	High	Mostly conceptual
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Fair		
Maintenance and serviceability	Good		
Availability	Poor	Low	
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>DIN Flow Table</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	High	
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Good		ASTM <sup>1</sup> standard
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<sup>1</sup> American Society for Testing and Materials.

<b>V-B Consistometer</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	High	<2-in slump
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Fair		
Maintenance and serviceability	Good		
Availability	Good		British Standard
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Fair		

<b>Compacting Factor</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Fair		
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Fair		
Maintenance and serviceability	Good		
Availability	Good		British Standard
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		



<b>K-slump</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	High	Better for high slump
Rheological simplicity	Poor	High	Does not test aggregate infl.
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Good	Low	Only measures near surface
Equipment testing (pump, paver, etc.)	Med	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Good		ASTM
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>Delivery Chute Torque Meter</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Low	
Works across a broad range of mixes	<sup>1</sup>		
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Poor	Med	
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Good		Delivery chute
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	<sup>1</sup>		Patented
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<sup>1</sup> Unpublished or unacquired information.

<b>Delivery Chute Vane</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Low	
Works across a broad range of mixes	<sup>1</sup>		
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Poor	Med	
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Good		Delivery chute
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Fair		Patented
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Poor	Med	
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<sup>1</sup> Unpublished or unacquired information.

<b>Remolding Test (Powers)</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	Med	
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Fair		
Testing time and labor	Fair	High	
Maintenance and serviceability	Good		
Availability	Fair		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>Thaulow Tester</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Poor	High	Different test for high slump
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Fair		
Testing time and labor	Poor	Med	
Maintenance and serviceability	Good		
Availability	Fair		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Poor	Med	
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>Vibrating Slope</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Low	
Works across a broad range of mixes	Fair		
Rheological simplicity	Poor	Med	Complicated by vibrator
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	Med	
<b>Cost:</b>			
Equipment cost	Fair		
Testing time and labor	Fair	Med	
Maintenance and serviceability	Good		
Availability	Good		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Poor	Low	
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>Kelly Ball</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	High	
Works across a broad range of mixes	Fair		
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Good		
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Good		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Good		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

<b>Wigmore Consistometer</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Low	
Works across a broad range of mixes	Poor	Med	Disturbed by large aggregate
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	Med	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Fair		
Testing time and labor	Fair		
Maintenance and serviceability	Good		
Availability	Good		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Fair		
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		



<b>BTRHEOM Rheometer</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Good		
Works across a broad range of mixes	Fair	Med	>2-in slump, >50-mm aggregate
Rheological simplicity	Good		
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Poor	High	
Equipment testing (pump, paver, etc.)	Poor	High	
<b>Cost:</b>			
Equipment cost	Poor	High	
Testing time and labor	Good		
Maintenance and serviceability	Fair		
Availability	Fair		Commercialized (France)
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity	Good		
<b>Ruggedness:</b>			
Ruggedness of components	Fair		
Immunity to elements and handling	Fair		

<b>Ring Penetration Test</b>	<b>Technical</b>	<b>Risk</b>	<b>Comments</b>
<b>Ability:</b>			
Operates at multiple shear rates	Poor	Med	
Works across a broad range of mixes	Poor	High	For fluid concrete
Rheological simplicity	Poor	High	
<b>Practicality:</b>			
Sample testing	Good		
In situ testing	Good		
Equipment testing (pump, paver, etc.)	Poor	Med	
<b>Cost:</b>			
Equipment cost	Good		
Testing time and labor	Good		
Maintenance and serviceability	Good		
Availability	Fair		
<b>User Friendliness and Simplicity:</b>			
Automation and simplicity			
<b>Ruggedness:</b>			
Ruggedness of components	Good		
Immunity to elements and handling	Good		

## APPENDIX C: HP-VEE DATA-ACQUISITION AND REDUCTION PROGRAM

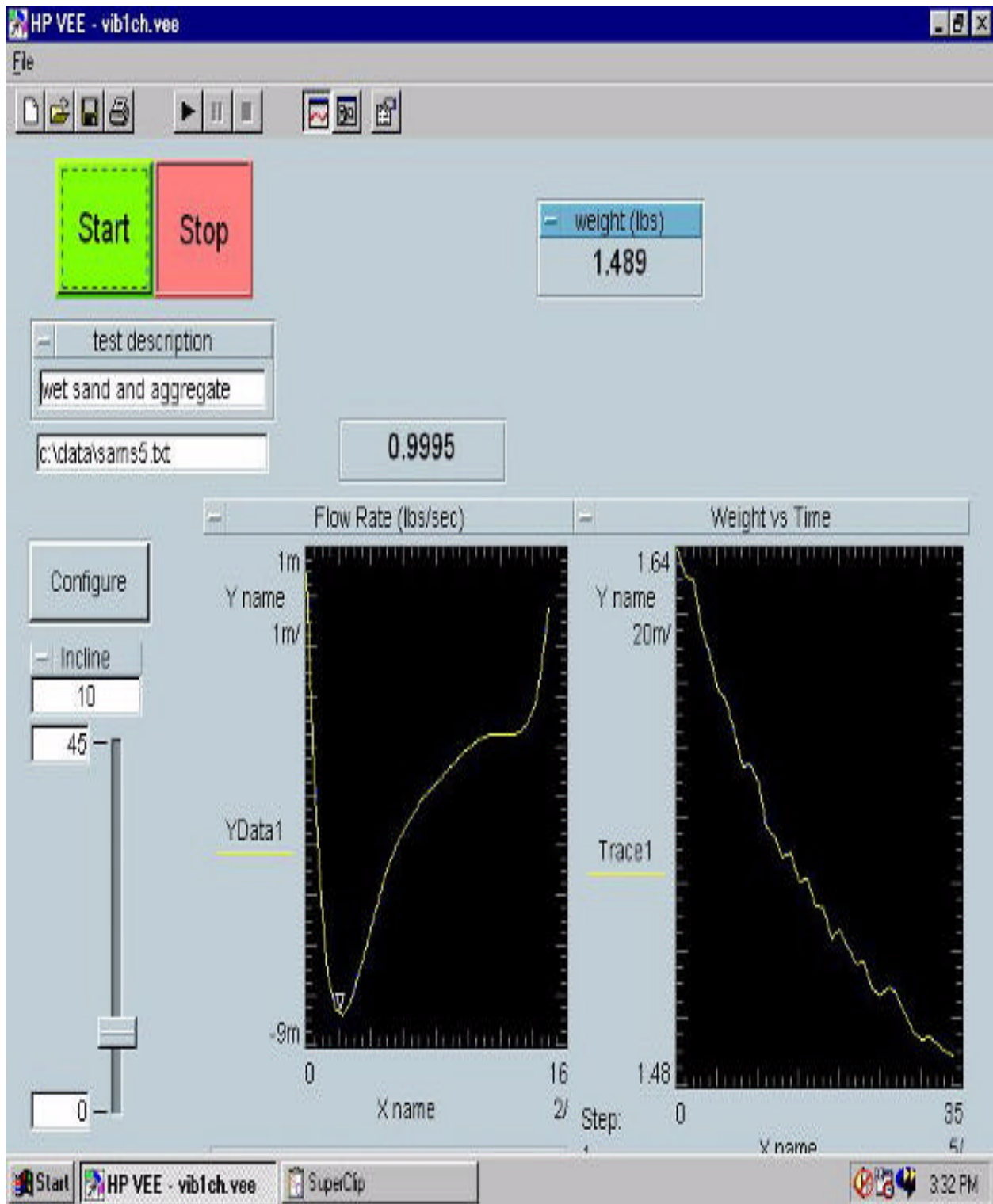


Figure 19. Data-acquisition screen.

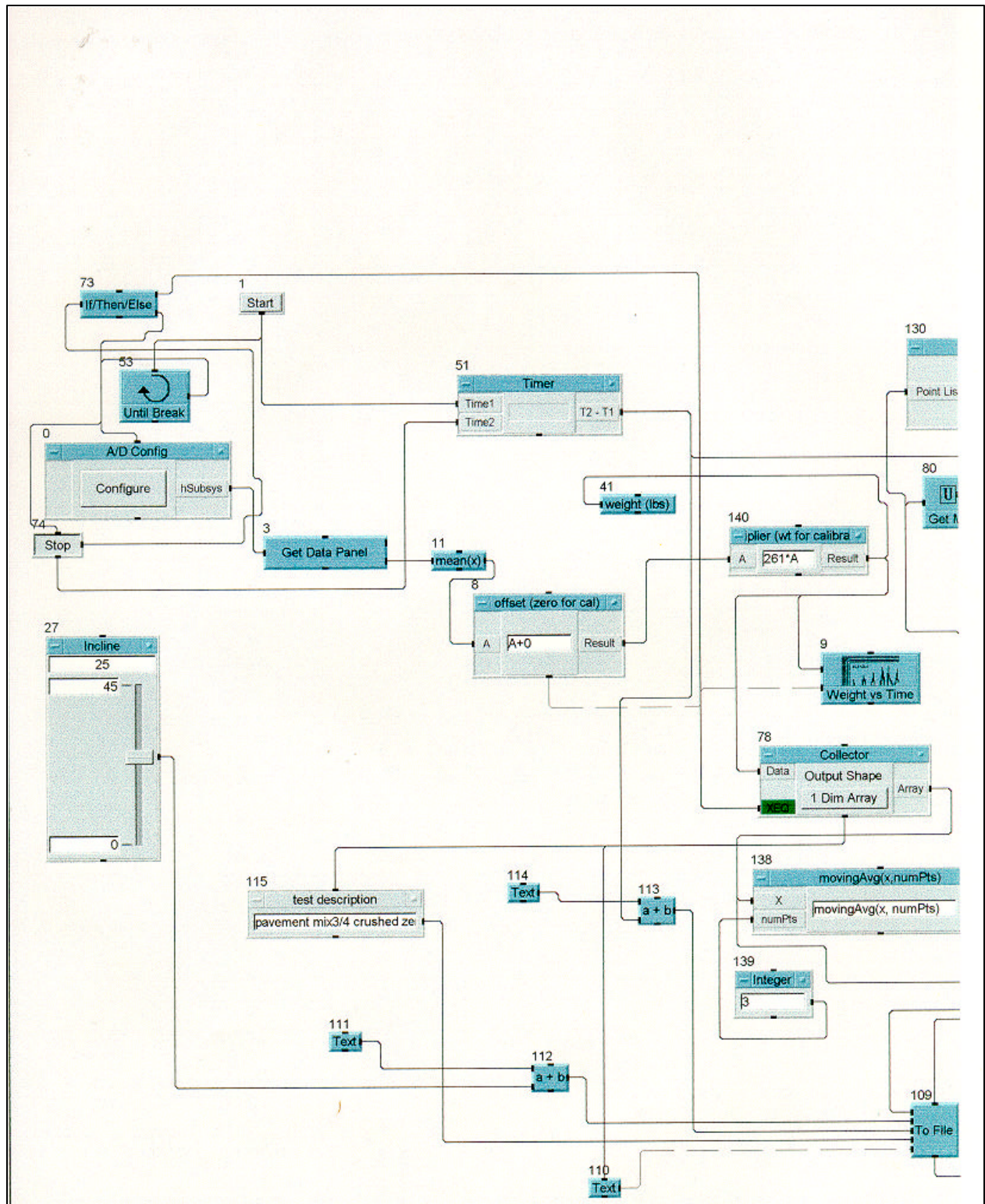


Figure 20. Data-acquisition program flow diagram and code (Sheet 1 of 2).



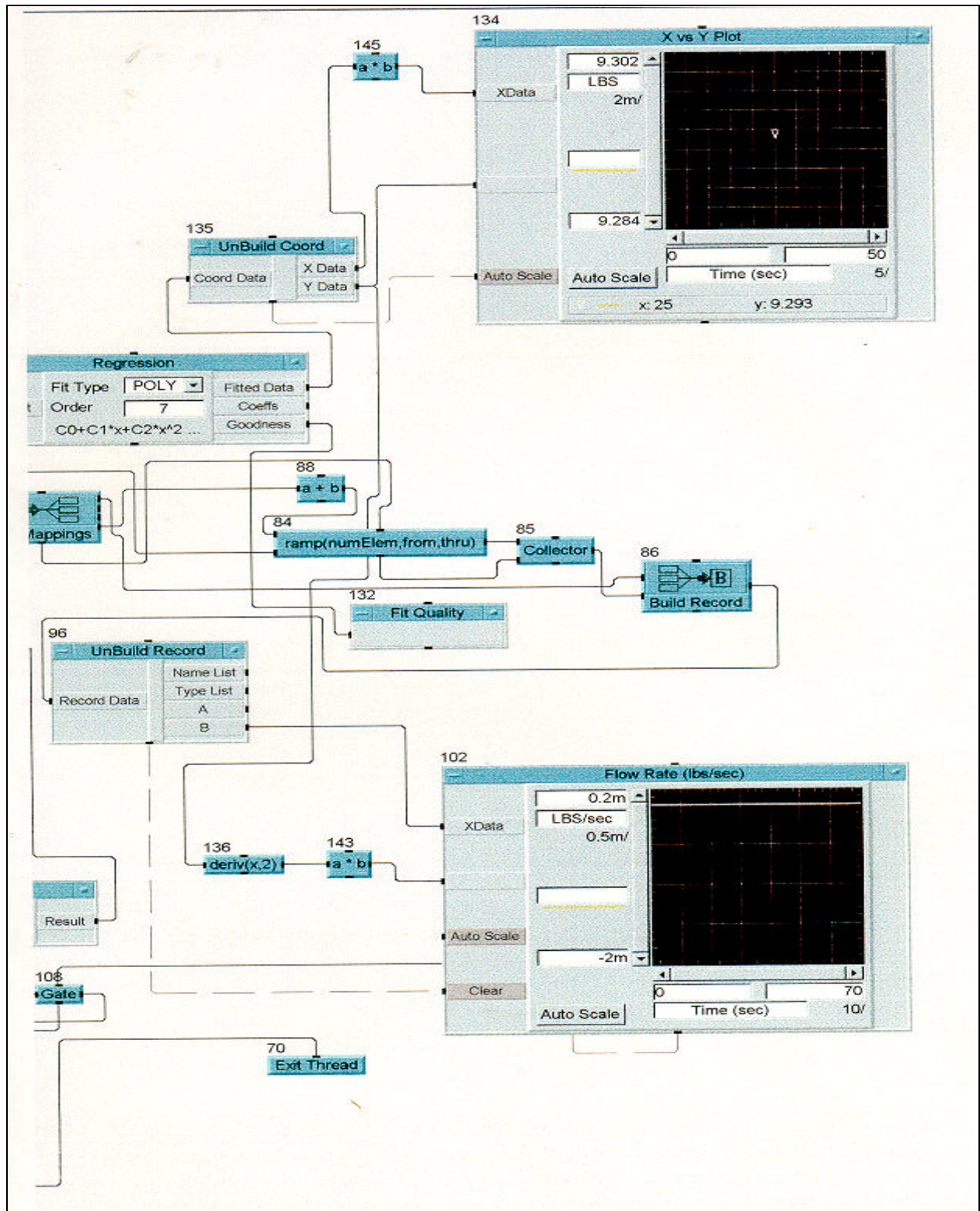


Figure 20. Data-acquisition program flow diagram and code (Sheet 2 of 2).

```

Main "Main"
- 0 at: C2 UserObject "A/D Config" is added to panel
- 1 at: A3 Start "Start" is added to panel
- 3 at: B3 UserObject "Get Data Panel"
- 8 at: C4 Formula "a + b"
  L Formula: A+0
- 9 at: D5 Y Plot "Weight vs Time" is added to panel
- 11 at: C3 Formula "mean(x)"
  L Formula: mean(x)
- 27 at: E2 Slider "Incline" is added to panel
  L Value Range: 0, 45
  L Detent Size: 1
- 41 at: C5 AlphaNumeric "weight (lbs)" is added to panel
- 51 at: B4 Timer "Timer"
- 53 at: B1 Until Break "Until Break"
- 70 at: F9 Exit Thread "Exit Thread"
- 73 at: A1 If/Then/Else "If/Then/Else"
  L If/Else cases: 0<A
- 74 at: C1 Toggle Control "Stop" is added to panel
  L Initialize At Prerun: true
- 78 at: D7 Collector "Collector"
- 80 at: B6 Get Mappings "Get Mappings"
- 84 at: C9 Formula "ramp(numElem,from,thru)"
  L Formula: ramp(numElem, 0, thru)
- 85 at: C11 Collector "Collector"
- 86 at: B12 Build Record "Build Record"
  L Record output shape: Array
- 87 at: F11 Logging AlphaNumeric "Logging AlphaNumeric"
  L Buffer Size: 256
- 88 at: C8 Formula "a + b"
  L Formula: A+1
- 96 at: D12 UnBuild Record "UnBuild Record"
- 102 at: E11 X vs Y Plot "Flow Rate (lbs/sec)" is added to panel
- 108 at: E9 Gate "Gate"
- 109 at: F8 To File "To File"
  L Transactions: 4 lines.
    L WRITE TEXT d EOL
    L WRITE TEXT b EOL
    L WRITE TEXT c EOL
    L WRITE TEXT a EOL
- 110 at: G6 Text Constant "Text" is added to panel
- 111 at: D3 Text Constant "Text"
- 112 at: E3 Formula "a + b"
  L Formula: A+B
- 113 at: F6 Formula "a + b"
  L Formula: A+B
- 114 at: F5 Text Constant "Text"
- 115 at: F3 Text Constant "test description" is added to panel
  L Auto execute: true
- 130 at: B8 Regression "Regression"
  L Fit Type: Polynomial
  L Polynomial fit order: 7
- 132 at: D9 AlphaNumeric "AlphaNumeric" is added to panel
- 134 at: A11 X vs Y Plot "X vs Y Plot"
- 135 at: A9 UnBuild Coord "UnBuild Coord"
- 136 at: B10 Formula "deriv(x,2)"
  L Formula: deriv(x, 1)
- 138 at: D9 Formula "movingAvg(x,numPts)"
  L Formula: movingAvg(x, numPts)
- 139 at: E7 Constant "Integer"
- 140 at: C5 Formula "a * b"
  L Formula: -1*A

```

Figure 21. Data-acquisition code.

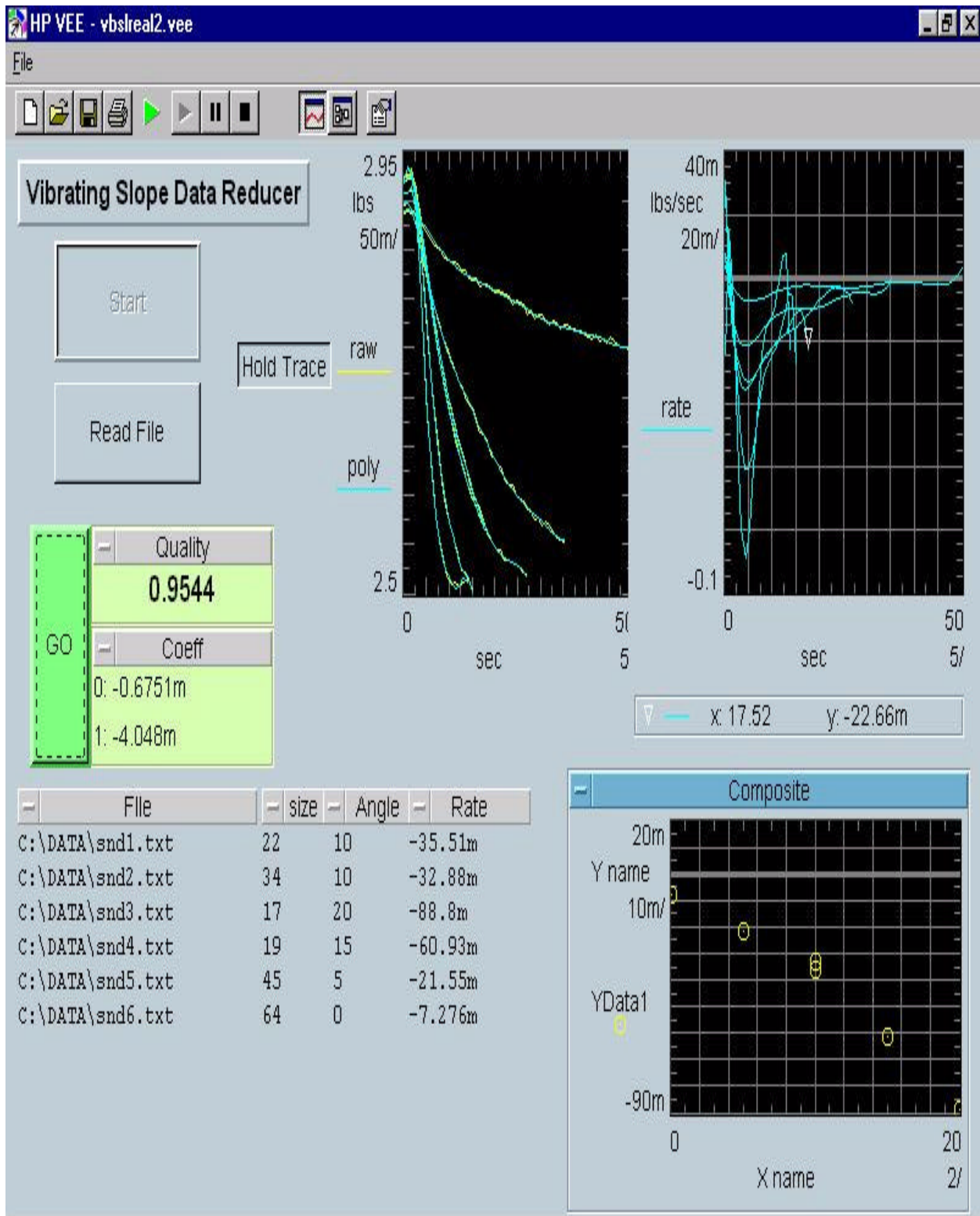


Figure 22. Data-reduction screen.



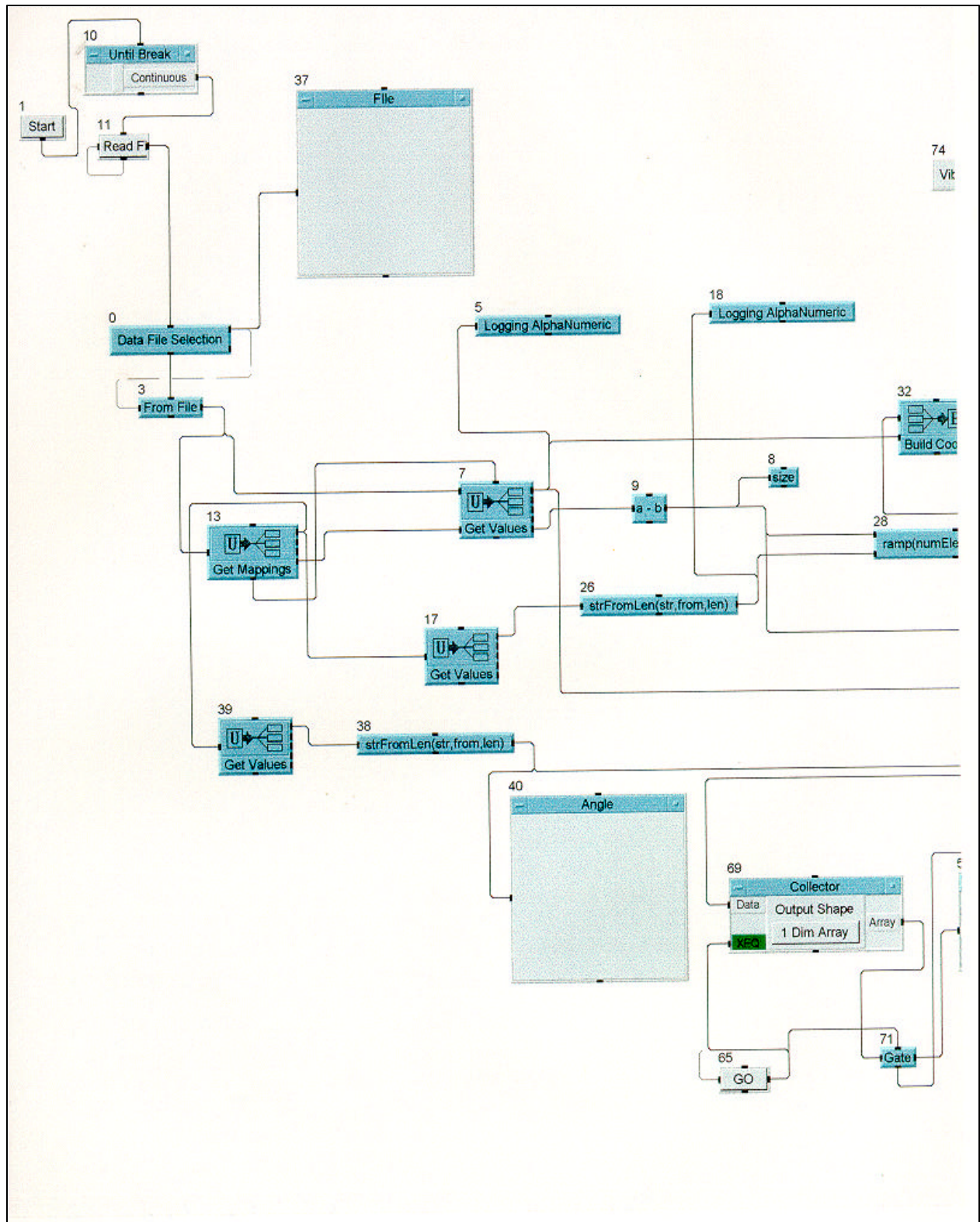


Figure 23. Data-reduction program flow diagram and code (Sheet 1 of 2).



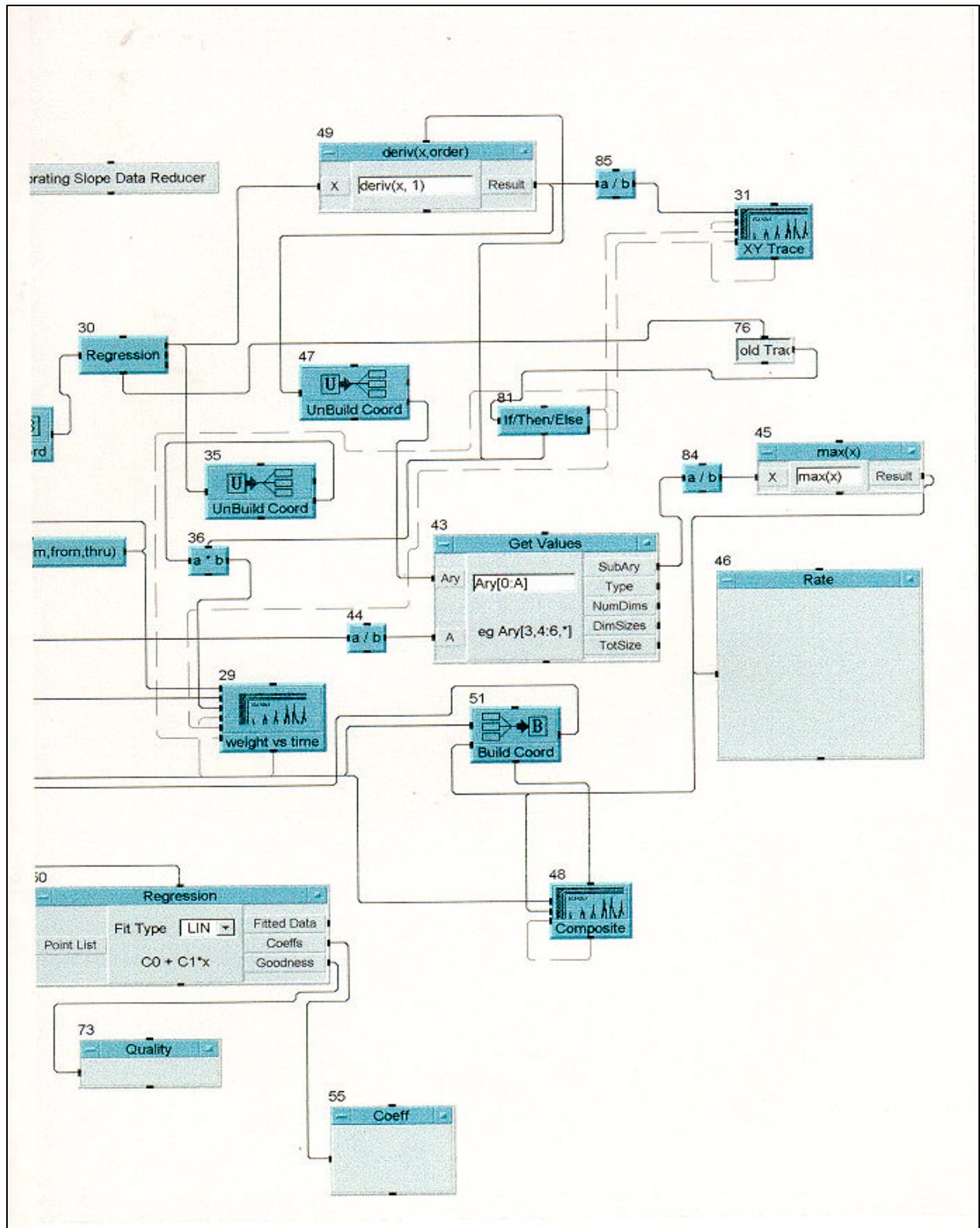


Figure 23. Data-reduction program flow diagram and code (Sheet 2 of 2).

```

Main "Main"
- 0 at: C2 File Selection "Data File Selection"
  | Prompt/Label: "Enter File Name:"
  | Initial Directory: "C:\\data\\*.*"
  | Initial File: "*.txt"
  | Dialog Mode: Reading
- 1 at: B1 Start "Start" is added to panel
- 3 at: C2 From File "From File"
  | Transactions: READ TEXT x STR ARRAY:*
- 5 at: C5 Logging AlphaNumeric "Logging AlphaNumeric"
  | Buffer Size: 256
- 7 at: D3 Get Values "Get Values"
  | Formula: Ary(3:A)
- 8 at: D5 Logging AlphaNumeric "size" is added to panel
  | Buffer Size: 256
- 9 at: D4 Formula "a - b"
  | Formula: A-3
- 10 at: A2 Until Break "Until Break"
- 11 at: B2 Toggle Control "Read File" is added to panel
  | Wait For Event: true
- 13 at: D1 Get Mappings "Get Mappings"
- 17 at: E3 Get Values "Get Values"
  | Formula: Ary(2)
- 18 at: D7 Logging AlphaNumeric "Logging AlphaNumeric"
  | Buffer Size: 256
- 26 at: E4 Formula "strFromLen(str,from,len)"
  | Formula: strFromLen(str, 26, 18)
- 28 at: E7 Formula "ramp(numElem,from,thru)"
  | Formula: ramp(numElem, 0, thru)
- 29 at: E9 X vs Y Plot "weight vs time" is added to panel
- 30 at: C8 Regression "Regression"
  | Fit Type: Polynomial
  | Polynomial fit order: 7
- 31 at: B12 Y Plot "XY Trace" is added to panel
- 32 at: C7 Build Coord "Build Coord"
- 35 at: D9 UnBuild Coord "UnBuild Coord"
- 36 at: D10 Formula "a * b"
  | Formula: A*1
- 37 at: B3 Logging AlphaNumeric "File" is added to panel
  | Buffer Size: 256
- 38 at: F4 Formula "strFromLen(str,from,len)"
  | Formula: strFromLen(str, 21, 3)
- 39 at: F3 Get Values "Get Values"
  | Formula: Ary(1)
- 40 at: F6 Logging AlphaNumeric "Angle" is added to panel
  | Buffer Size: 256
- 43 at: C13 Get Values "Get Values"
  | Formula: Ary(0:A)
- 44 at: E7 Formula "a / b"
  | Formula: A/2
- 45 at: F12 Formula "max(x)"
  | Formula: max(x)
- 46 at: F13 Logging AlphaNumeric "Rate" is added to panel
  | Buffer Size: 256
- 47 at: C10 UnBuild Coord "UnBuild Coord"
- 48 at: G11 X vs Y Plot "Composite" is added to panel
- 49 at: B9 Formula "deriv(x,order)"
  | Formula: deriv(x, 1)
- 50 at: G6 Regression "Regression"
  | Fit Type: Linear
- 51 at: F11 Build Coord "Build Coord"
- 55 at: G7 AlphaNumeric "Coeff" is added to panel
- 65 at: F3 Toggle Control "GO" is added to panel
  | Wait For Event: true
- 69 at: F4 Collector "Collector"
- 71 at: G4 Gate "Gate"
- 73 at: G8 AlphaNumeric "Quality" is added to panel
- 74 at: B5 Label "Vibrating Slope Data Reducer" is added to panel
  | Label: "Vibrating Slope Data Reducer"
- 76 at: B11 Toggle Control "Hold Trace" is added to panel
  | Auto execute: true
- 81 at: D11 If/Then/Else "If/Then/Else"
  | If/Else cases: A>0
- 84 at: F13 Formula "a / b"
  | Formula: A/-1
- 85 at: B11 Formula "a / b"
  | Formula: A/-1

```

Figure 24. Data-reduction code.

## APPENDIX D: VIBRATING-SLOPE APPARATUS TEST METHOD

### Standard Test Method for Determining Workability of Freshly Mixed Hydraulic-Cement Concrete Using the Vibrating-Slope Apparatus<sup>1</sup>

1. This test method covers determination of workability of low-slump hydraulic-cement concrete, both in the laboratory and in the field, using the vibrating-slope apparatus.

1.1 The values stated in SI units are to be regarded as standard.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 The text of this standard references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables and figures) shall not be considered as requirements of the standard.

#### 2. Reference Document

2.1 *ASTM Standard-*

C 172-Practice for Sampling Freshly Mixed Concrete (ASTM 1994d)

C 143/C 143M-Standard Test Method for Slump of Hydraulic-Cement Concrete (ASTM (1994c)

#### 3. Summary of Test Method

3.1 A sample consisting of approximately 0.1 m<sup>3</sup> sample of freshly mixed concrete is placed and compacted by vibrating in the chute. The chute is raised to predefined angle and vibrated to allow the concrete to flow out of the chute. The rate of discharge is measured and recorded. A second sample is prepared in the same manner and tested at a predefined angle different than that which was used in the first measurement. The workability is defined as the slope of the line defining the two discharge rates versus the angle of the discharge chute.

---

<sup>1</sup> American Society for Testing and Materials (ASTM). Reference information is found on page 97 at end of main text.

#### 4. Significance and Use

- 4.1 This test method is intended to provide the user with a procedure to determine workability of freshly mixed hydraulic-cement concrete.
- 4.2 This test method is considered applicable to freshly mixed concrete having coarse aggregate of not greater than 37.5 mm in nominal maximum size
- 4.3 This test method is considered applicable to cohesive and noncohesive concrete.

Note 1—This test method may not adequately test concrete having slumps greater than 50 mm.

#### 5. Apparatus

- 5.1 Angle indicator shall be a device with one flat edge that can be used to measure the angle of the floor of the chute when elevated to different angles.
- 5.2 Vibrating slope apparatus shall consist of chute measuring 0.6 m long by 229 mm wide (2 ft by 9 in) by 300 mm high (12 in). It shall be mounted with a vibrator such as to consolidate the sample as well as to cause the concrete to move during the testing. The vibrator shall have a 227.79-kg (500-lb) force capacity running at 4,000 RPM. The apparatus shall have the ability to raise the chute to different angles prior to initiating the test. The apparatus shall have a method by which the rate at which concrete is discharged from the chute can be determined. One method as described in figure 25 is to mount the chute on load cells which can be used to continuously monitor the amount remaining in the chute, thus a calculation can be made to determine the rate concrete is discharged from the chute. Load-cells shall contain a 120-ohm bridge, 20-v maximum excitation (+/- 10 v implemented), and have a 227.78-kg (500-lb) tension/compression fatigue rating.

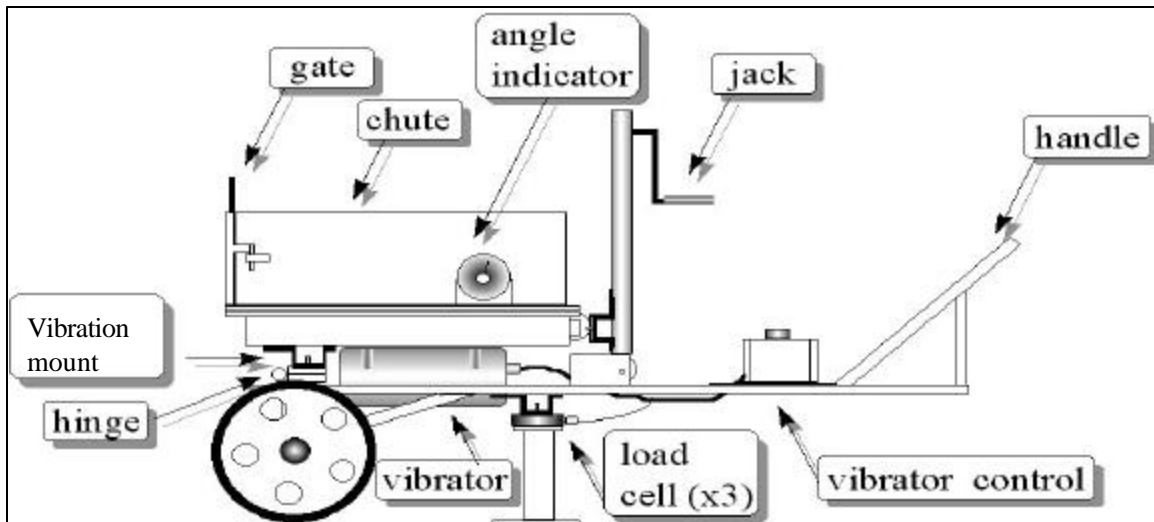


Figure 25. Vibrating-slope apparatus.

- 5.3 The data-collection program allows the user to change data-acquisition parameters (angle of incline, test description, data file and length of test). The length of time for the test can be set and the chute angle can be entered into the data. The time of test is usually set at 60 sec or less, and the test is usually stopped at less than 45 sec, depending on the chute angle and the workability of the concrete. When the user clicks the start button, the software activates a timer that keeps up with the elapsed test time. This start button also begins the data acquisition. During acquisition, 4,096 samples are collected at a rate of 100,000 samples/second and then averaged to generate each data point. This sampling process is repeated until the stop button is pressed. A multiplier and offset are used to apply a calibration to the data. Periodic calibration is performed using dead weights.
- 5.4 Data files are used to construct a wave form that relates amplitude as a function of elapsed time. A seventh-order polynomial fit is applied to the data as a type of low-pass filter. A first-order derivative is then applied to the data to convert it from mass to mass flow rate. The maximum mass flow rate (R) that occurs in the first half of the data is then extracted.

## 6. Sample

- 6.1 The sample of concrete from which test specimens are made shall be representative of the entire batch and obtained in accordance with Practice C 172 (ASTM 1994d).

## 7. Procedure

- 7.1 Level the bottom of the chute. Dampen the chute and let drain so that no standing water remains in the chute. Place the concrete into the chute in a single lift, bringing the level of the concrete 4 in (10 cm) above the bottom of the chute. Using the vibrator attached to the apparatus, vibrate the concrete to consolidate the concrete. This should take approximately 5 sec, depending on the stiffness of the concrete.
- 7.2 Raise the angle of the chute to 10 deg, open the gate, and begin data acquisition and vibration.
- 7.3 Clean the residual concrete from the chute and relevel chute. Place a second sample of concrete into the chute to the same height and treat sample as in paragraph 7.1. After consolidation, raise the chute angle to 25 deg and repeat the test as described above.

## 8. Calculation

Calculate the workability index as follows:

$$R = WA + C$$

R = rate of discharge, mass/unit time

A = angle of discharge, degrees

W = workability index

C = calculated yield offset

$$W = (R_2 - R_1)/(A_2 - A_1)$$

$$C = R - WA$$

## 9. Report

- 9.1 Report the angle of discharge chute and the discharge rate for each sequence.
- 9.2 Report W, C, and slump. The resistance of the concrete to move is a function of workability W and yield stress C as calculated or slump as measured by ASTM C 143 (ASTM 1994c).

## 10. Precision and Bias

- 10.1 No precision or bias information are available for this test method.

## 11. Keywords

- 11.1 Concrete; consistency; plasticity; slump; workability.

APPENDIX E: DETAILED DRAWINGS OF VSA

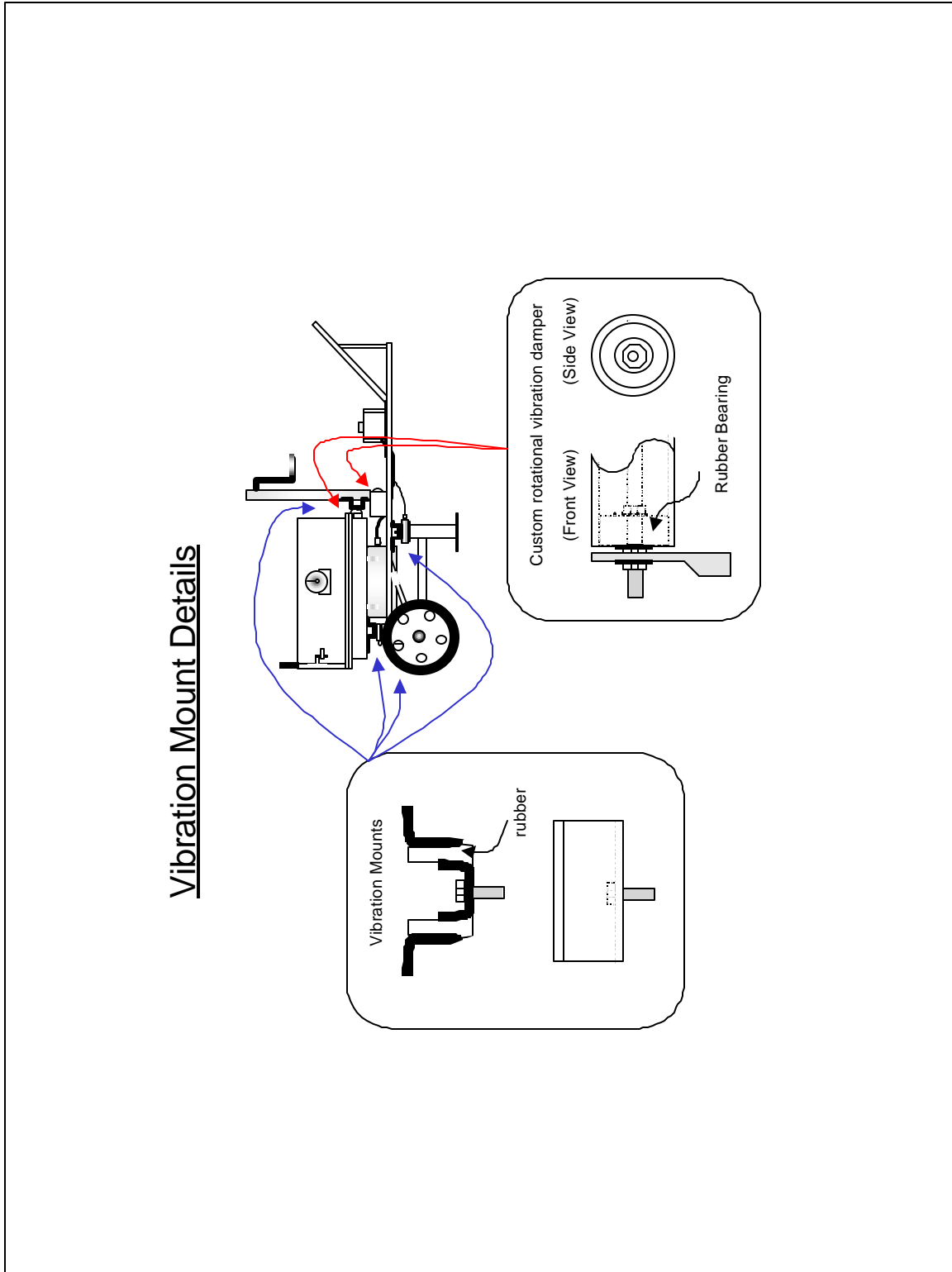


Figure 26. Details of vibration isolation mounts.

## Portable Vibrating-Slope Device

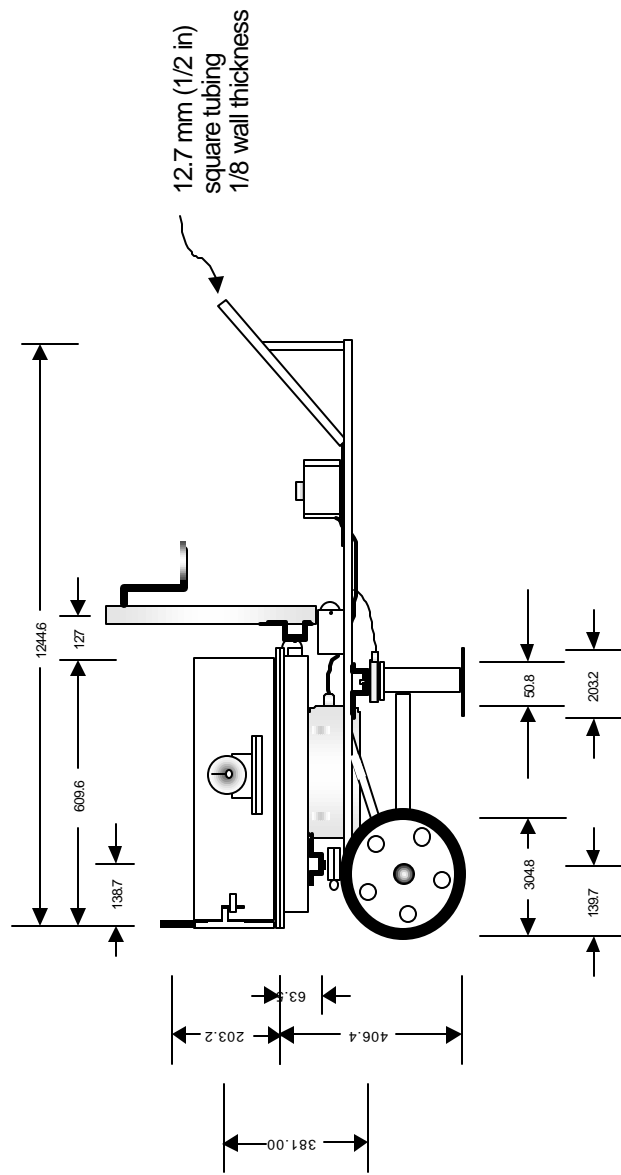


Figure 27. Dimensions of VBA device.



### Portable Vibrating-Slope Chute

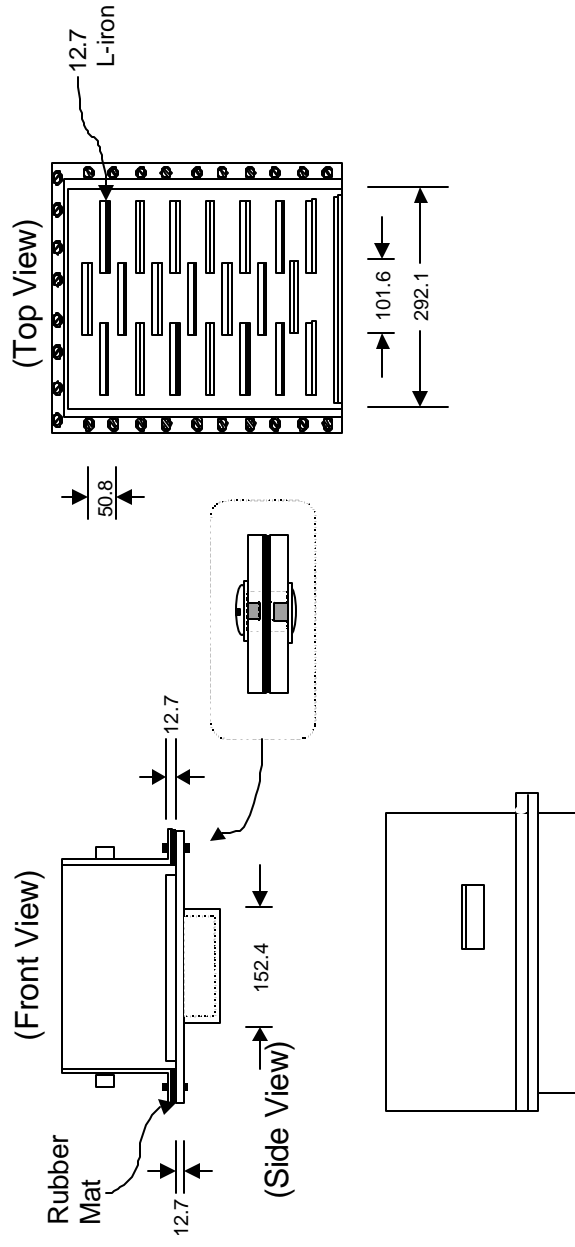


Figure 28. Chute walls are isolated from vibration, and the floor of the chute is ribbed to minimize slippage.

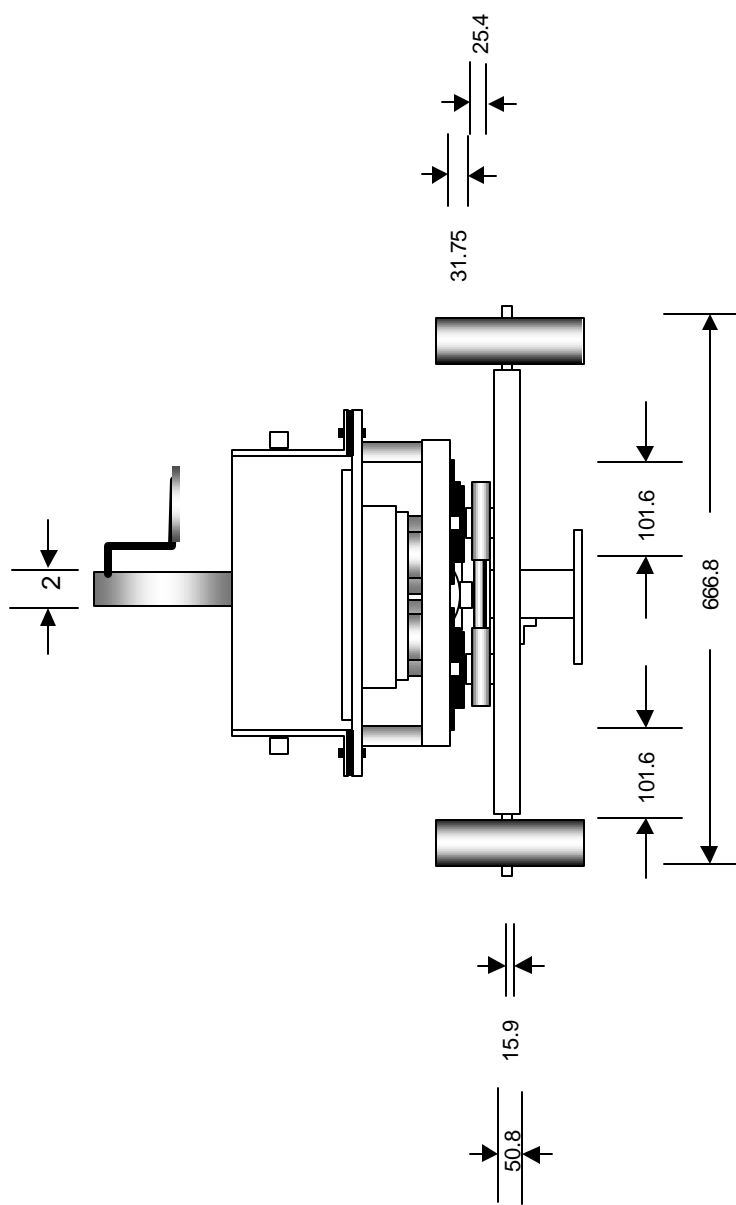


Figure 29. Rear view of VBA.

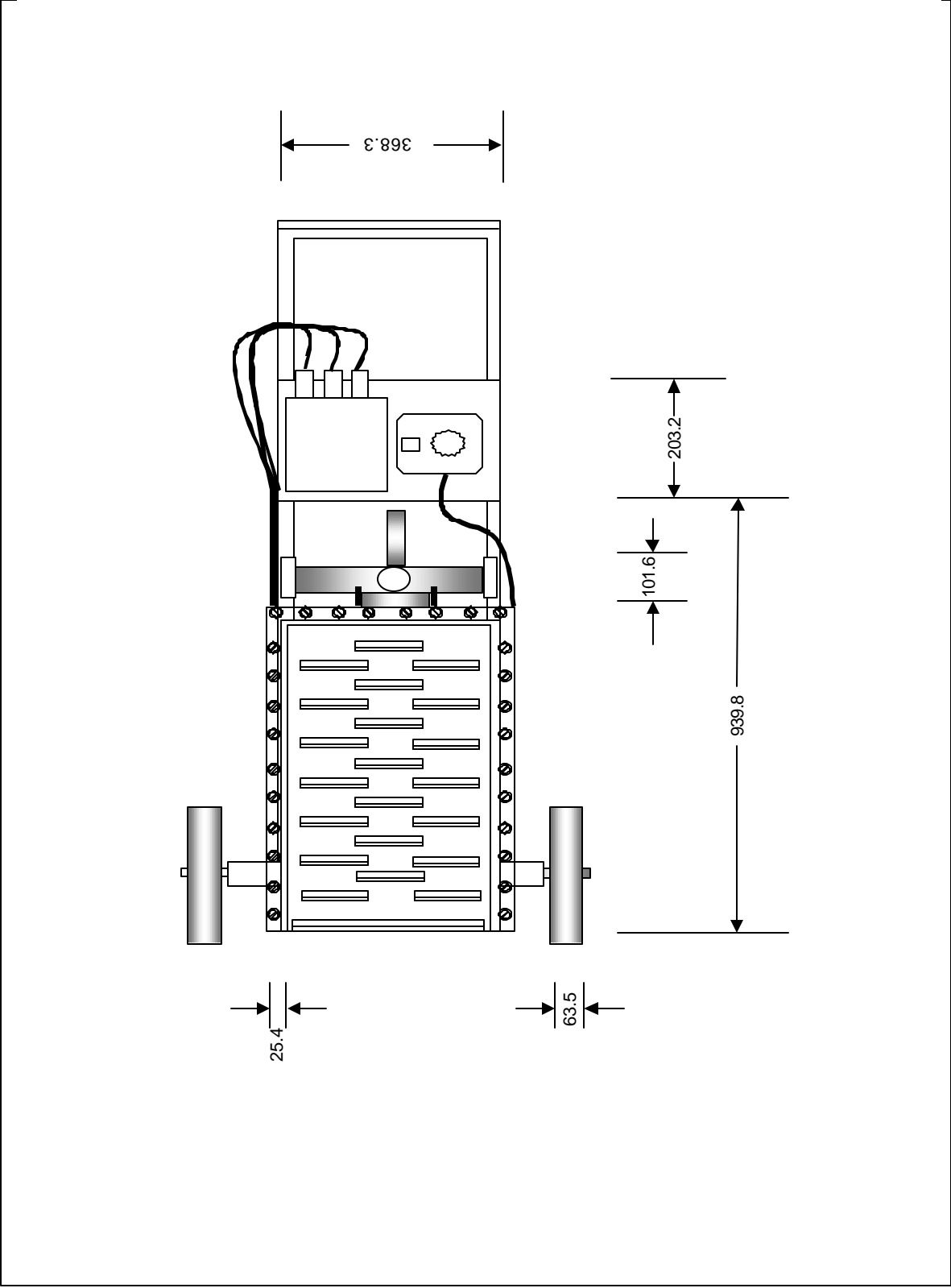


Figure 30. Map view of the VBA.

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  - f. Designation C 360, "Standard test method for penetration in freshly mixed hydraulic cement concrete."
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